IMPROVING THE IMPLEMENTATION OF NEW TECHNIQUES AND TECHNOLOGIES IN RADIATION ONCOLOGY

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STATEMENT OF ORIGINALITY

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

In addition, ethical approval was obtained from a Human Research Ethics Committee for the work presented in Chapter 4, 5, 7 and 9.

Signature

Elizabeth Ruth Claridge Mackonis

Prof Annette Haworth

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I designed the study, collected the data, analysed the data, wrote the first draft manuscript and implemented the contribution of the co-authors and external reviewers up to final publication.

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I designed the study, wrote the interview questions, interviewed radiation oncology professionals across NSW, analysed the data, wrote the first draft manuscript and implemented the contribution of the co-authors and external reviewers up to final publication.

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Date:

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Prof. Annette Haworth

Date:

GENERATIVE AI STATEMENT

I acknowledge the use of ChatGPT (https://chatgpt.com/) brainstorm ideas for the title of paper 4, to assist with the connection of the AusCAT/ACDN database to the hospital patient databases and in assisting with the coding required for the work in Chapter 9.

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ABSTRACT

For many cancer patients, radiation therapy forms an important part of their treatment. Radiation therapy is a highly technical discipline with new techniques and technologies being introduced frequently, aiming to improve patient outcomes and increase efficiency. The timing of the implementation of new technologies and techniques is highly variable across radiation therapy centres and can be delayed due to concerns related to safety and quality. The purpose of the work described in this thesis was to identify barriers to rapid uptake of new techniques and technologies, and explore solutions to enable equitable access for all patients to receive advanced treatment approaches. The overarching hypothesis for the work contained in this thesis: Barriers to the safe, high-quality and timely implementation of new technologies and techniques into New South Wales (NSW) radiation oncology centres can be identified and minimised using targeted interventions.

The initial work in this thesis assesses the implementation of a new technique into radiation therapy centres in NSW, identifying potential barriers and areas for improvement. The thesis continues with two group projects aimed at improving the implementation of technological advancements into radiation therapy through collaboration. Both projects facilitated knowledge-sharing and evaluated the success of each methodology. The studies in the later chapters of the thesis were specifically designed to assist the implementation of new techniques and technologies into radiation therapy centres by addressing the barriers and areas for improvement identified in the earlier work.

The first two peer-reviewed manuscripts included in this thesis investigate the timing and quality of the implementation of stereotactic ablative body radiation therapy (SABR) into New South Wales radiation therapy centres. These works show that the implementation of SABR was delayed in some centres relative to other centres and that some quality indicators were not met at many of the centres in NSW.

The topics of the third and fourth published manuscripts investigated the benefit of forming collaborative groups to improve the timeliness and quality of the implementation of new techniques. The first paper focussed on knowledge-based planning and the second on motion management techniques. The work in these papers demonstrated that collaboration can improve knowledge-sharing, but that direct sharing of resources may be limited by a lack of standardization between centres.

Chapters 7, 8 and 9 describe three projects instigated to address barriers to the high-quality and safe implementation of new techniques and technologies which were identified in the earlier chapters. The first of these projects introduces a new peer-to-peer training program which has increased the use of prospective risk assessment processes during the implementation phase of a new technique, and increased knowledge about risk assessments within the NSW radiation therapy community. The second project introduces an innovative sharing platform which encourages collaboration and creates efficiencies by providing the radiation therapy community with access to documents, scripts, presentations and information from radiation therapy departments around Australasia.

The third targeted project used an existing research framework to introduce automated, consistent auditing against quality standards across multiple hospitals, creating a template for future audits and self-assessments. This innovation has the potential to change practice, and from this, improve patient outcomes. Automated auditing will allow fast and flexible audits with reduced manual labour, and the correlation of audit results with patient outcomes. This new method of auditing will change and complement current auditing practices.

In summary, this thesis demonstrates that barriers to the timely, safe and high-quality implementation of new techniques and technologies can be addressed using well-planned, targeted and collaborative strategies, ensuring equitable access for NSW patients. The work in this thesis provides a template for future collaborative and automated projects, particularly for those focussing on the implementation of technology-based innovations into radiation therapy, in and beyond NSW.

PUBLICATIONS

Papers

Paper 1 **Stereotactic ablative body radiation therapy (SABR) in NSW**

Elizabeth R. Claridge Mackonis, Nicholas Hardcastle, Annette Haworth

Physical and Engineering Sciences in Medicine, 2020

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Paper 3 **A comparison of in-house and shared RapidPlan models for prostate radiation therapy planning**

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Paper 4 **Improving motion management in radiation therapy: findings from a workshop and survey in Australia and New Zealand**

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Physical and Engineering Sciences in Medicine, 2024

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Paper 5 **Increasing the use of prospective risk assessment through training**

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Conference presentations

Engineering and Physical Sciences in Medicine 2018

Stereotactic ablative body radiotherapy (SABR) in NSW: where are we now?

Elizabeth Claridge Mackonis, Nicholas Hardcastle, Maddison Shaw, Jessica Lye, Annette Haworth

Engineering and Physical Sciences in Medicine 2019

Should we share RapidPlan models or make our own?

Elizabeth Claridge Mackonis, Anthony Espinoza, Alison Brown, Gino Perez, Brigitte Evans, Annette Haworth, Jonathan Sykes

IUPESM World Congress on Medical Physics and Biomedical Engineering 2022

Comparing In-House and Externally Developed Rapidplan Models for Prostate Radiation Therapy

Elizabeth Claridge Mackonis, Jonathan Sykes, Nicholas Hardcastle, Anthony Espinoza, Alison Brown, Gino Perez, Bridgitte Evan, Hayden Sheehan, Annette Haworth

Engineering and Physical Sciences in Medicine 2023

Australasia's Approach to Motion Management in Radiation Therapy: Analysis of Surveys from a multi-day workshop

Elizabeth Claridge Mackonis, Rachel Stensmyr, Rachel Poldy, Paul White, Zoë Moutrie, Tina Gorjiara, Erin Seymour, Tania Erven, Nicholas Hardcastle, Annette Haworth

2025 Annual ROECSG (Radiation Oncology Education Collaboration Study Group) Symposium

Implementing Targeted Training in the use of Prospective Risk Assessments

Elizabeth Claridge Mackonis, Anna Ralston, Johnson Yuen, Nicholas Hardcastle, Annette Haworth

IUPESM World Congress on Medical Physics and Biomedical Engineering 2025

Increasing the use of prospective risk assessments through targeted training

Elizabeth Claridge Mackonis, Anna Ralston, Johnson Yuen, Nicholas Hardcastle, Annette Haworth

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

3DCRT	Three-dimensional conformal radiation therapy
4DCT	Four-dimensional computed tomography
4DCBCT	Four-dimensional cone-based computed tomography
AI	Artificial Intelligence
AAPM	American Association of Physicists in Medicine
ACDN	Australian Cancer Data Network (encompasses AusCAT)
ACPSEM	Australasian College of Scientists and Engineers in Medicine
AusCAT	Australian Computer Assisted Theragnostics (within the ACDN)
CBCT	Cone-based computed tomography
CT	Computed Tomography
COPPER	Collaborative Online Platform for Physicists in Radiation
CTV	Clinical target volume
DCAT	Dynamic conformal arc therapy
DVH	Dose Volume Histogram
EPID	Electronic portal imaging device
GTV	Gross tumour volume
FFF	Flattening filter free
IGRT	Image guided radiation therapy
IMRT	Intensity modulated radiation therapy
KBP	Knowledge-based planning
kV	Kilo-voltage
MLC	Multi-leaf collimator
MRI	Magnetic resonance imaging
MV	Mega-voltage
MVCT	Mega-voltage computed tomography

NSW	New South Wales
OAR	Organ-at-risk
PTV	Planning target volume
PRA	Prospective Risk Assessment
QA	Quality Assurance
RANZCR	Royal Australia and New Zealand College of Radiology
SABR	Stereotactic ablative body radiotherapy, also known as SBRT
SBRT	Stereotactic body radiation therapy, also known as SABR
SGRT	Surface guided radiation therapy
SRS	Stereotactic radiosurgery
VMAT	Volumetric modulated arc therapy

CHAPTER 1

Introduction

1. BACKGROUND

According to the World Health Organization, cancer is the leading cause of death worldwide, accounting for nearly one in every 6 deaths and totally 10 million deaths in 2020 (1). Every year in Australia, over 160,000 people are diagnosed with cancer, and over 460,000 people are living with cancer (2). In New South Wales, this equates to 1 in every 2 people being diagnosed with cancer by the time they are 85 years old (3).

The good news is that many cancers can be cured if detected early and treated effectively (1) and 5-year cancer survival rates have increased over time (4) . While much of this improvement can be attributed to reductions in smoking rates and improved detection, modern cancer treatments have also contributed with the overall survival following radiation therapy improving over time (5, 6).

Radiation therapy uses ionizing radiation to kill cancer cells and would be of benefit to 48% of cancer patients at sometime during their cancer journey (7). Radiation therapy is one of the most technologically driven disciplines in medicine (8) and the improvements seen in local control, survival and toxicity can be attributed to technological advancements and the changes in treatment techniques that these advancements allow (8-11). It is therefore important to ensure these improvements are implemented in a timely manner and are available to all patients.

However, the introduction of new technology is not without risk. In a review of all major radiation therapy incidents that lead to patient injury or death, the Internation Atomic Energy Agency found that 45% these incidents were due to errors that occurred during the introduction of new systems and/or equipment (12). Given the significant impact of these errors, the challenge is then to introduce technological improvements both safely and quickly, ensuring high quality treatments are available to all patients.

The work in this thesis aims to identify barriers which prevent new radiation therapy techniques and technologies being available to all patients in a high-quality, safe and timely manner, and, where possible, reduce or remove the identified barriers. Previous studies have identified barriers to quality radiation therapy care (13), radiation therapy utilisation (14) or the implementation of particular new technologies or techniques (15, 16), but no information is available specifically on the barriers to the implementation of high-quality new technologies and techniques. The work in this thesis aims to fill that knowledge gap and looks at methods to address these barriers and improve access to new high-quality radiation therapy techniques specifically in the New South Wales context.

1.1 HYPOTHESIS AND AIMS

The central hypothesis of this thesis is that:

> Barriers to the safe, high-quality and timely implementation of new technologies and techniques into NSW radiation oncology centres can be identified and minimised using targeted interventions.

This hypothesis is then addressed within the thesis by looking at a number of research questions.

Research Questions

1. Where in NSW is stereotactic ablative body radiation therapy (SABR) available and when did it become available? Was this technique available to all patients in a timely manner?

SABR is a hypofractionated, radiation therapy treatment technique which utilises advanced imaging techniques. To address this question, Chapter 3 presents the results of a state-wide survey looking at the implementation of SABR including the timeline for implementation and the treatment sites for which SABR was implemented. This work provides information on the timeliness of the implementation of this new technique.

2. Has the implementation of SABR across NSW been in accordance with the RANZCR published recommendations?
    a. If not, in what areas are the recommendations not being met and what are the barriers to this? What can be done to address these barriers?

In Chapter 4, in-person site visits and interviews were completed to radiation therapy centres around NSW to assess the level of compliance with The Royal Australian and New Zealand College of Radiologists (RANZCR) SABR recommendations (17) and the barriers which existed to compliance with these recommendations. This work addressed research question 2, assessed the quality of the implementation and identified barriers and potential mitigation strategies utilized later in this work.

3. Can knowledge-based planning models, created using the Varian RapidPlan software, be successfully shared between centres?

Research question 3 is addressed in Chapter 5, which looks at the implementation of new technology, and specifically, whether this type of collaborative effort could improve the implementation of RapidPlan. RapidPlan is a specific implementation of knowledge-based planning, where information from previous patient plans is used to optimise future patient plans. This work looks at whether a prostate knowledge-based planning model developed at one centre would satisfy the requirements of another centre, identifying barriers and the potential for collaboration to improve implementation.

4. What is the current usage of radiation therapy motion management in Australia and New Zealand and what benefits can be gained by running a workshop focused on motion management techniques?

The findings of a workshop focused on motion management are presented in Chapter 6, addressing research question 4. This chapter presents the current practice and anticipated future directions of motion management in Australia and New Zealand and discussed how the workshop facilitated knowledge-sharing through the workshop presentations and discussion. This chapter considers the use of workshops as a means for collaboration to overcome barriers to implementation of new technologies.

5. Can focused risk assessment training increase the use of prospective risk assessment for new technologies and techniques in NSW radiation oncology centres?

Chapter 7 describes the implementation of a new prospective risk assessment training program, designed to address barriers to safety identified earlier in the thesis. This work addresses research question 5 looking for changes in practice amongst participants following the training program.

6. Will the facilitation of file sharing between NSW (and Australasian) radiation oncology centres be utilized and useful? What barriers are preventing this?

Research question 6 is addressed in Chapter 8, which describes a new and innovative resource-sharing initiative. This work is ongoing but aims to ensure all centres can offer the most up-to-date treatment techniques more quickly by sharing resources. This work aims to address barriers to timely implementation identified in earlier chapters through collaboration while also identifying barriers to this style of collaboration.

7. Can the Australian Data Cancer Network (ACDN) (18, 19) research framework be used to simplify the auditing of patient treatments against published standards, such as eviQ (20)?

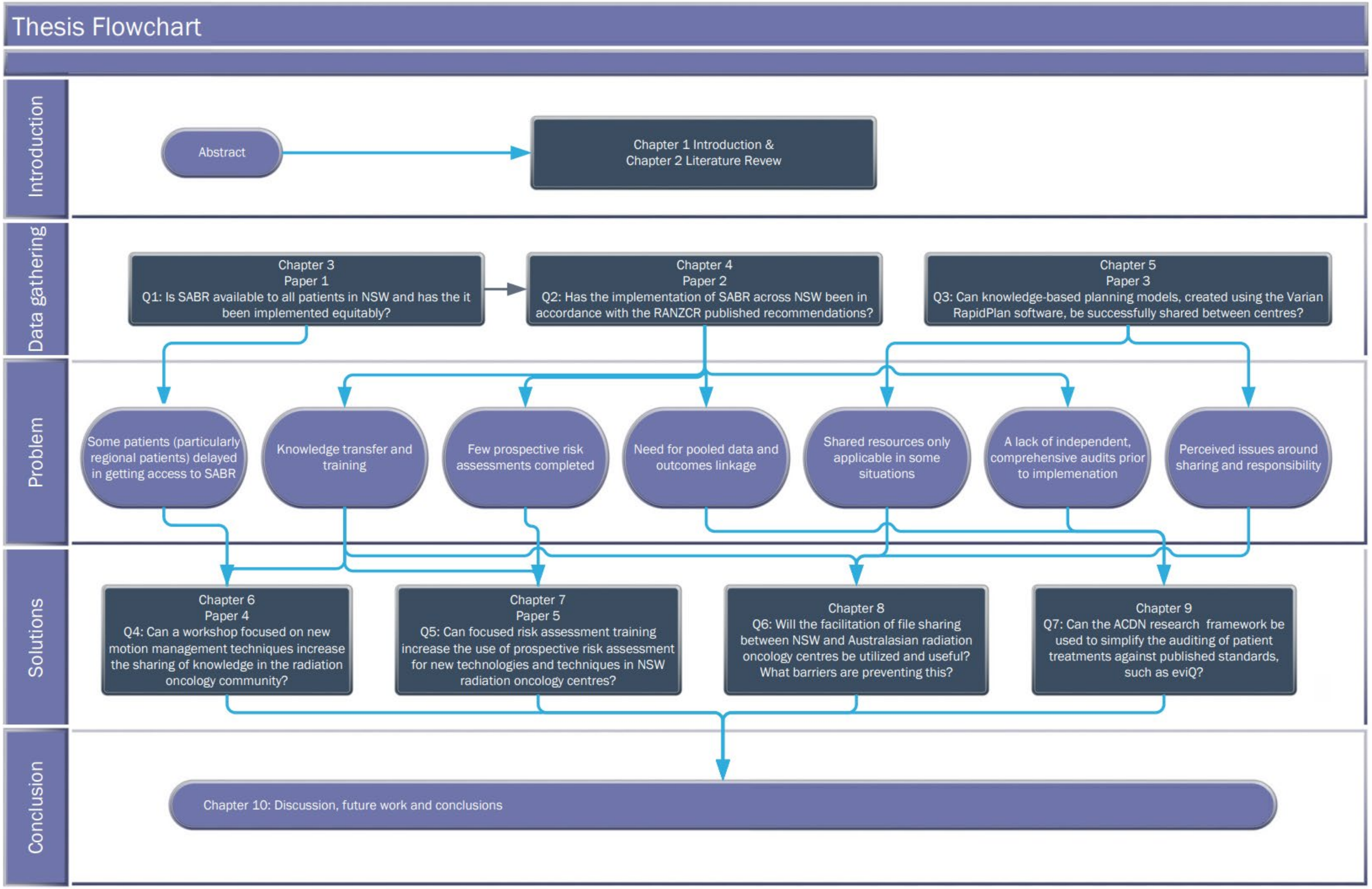
The final research question is addressed in Chapter 9. This chapter demonstrates how an established research network can be used to perform an audit of practice against recommendations over a number of centres, providing quantitative data and a template for similar future work. This work looks to address barriers to quality identified earlier in the thesis.

The framework and background for this thesis are established in Chapters 1 and 2. The broad themes and implications of the thesis, future work and conclusions are contained in Chapter 10.

Section 1.2 of this thesis provides a graphical representation of the thesis flow.

1.2 THESIS ORGANIZATION

Figure 1: Thesis organisation diagram


Thesis Flowchart
Introduction
Data gathering
Problem
Solutions
Conclusion
Abstract
Chapter 1 Introduction & Chapter 2 Literature Revew
Chapter 3 Paper 1 Q1: Is SABR available to all patients in NSW and has the it been implemented equitably?
Chapter 4 Paper 2 Q2: Has the implementation of SABR across NSW been in accordance with the RANZCR published recommendations?
Chapter 5 Paper 3 Q3: Can knowledge-based planning models, created using the Varian RapidPlan software, be successfully shared between centres?
Some patients (particularly regional patients) delayed in getting access to SABR
Knowledge transfer and training
Few prospective risk assessments completed
Need for pooled data and outcomes linkage
Shared resources only applicable in some situations
A lack of independent, comprehensive audits prior to implemenation
Perceived issues around sharing and responsibility
Chapter 6 Paper 4 Q4: Can a workshop focused on new motion management techniques increase the sharing of knowledge in the radiation oncology community?
Chapter 7 Paper 5 Q5: Can focused risk assessment training increase the use of prospective risk assessment for new technologies and techniques in NSW radiation oncology centres?
Chapter 8 Q6: Will the facilitation of file sharing between NSW and Australasian radiation oncology centres be utilized and useful? What barriers are preventing this?
Chapter 9 Q7: Can the ACDN research framework be used to simplify the auditing of patient treatments against published standards, such as eviQ?
Chapter 10: Discussion, future work and conclusions

CHAPTER 2

Literature review

This work looks to improve the implementation of new techniques and technologies in radiation oncology. This improvement could focus on quality, safety, availability (in general or of new innovations), appropriateness or efficiency. As described in the introduction, the work in this thesis focuses on both quality, which can encompass safety, and availability of new techniques and technologies. These topics are explored below.

2.1 QUALITY IN RADIATION ONCOLOGY

2.1.1 Quality in Health Care

The term quality is itself not simple to define with the assessment of quality dependent on the comparators used. This holds true for quality in health care where perceived quality may change as the goals and values of the health care system change. It is important, therefore, to find standardised methods of assessing quality in health care in order to measure improvement. The seminal work by Donabedian in 1966 (21) discussed three categories of quality assessment methods; outcomes, the process of care and structure.

More recently, the Institute of Medicine (USA) published a report and recommendations (22) aiming to improve the quality of health care in the USA. They state that health care should be safe, effective, patient-centred, timely, efficient and equitable. They believe that these aims cannot be achieved by simply working harder but require changes to the systems of care. Technology is listed in this report as both a reason for the current inadequacy of care and a potential solution.

2.1.2 Quality in Radiation Oncology

While the broad definitions of quality in health care are valid for radiation oncology, establishing quality indicators for radiation oncology can be more difficult as unique challenges exist when compared to other parts of the health care system. Outcomes are often used in health care as a quality indicator. However, oncological outcomes can be long term in nature (23), with positive and negative outcomes of treatment manifesting many years later. In many cases, treatments and technology may have progressed and changed before long-term outcomes can be assessed. Measuring outcomes over an extended period can be difficult, and long-term outcomes are not routinely assessed outside of prospective clinical trials or registries. Instead, quality indicators which have been shown to correlate with patient outcomes, and can therefore be used as a surrogate, may be used to assess quality in radiation oncology.

Establishing quality indicators looking at the process of care is also challenging in radiation oncology as technology and treatment changes result in established quality indicators becoming obsolete.

Two early attempts to create quality indicators in radiation therapy were published in 2007. Cionini et al (24) published a set of 13 quality indicators including structural indicators such as workload, process indicators (such as wait times) and outcome indicators (such as patient feedback). Also in 2007, the IAEA published a document describing the quality indicators contained in its quality audit (25). This report is more detailed than previously published works, with checklists of specific assessment items covering structural and process type indicators as well as training. While many of these quality indicators in these reports would still be relevant today, both reports contain items which would now be considered outdated in modern radiation therapy such as the proportion of plans using CT-based planning, or the location of film viewing boxes.

Table 1: Examples of quality indicators use in radiation therapy

Broad category	Topics	Example Quality Indicator	Standard (where given)	Ref.
Structure/ Infrastructure/ Facility Management	Personnel/staff	Number of Radiation Oncologists	250-300 patients/year/worker	(24)
		Professional qualifications		(25)
	Premise/Facility	Physical infrastructure supports safe practice		(26)
Process/ Patient & Equipment related procedures/ Treatment planning and delivery	Policies and procedures	Patients consent to treatment	Documented consent polices	(26)
		Identification of patients	Appropriate system in place	(25)
	Technical aspects	Calibration of all treatment units	Records of traceable calibrations	(26)
Outcomes/ Safety and Quality management	Disease-specific outcomes	Proportion of patients with grade 2 radiodermatitis		(27)
	Safety, quality and improvement processes	"Blame-free" safety reporting process	In place	(28)

Following these publications, a number of groups have attempted to collate both general and treatment-site specific quality indicators (29-31), often expanding on the three Donabedian categories. Chiew et al. (29) created a conceptual framework based on their expansion into 10 subcategories. Donaldson et al. (30) also divided the 3 Donebedian categories but into 12 subcategories, in this case by dividing each category into 4 additional subcategories: patients, staff, equipment or clinical process. Examples of quality indicators are given in Table 1.

Several countries have published standards containing quality indicators (27, 28), including Australia and New Zealand (32). The Australian and New Zealand *Radiation Oncology Practice Standards* (32) were first published in 2011 with standards grouped under three headings; facility management, treatment planning and delivery, and safety and quality management. These standards require that patients receive timely, patient-centred and equitable care. The standards address safety by requiring risk management processes, incident reporting, radiation safety planning and qualified staff. These standards also include requirements for documentation and recording, specifying the protocols which should be in place and the information which must be recorded for each patient's treatment. Requirements for treatment accuracy are articulated with requirements for dosimetric intercomparisons, accurate dose calculation and geometric accuracy checks. The standards address the management of radiation oncology centres, covering workforce issues and future planning, and the need for treatments to be evidence-based.

Updated versions of this document were published in 2017 and 2022 (26, 33) to reflect the change in service delivery during this time. The main changes from the 2011 to the 2022 version were the requirement for a dosimetry intercomparison for new equipment, an appendix covering the requirements for dosimetry audits, reference to the safe use of artificial intelligence, the inclusion of the Cancer Care Nurses Society of Australia and references to nursing practice principles, additional requirements regarding minority groups, the introduction of telehealth principles and references to other guidelines for complex treatments such as SABR and additional requirements for SABR and SRS treatments.

The pace of practice change is one of the challenges in creating and using practice standards, necessitating frequent updates to guidelines (23, 34). As previously mentioned, radiation oncology outcomes can be difficult to use as indicators because of the changes in practice that may occur in the interval between treatment and outcome reporting. In addition, outcomes may be dependent on non-radiation therapy interventions or other patient specific factors (23). Salma et al. (34) also note that creating universal quality indicators can be difficult due to the geographic, socioeconomic and cultural context of the patient population.

The demonstration of quality against these published indicators can be seen as a burden on radiation therapy departments (35) if additional support is not provided. This can be an issue for collecting quality indicators across a number of centres and past attempts in Australia have only had limited participation (36). Electronic collection has been suggested as a less labour-intensive method of quality indicator data collection but has not been found to be feasible currently (37) due to variability in practice and a lack of data harmonization (35, 36). Potentially for these reasons, there are currently few publications on the use of quality indicators and their impact on the quality of care (37).

2.1.3 Auditing in Radiation Oncology

Auditing in healthcare is part of quality improvement and involves measuring clinical outcomes or processes against standards. As mentioned above, in radiation oncology, many clinical outcomes take a long time to measure and can be complicated by other factors, thus many audits focus on structures and processes (38).

Trial credentialling is similarly part of a quality process but rather than aiming to ensure high quality treatments for all or a subset of patients, trial credentialing aims to ensure the credibility of trial results. Trial quality assurance programs ensure patients are treated in a technically optimal manner and aim to minimize deviations from the trial protocol (39-41). The testing involved in trial credentialing can act as a review of treatment processes, provide feedback on potential improvements, and lead to improved treatments for non-trial, as well as trial, patients (39).

Both auditing and credentialling can provide feedback to radiation oncology centres and highlight areas of potential improvement. Unfortunately, these processes can also be time consuming and difficult to access. The administrative burden of trial participation can limit the number of trials a centre can participate in, and only a limited number of centres may be selected to participate in a trial. External audits require time and use of external auditors may add to the cost (42). The IAEA QUATRO audit program provides external auditors and audits centres on request. However, in a ten-year period, this program audited just 89 radiotherapy centres across the world, none of which were from Australasia (13). In addition, audits rely on standards being updated and relevant, which can be a challenge in a fast-moving, technology-based area.

Radiation Oncology specific accreditation through a process audit is not mandated in Australia. General practice standards have been published (26) and can be used for self-auditing, and in some jurisdictions conformity with the guidelines is required. However, there are no direct government incentives or requirements for the external auditing of radiation oncology centres against these standards.

In contrast, level 1 dosimetric audits are required in order to receive specific types of government funding (43). The Australian Clinical Dosimetry Service (ACDS) is the longest serving national provider of a comprehensive dosimetry service which was officially launched in 2011. The service provides Level 1, 2 and 3 audits with level 3 (end-to-end testing) for advanced techniques such as SABR and motion management. Whilst Level 3 audits provide a comprehensive end-to-end test for dosimetric accuracy, there remain potential areas of treatment delivery quality, such as a comprehensive document management process, that remain un-assessed.

For a radiation therapy centre wishing to be audited prior to or during the introduction of new techniques or technologies into the clinic, there are limited options available. Trial credentialling is an option but this would require an appropriate trial, maybe limited in scope and requires additional resources. As mentioned, the ACDS provides dosimetry audits for a number of complex techniques but are restricted to auditing the dosimetric accuracy and require time to develop comprehensive dosimetric audits to cover new treatment techniques. Further options are needed to help ensure quality and safety are maintained when introducing a new technique or technology.

Internal or self-auditing could provide a low-cost method to systematically assess quality and safety. The AAPM Safety Profile Assessment Tool (44) is an example of a self-auditing tool and publications have demonstrated the roll of self-auditing in departmental audits (45), patient reviews (46) and process audits (47). Electronic auditing could also play a role, as this reduces the administrative burden on radiation oncology centres and could provide a more agile solution.

2.2 NEW TECHNOLOGY AND TECHNIQUES IN RADIATION ONCOLOGY

2.2.1 The Pace of Change in Radiation Oncology

Radiation Oncology is one of the most technologically-driven medical specialties (8). Modern radiation therapy uses highly sophisticated engineering, computing, physics and mathematics to ensure the accurate delivery of radiation to tumours while avoiding healthy tissue. Over the past three decades, advancements in technology have been integrated into radiation therapy leading to dramatic technology-driven changes (8-10, 48).

Advances in computing have allowed radiation therapy planning to move from simple manual calculations to modern planning including advanced radiation dose modelling, computerized dose optimization and customization, and registration of functional images. Advances in engineering have resulted in multi-leaf collimators (MLC) and robotic and helical linear accelerators, with the ability to tailor radiation dose distributions. Advances in imaging technology have led to image guided radiation therapy and adaptive radiation therapy, further sparing normal tissue and allowing dose escalation. Further advances such as radiomics, particle therapy and FLASH radiation therapy can be expected in the future.

These technological improvements have been shown for some patients to reduce the unwanted side effects of radiation and improve overall survival. Patients previously considered incurable can now be offered radiation therapy, aiming to provide long-term disease control and potential cure (8, 10). For other patients, technological improvements allow for more durable symptom control and improved quality of life (8).

It is worth restating the information discussed in the paragraph above in a different way. If patients who have access to this new technology and the resulting new treatment techniques are benefiting, then the patients who do not have access potentially have worse health outcomes. The timeliness of implementation of technology is therefore vital as delays may result in inequity within the health system and worse outcomes for some patients.

2.2.2 Technology-based Improvements in Radiation Oncology and their Availability

The 1990's saw a period of significant technological improvement in radiation therapy. The broader implementation of computed tomography (CT) and three-dimensional (3D) planning allowed the visualisation of internal anatomy, personalisation of treatment plans and sparing of organs-at-risk (OARs) in ways that were not possible with two-dimensional (2D) planning. Despite the advantages of 3D planning, 2D planning was still in use well into the 2000's, particularly for palliative cases (49).

Another innovation which became available in the 1990's was the multi-leaf collimator (MLC) (50-52). An MLC is a beam-limiting device consisting of a number of thin, high-density blocks or leaves, which can be used to shape the radiation beam to the target, avoiding unnecessary irradiation of normal tissues. While some early MLCs could be added onto existing linear accelerators (53), MLCs became more common in radiation therapy as older linear accelerators were replaced with newer MLC-equipped models (54-58).

The introduction of MLCs and improved computing power lead to one of the most significant technological improvements in radiation therapy, intensity modulated radiation therapy (IMRT). IMRT is a treatment technique where the intensity of the radiation fluence from the linear accelerator is modulated using MLCs. By delivering the radiation dose in a number of small beams, it conforms to the target, avoiding the organs-at-risk (OARs) in a way which is not achievable with three-dimensional conformal radiation therapy (3DCRT) (9). Concurrent with and integral to the introduction of IMRT was the introduction of inverse planning. Inverse planning involves giving the treatment planning system a set of goals for the patient treatment and allowing an algorithm to provide a treatment plan, including MLC positions, which will best meet these goals (59). The term IMRT now implicitly incorporates inverse planning.

The introduction of IMRT had the dual impact of reducing radiation-induced side-effects and, consequently, allowing dose escalation aimed at increasing tumour control and survival. An example of the reduction of side-effects is seen in head and neck radiation therapy. Xerostomia, a long-term side effect of head and neck radiation therapy, has been shown to be reduced in patients treated with IMRT (10). In the treatment of prostate cancer, the proximity of the rectum and bladder limited the dose that could safely be delivered to the prostate with 3DCRT. However, the reduced doses to these organs achievable with IMRT allowed for dose escalation. By escalating the dose to the prostate, higher tumour control rates could be achieved (60-62).

Despite the growing evidence and recommendations for the use of IMRT, the implementation of IMRT was delayed in some centres and for some patients compared to others. The first 'large-scale' implementation of IMRT was published in 1997 (63) but wide-spread use came later. In Canada, IMRT was introduced by 2001 but, six years later, in 2007, IMRT was only available at 50% of radiation therapy centres (64). In Germany, 96 patients were treated with IMRT in 2002 increasing to 44% of all patients 12 years later (in 2014, (56)). The percentage of centres offering IMRT can also be deceptive. By 2010, 76% of centres in the UK were offering IMRT but only 2% of patients were being treated with this technique (65).

In Australia, 37% of patients were treated with IMRT by 2013 (66). This value is compared to published data from around this time in Table 2, where a variation in IMRT use rates can be seen between regions. This variation is also seen between Australian states with 56% of patients in NSW and only 15% of patients in Tasmania receiving IMRT. Within NSW, differences existed in the use of IMRT between radiation therapy centres with a study in 2017 reporting that some centres only treated 18% of patients with IMRT, compared to other metropolitan centres treated 71% of patients with IMRT (67).

Table 2: Percentage of patients treated with IMRT

Country/Region	Date	Range	Total Percent	Ref.
UK	2012		15.3%	(65)
Germany	2014		44%	(56)
USA	2010		54%	(68)
Michigan	2012	23-96% (Centres)	42% (State Median of Treatments)	(69)
Australia	2013	15-56% (States)	37%	(66)
NSW	2017	18-71% (Centres)	56%	(67)

Table 2 shows the percentage of patients treated with IMRT in first world countries for comparison to the published Australian data from 2013 and NSW data from 2017. Australia, in 2013, was treating fewer patients with IMRT than the USA in 2010 or Germany in 2014 by 17% and 7% respectively. Differences in IMRT utilisation are also seen between Australian states (41% in the 2013 Australian data (66)) and between regional and metropolitan centres in NSW (53% in the 2017 NSW data) (67).

The variation in IMRT adoption in Ontario prompted a study which identified key factors influencing IMRT implementation (70). Their study found that resistance to change and the desire for clinical trials evidence delayed implementation, whereas strong leadership and collaboration, both informal and through workshops, led to faster adoption of IMRT.

Concurrent to the implementation of IMRT, the technology required for image guided radiation therapy (IGRT) was being introduced. The first evolution in treatment verification imaging occurred in the late 1980's with the introduction of electronic portal imaging devices (EPIDs) (71, 72). EPIDs are imaging devices mounted on a linear accelerator to produce an image of the patient using a megavoltage linear accelerator beam. Until this point, radiographic films were used to assess the accuracy of the patient's positioning after the patient's treatment. The introduction of the EPID made real-time imaging and position verification available for the first time in radiation therapy. By the early 1990's, small studies using EPIDs to perform "online imaging" were published (73-75).

While EPIDs are still used today, their use was limited by the poor image quality achievable using megavoltage beams. By the mid-1990's, the next technological improvement in IGRT, the kilovoltage (kV) on-board imaging system (OBI), had been built and was being tested (76). Comprising of an imaging panel and kV x-ray source mounted on the linear accelerator gantry, this new imaging system produced better quality images but also allowed for soft tissue visualization by creating a cone-beam computed tomographic image (77). Routine use of OBI systems began in 2003 on Elekta linear accelerators (78) and 2004 for Varian linear accelerators (79).

With the introduction of the EPID and OBI, daily imaging became available with the potential to reduce field misalignment, thereby reducing unnecessary dose to OARs and treatments that missed or partially missed the target. Like the introduction of IMRT, the use of online imaging became more common as linear accelerators equipped with EPIDs and OBIs were installed.

By 2009, more than 80% of radiation oncologists in the USA reported prescribing kV-based IGRT (80) and approximately 50% of centres in Australia and in the UK had kV-based IGRT available (65, 81). Not all patients were benefiting from this technology though, with IGRT being used for a only a subset of patients with most patients in the USA not treated using IGRT (80). Many of the benefits of IGRT come from performing online corrections on a daily basis (82, 83). These two changes in practice (daily imaging and online correction) have been gradually implemented into use across tumour sites. Despite the benefits, recent publications show that some patients are still treated without daily, online imaging (49, 82, 84, 85). Breast patients were some of the last to benefit from daily, online imaging. More than ten years after the first implementation of OBI systems, centres in the USA, Canada and New Zealand were still using offline image guidance and imaging less often than daily (49, 82, 86).

As daily imaging became more common, the movement of targets and OARs during treatment became more apparent and a potential area for improvement. A range of techniques aimed at accounting for or minimizing tumour and OAR movement began to be introduced using the collective term motion management. The described motion may be due to respiratory, digestive, cardiac or other physiological motion (87). The techniques used in motion management may include x-ray imaging, MR imaging on MR-equipped linear accelerators, ultrasound imaging, surface imaging, physical interventions to reduce motion such as compression, tracking implanted markers, patient coaching, monitoring of the patient's breathing or planning techniques which account for the expected movement (87-95). In 2006, the AAPM recommended that motion of the tumour be measured and managed for each patient (87), and provoking further interest in motion management locally. By 2020, motion management was in use at nearly all Australasian radiation therapy centres (96) with two approaches, internal target volumes (ITV) and breath-hold gating being used most commonly.

These advances in IGRT and motion management allowed for a significant change in the treatment of certain cancers through the use of stereotactic ablative body radiotherapy. Stereotactic Ablative Radiation Therapy (SABR) (also known as Stereotactic Body Radiation Therapy (SBRT)) describes a highly conformal treatment delivered in a small number of high-dose fractions using specialized image guidance. In the mid-1990's, the Karolinska hospital in Sweden demonstrated that high local control could be achieved by delivering high hypofractionated doses for patients with liver, lung and retroperitoneal tumours (97). This work was followed by several studies looking at hypofractionation for small, non-small cell lung tumours (98-100) with SABR becoming the standard of care for a subset of lung patients by 2017 (101). Since then, SABR usage has expanded to treat a larger range of patients. The use of SABR for lung tumours has expanded to treat more central tumours (102) and oligo-progressive disease (103, 104), and is supported by a greater body of evidence (105, 106). For liver SABR, the publication of results from phase 1 and 2 trials (107-112) has now been followed by phase 3 trial evidence showing improved progression free survival with liver SABR compared to alternative treatments (113, 114). Encouraging 5-year results (115) from prostate SABR trials have led to larger phase III trials (116). Large trials looking at SABR treatments for abdominal sites are continuing (117, 118) with good results from smaller studies (119, 120). The use of SABR has also expanded with initial studies looking at breast SABR (121) and cardiac SABR to treat ventricular tachycardia (122, 123).

As more evidence became available showing the benefits of SABR, the uneven implementation and availability of SABR within and between countries has become important. Patterns of practice surveys from the UK and Canada were published in 2014 (124, 125) discussing the challenges in implementing SABR and the low number of centres where SABR was available (23% and 34% respectively). Lund et al (124) highlight that, in a sparsely populated country, accessibility to such treatments is even more difficult. While later surveys show that the number of centres offering SABR is increasing (126), both local and international studies show variabilities in practice between centres (96, 127, 128).

Knowledge-based planning (KBP) is a recent technological innovation, which has the potential to ensure more consistent and higher quality radiation therapy plans. KBP uses machine learning to predict the achievable dose values for organs-at-risk based on previous radiation therapy plans. This technology has been introduced into existing planning systems with the Varian RapidPlan system an example of this (129). KBP has been shown to improve the quality of radiation therapy plans (130-132).

Many of the technology-based improvements described in this chapter have been shown to lead to increased survival and decreased toxicity for patients. However, the implementation of these improvements has at times been uneven, leading to inequity in access (8, 125, 133, 134). In addition, poor implementation of new technology can result in adverse outcomes for patients (135). It is therefore important to ensure timeliness and quality when implementing technological advances into radiation therapy.

Risk management tools are specifically designed to ensure safety and can be used in radiation therapy (136). Tools such as failure mode and effects analysis (FMEA), system theoretic process analysis (STPA) and the risk and benefit balance impact template (RABBIT) have been using in radiation therapy, particularly in the implementation of new techniques and technologies (137-140). Such instruments are likely to play an important role in ensure quality and safety for future treatment advances.

2.3 THE AUSTRALIAN AND NEW SOUTH WELSH CONTEXT

The Australian health system has been consistently found to be one of the best in the world in terms of quality and cost efficiency (141, 142). However, the Australian health system does face significant challenges for example the cost of new technology, unaddressed quality and safety concerns and the delivery of health services to regional and rural areas (143).

Health care services in Australia are provided by a mix of both public and private providers with funding coming from a range of sources including the Federal government, state governments and private health insurance providers (144). Public health services within individual states are often provided through independent authorities which are responsible for the provision of public hospital services within a geographic area, such as the 15 local health districts operating within NSW (145).

Radiation therapy services are provided by both public and private providers in NSW (146, 147), with both receiving public funding to provide this service (148). All NSW local health districts have at least one radiation therapy provider with some having only one public or private provider and other metropolitan districts containing up to five providers (146).

The challenges in providing health services to rural and regional parts of Australia and NSW stem from the low human population density in Australia and NSW, with NSW having a population density of below 20 people per square kilometre but inconsistently spread, with areas of Western NSW having a population of less than 1 person per square kilometre (149). This population spread is particularly challenging for the provision of radiation therapy where patients may have to attend many times to complete a course of treatment (150). Several studies have shown that patients are less likely to receive radiation therapy with increasing distance from a radiation therapy centre (151-153) potentially compromising the local control and overall survival of hundreds of people in NSW every year (154), and that the provision of local radiation therapy services can increase the use of radiation therapy in rural areas (155). In addition to distance, a lower socio-economic status may also be associated with a lower utilisation of radiation therapy services within NSW (153, 154).

While these studies relate to the general availability of radiation therapy, the availability of new technologies and techniques should also be considered. Section 2.2.2 outlines both the improvements in patient outcomes which can result from technological improvements and the uneven implementation of these improvements between regions and centres. In NSW, the Cancer Institute of NSW (146) reports that complex treatments such as stereotactic techniques are only available at some centres, while the proportion of patients receiving IMRT is also uneven. In less densely populated areas, it is not always practical to refer a patient to another centre where a more advanced treatment may be available. The results of uneven implementation of advanced techniques are, therefore, likely to have a larger impact compared with more-densely populated regions. This thesis focuses on the implementation of new techniques and technologies in NSW, a state with widely varying population densities, where uneven implementation may be impactful.

2.4 SUMMARY

Quality and safety in the provision of radiation therapy are essential. Due to the challenges associated with quantifying quality in radiation therapy, quality indicators and standards are often used as tools to assess quality. However, radiation therapy is a quickly evolving field, heavily reliant on technology. As a result, quality indicators can become outdated and other methods, such as prospective risk assessments may be required to ensure safety for new technologies. Audits or assessments against quality standards can also be burdensome for radiation therapy centres, with electronic data collection and self-auditing providing potential solutions.

New technologies, and the techniques they enable, can provide better treatment for patients with the potential for reduced toxicity and increased survival (156, 157). Unfortunately, the implementation of new technologies has been shown to be uneven, both internationally and locally, meaning that some patients are not able to benefit from these advances. Additionally, the inappropriate or unsafe implementation of new technologies could result in harm to patients.

The work in this thesis looks to assess the quality and timeliness of new radiation therapy technologies in NSW. Further, it seeks to identify barriers to the high-quality implementation of new technologies and techniques into NSW and attempts to reduce or remove such barriers, improving the safety and availability of high-quality radiation therapy for all patients within NSW.

CHAPTER 3

The Implementation of Stereotactic Ablative Body Radiotherapy into New South Wales

3.1 PREAMBLE

Equity within a health care system describes a situation where everyone has fair and just access to the highest-level of health care within the boundaries of that system. This could be within the whole of Australia, or within a given state etc. When clinical evidence shows that a new technique has better health outcomes, this technique should be available to all patients. Delays in the implementation of this technique could result in health inequities.

Stereotactic Ablative Radiation Therapy (SABR) was, and for some centres still is, considered a new and complicated technique, requiring careful implementation. This Chapter considers SABR as a recent example of the introduction of a new technique into radiation therapy centres in New South Wales (NSW). At the time of the study (2018), no information was available on the implementation of SABR in Australia. This paper describes the results of a survey of NSW radiation therapy centres and includes a graph of the implementation over time, and comparisons to utilization of this technique in similar countries around the world.

Chapter 3 of this thesis is published as 'Stereotactic ablative body radiation therapy (SABR) in NSW' in the Physical and Engineering Sciences in Medicine journal in 2020 (158).

This work addresses research question 1:

Is stereotactic ablative body radiation therapy (SABR) available to all patients in NSW, has it been implemented in a timely manner and has the implementation of this technique across the state been equitable?

3.2 PUBLICATION 1

Stereotactic ablative body radiation therapy (SABR) in NSW

Physical and Engineering Sciences in Medicine
https://doi.org/10.1007/s13246-020-00866-3

SCIENTIFIC PAPER

Stereotactic ablative body radiation therapy (SABR) in NSW

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Abstract

A survey was conducted to establish the current utilisation of stereotactic ablative radiation therapy (SABR) services in NSW. The objective of the survey was to generate baseline data to inform requirements for a networked approach to the implementation of new radiation therapy techniques and technologies. All radiation therapy services in NSW were contacted by email with a request to complete a SABR service survey. Questions were designed to identify equipment used, treatment techniques in place, clinical sites treated with a SABR technique and plans to expand the current services offered. Each professional group was asked to identify areas of service delivery they would most like to improve. Sixteen responses were received representing 24 of 27 (89%) of NSW radiation therapy centres. The results indicate that most centres now treat with SABR, however the number of centres and the treatment sites are still increasing. VMAT treatments and 3D imaging are now commonplace. Liver was the most commonly reported treatment site where confidence in service delivery needed improvement. Data from the survey will be useful in formulating future collaborative and educational activities aimed at improving safety and efficacy in SABR service delivery to all patients in NSW and potentially the rest of the country.

Keywords SABR · SBRT · Stereotactic body radiation therapy · NSW · Survey

Introduction

Several definitions of stereotactic ablative radiation therapy (SABR or SBRT) exist with a general consensus that SABR uses high doses per fraction, a small number of fractions and is reliant on specialised planning, image guidance, precision treatment delivery and quality assurance.

Following early reports from Japan and Europe in the 1990s [1, 2], prospective studies from the United States lead to more wide-spread implementation of SABR [3]. SABR is now considered the standard of care for medically-inoperable early stage non-small cell lung cancer [4]. Recent trial data now supports the use for SABR for oligometastatic lesions from a range of primary tumour sites [5, 6]. Recently a phase II trial demonstrated improved pain response with single fraction SABR to vertebral metastases compared to standard 3DCRT radiation therapy [7]. For prostate and liver, initial trial data have also shown favourable results [8] with larger trials ongoing [9–14]. Trials are also ongoing for other abdominal sites [15, 16].

While recommendations exist regarding the technical aspects of SABR [17, 18], there are still significant risks associated with introducing SABR [19] with errors occurring at a higher rate for SABR compared to other procedures and have a greater effect [20]. Reiber et al. [21] show that experience at treating SABR is associated with better outcomes. However, within Australia, with its wide-spread population, centre specialisation may not be practical and patients are likely to be treated at centres with low case loads. In this context, sharing of knowledge and expertise across centres may reduce this risk and expedite the introduction of safe and effective services. To establish baseline data on use of SABR in NSW, a survey was conducted to identify variations in practice across NSW centres. The survey included questions related to the number of SABR patients treated by site, treatment modalities and image guidance used, and confidence of staff in the SABR treatments available ("Appendix").

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Methods

The survey was designed to assess uptake and utilisation of SABR, equipment use for SABR and confidence and concerns regarding current practice. The survey contained demographic questions and 44 questions relating to SABR usage ("Appendix"). The survey was emailed as a Microsoft Excel™ spreadsheet to Chief Physicists of all radiation therapy centres in New South Wales in May 2018 to be completed by a multidisciplinary team within each centre. Where no response was received, additional efforts were made to contact the centres. All responses included for analysis were received by October 2018.

Within NSW, some radiation therapy centres exist within collaborative groups where they may share resources including software, protocols and staff. In some cases, responses were received from each centre within a group while in other cases a single response was received, covering the entire group of centres. Analysis was based on the number of individual responses to each question.

As part of the survey, all three professional groups (oncologists, therapists and physicists) were asked to indicate their confidence levels in SABR spine, in their most confident SABR site and in their least confident SABR site under the five categories listed in Table 1.

Table 1 All three professional groups were asked to indicate their confidence level in each of these five listed components of treatment as applied to three anatomical sites

Component
Technique overall
Contouring
Planning
Positional accuracy
Dose accuracy

Results

Sixteen separate survey responses were received representing 89% of radiation therapy centres in NSW (24 of 27); 82% of public centres and 100% of private centres. Three out of 16 surveys were returned incomplete; in two cases the number of patients treated with SABR was not provided, and in two cases the questions relating to radiation oncologist and/or radiation therapist confidence were not answered.

Eighty-four percent of respondents indicated that they were using SABR, with 100% of these treating lung malignancies. Figure 1 shows the distribution of other sites being treated, with nearly half of respondents indicating that they treat vertebral metastases and approximately one third of respondents indicating that they treat either prostate or liver malignancies. Despite some centres including details related to brain treatments, they have not been included as this survey was limited to SABR.

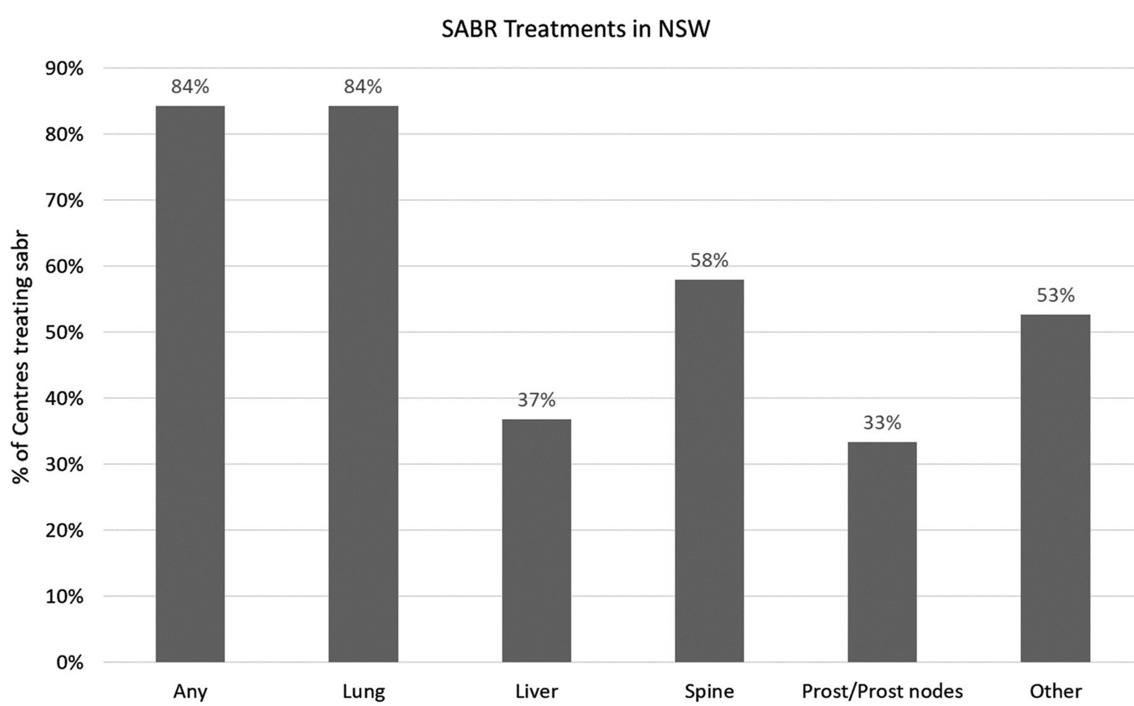
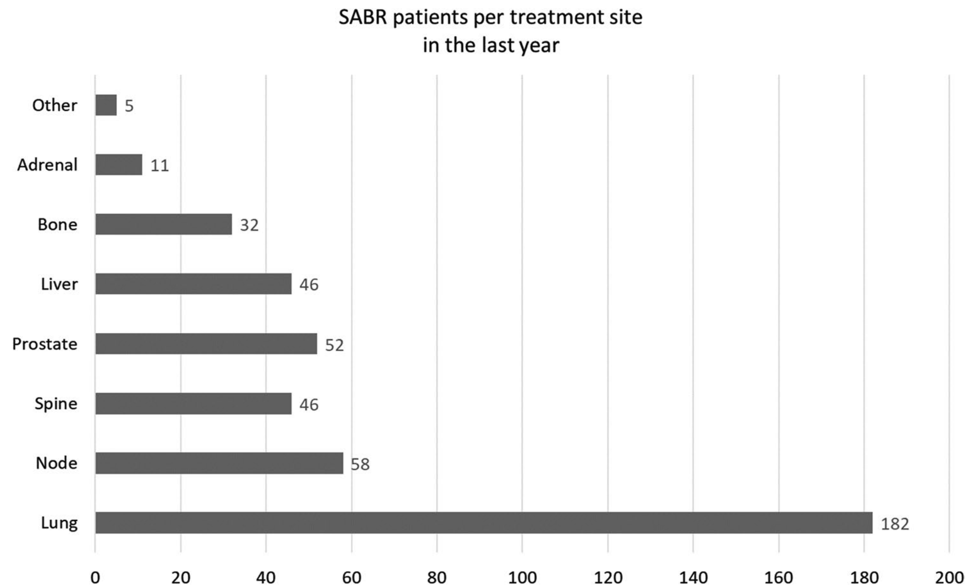


Fig. 1 Percentages of respondents indicating that the specified site is treated at their centre, with 'other' including node, bone, adrenal, bladder, kidney and abdomen

Fig. 2 SABR patients per treatment site treated in the last 12 months



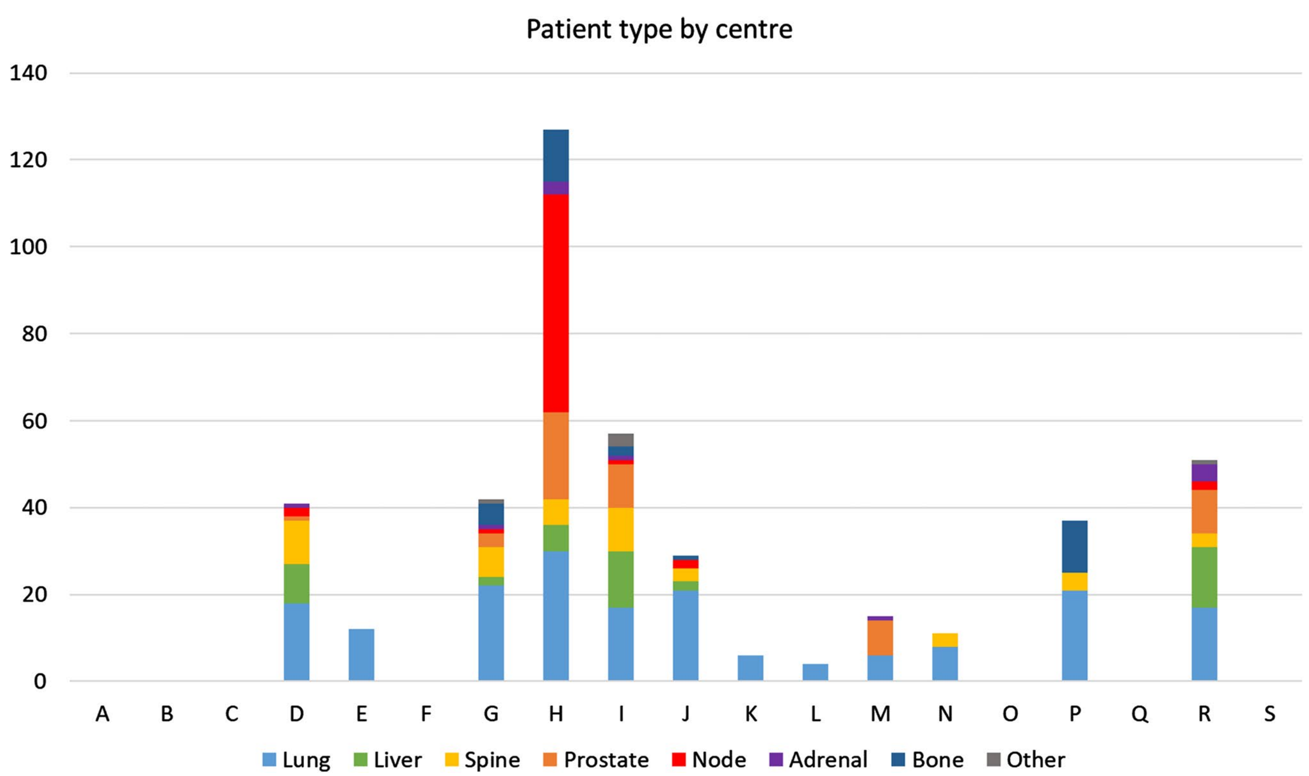


Fig. 3 SABR patients in NSW by type and centre. Note that centres A-C and S indicated that patients are treated with SABR but did not provide the numbers of patients being treated

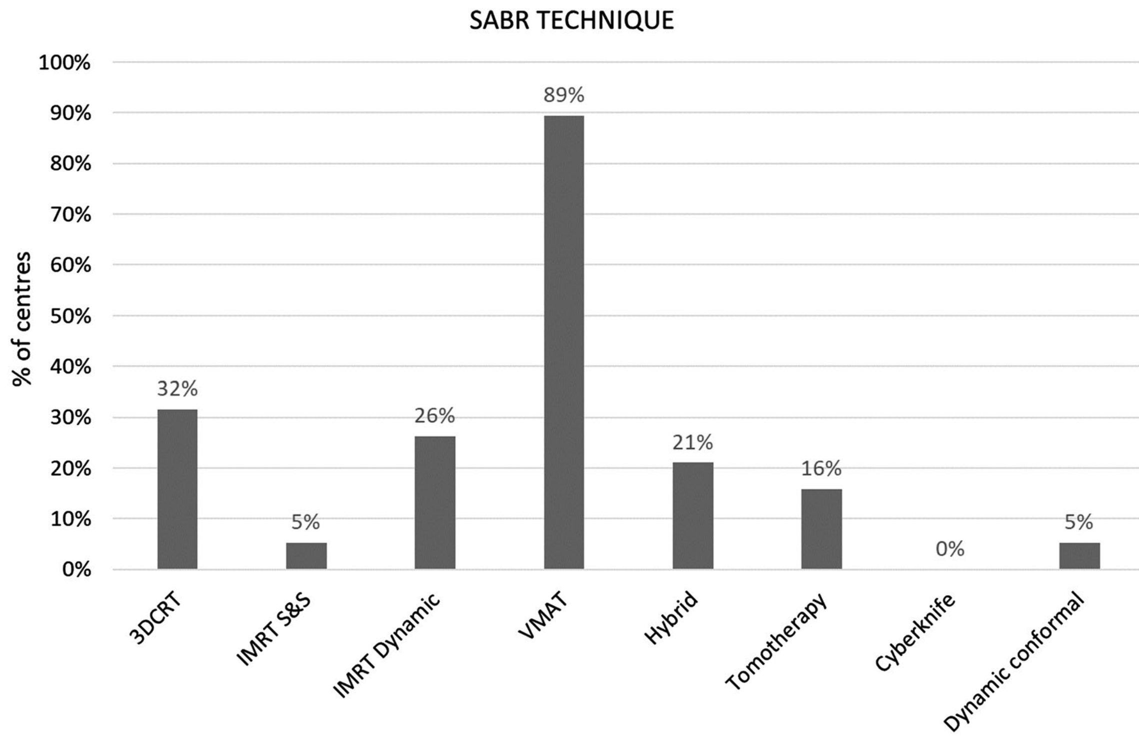


Fig. 4 Techniques used for SABR treatment in NSW, 2018. Centres which do not currently treat SABR are included with the techniques they intend to use

Figure 2 shows the number of patients treated using SABR in NSW in the last year. As not all respondents provided patient numbers, the numbers shown are likely to underestimate the true value. Lung SABR treatments are the most common based on the survey data.

Figure 3 shows the number of patients treated by each centre and the types of treatments. The data show that one centre treated a substantially larger number of patients than any other, with a larger number of pelvic nodal treatments. Five centres treated more than 40 patients to a variety of treatment sites over the previous year. Three of these five centres treated 9 or more liver SABR patients in the previous year.

All sites who indicated they were not yet treating SABR were in regional locations. The number of SABR patients treated in the previous year was also lower for the regional centres which are treating SABR, 45 patients per year at metropolitan centres versus 23 patients per year for regional centres treating SABR.

Further analysis of these data comparing multi-centre groups versus stand-alone radiation therapy centres shows that multi-centre groups were somewhat more likely to offer SABR (91% versus 75%). However, the stand-alone centres treated many more patients (53 vs. 19 patients per year).

Participants were asked to indicate which year their centre started SABR treatments. These data are displayed in Fig. 5 and show a steady increase from implementation in 2007 through to 2018.

By far the most popular treatment delivery technique for SABR treatment was volumetric modulated arc therapy (VMAT) with multiple arcs, with 89% of respondents indicating this treatment technique was used (Fig. 4). Multiple responses were allowable for this question with 74% of respondents selecting 2–4 different techniques.

CBCT was the most popular imaging modality used for SABR with 79% of respondents indicating this was used. 4DCBCT, kV imaging and MV or MVCT imaging represented 42%, 26% and 26% respectively. The choice of imaging was somewhat dependent on the type of treatment unit used for SABR, with MVCT and 4DCBCT only available from certain vendors. All respondents selected an imaging modality other than or in addition to kV or MV imaging indicating that all centres use 3D imaging of some kind. More than half the respondents indicated that they used Varian linacs (56%) for SABR treatments, with lower numbers for Elekta (33%) and Tomotherapy (16%).

The survey questions relating to confidence are outlined in "Appendix". All three professional groups selected lung as their most confident site (69% of radiation oncologists, 64% of radiation therapists and 43% of radiation oncology

Table 2 The ways respondents would like to improve SBRT at their centre; themes present in the responses, sorted from most to least popular

Localisation, visualisation and imaging
Motion management
Use of FFF beam
Immobilisation and positioning
Planning
Audits and comparisons
Algorithm accuracy
Time and speed
Image Registration
Contouring
Specific treatment site to be added
Training
Film dosimetry
Upgrade or change equipment

medical physicists) and all three professional groups selected liver as their least confidence SABR treatment (38% of radiation oncologists, 33% of radiation therapists and 33% of radiation oncology medical physicists).

Participants were asked to specify any additional sites they would like to be able to treat at their centres and what they would like to see improved. The most popular additional treatment sites were spine, bone and pancreas for oncologists, prostate and liver for radiation therapists and liver for physicists.

The responses relating to the improvements or further developments participants would like to see in their centres were thematically analysed into 14 separate categories. The categories are listed in Table 2. Half of all participants had responses categorised as relating to localisations, visualisation and imaging or motion management. These themes were popular with all professional groups with > 45% of participants in each profession submitting responses for one of these two categories. Greater than 10% of respondents indicated a desire to begin using flattening filter free (FFF) beams. It should be noted that the different professional groups were not blinded to the responses of others within their centre. This may have led to increased correlation between responses and a reluctance to indicate a lack of trust in the work of others.

Discussion

The high response rate to this survey indicates that the data are representative of NSW, covering most sites and including both metropolitan and regional locations, and ranges in experience. Based on the current number of sites not treating patients with SABR and those who currently only treat lung, there is the potential to see further expansion of SABR is NSW in terms of both sites offering this treatment and the range of treatment areas being treated with SABR.

Five sites indicated that they had treated less than 25 patients in the past year. Three of these five centres started SABR treatments in 2017, therefore it is possible that the patient numbers did not represent an entire calendar year and that in the future the total number of patients will be higher. With these lower patient numbers, these centres are below the recommended number of 25 patients required to

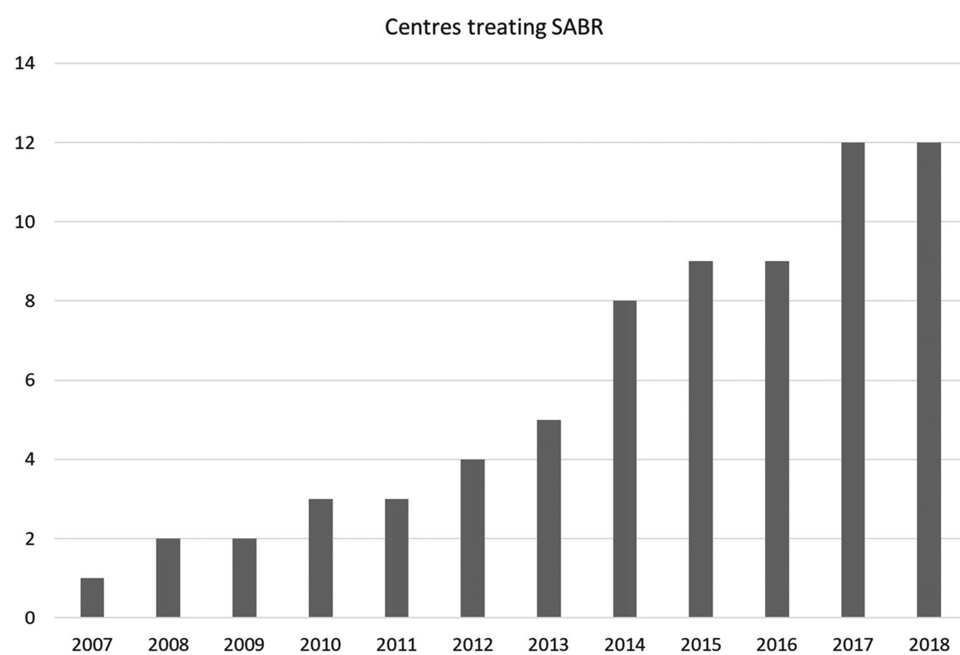


Fig. 5 The number of NSW radiotherapy centres or groups of centres (indicated by a combine response to this question) offering SABR by year (2007–2018) who answered this question

maintain professional competence of all members of the treating team by the National Health Service (UK) [22]. However, the RANZCR (Australia and New Zealand) recognise that this level may not be achievable in Australia with the more dispersed population and that regional networks could be established to achieve similar numbers [23].

All of the responding centres who do not currently treat with SABR indicated that they intended to start in late 2018 or early 2019. However, extrapolation of Fig. 5 combined with the linear increase in radiation therapy centres in NSW suggests that it may take longer for SABR to be available at all centres in NSW, possibly as late as 2021.

Earlier surveys have been conducted in other countries [19, 24–27] the results of which can be compared with the results of the current study, the first SABR survey conducted within Australia. These previous international survey data show a large variation in the number of centres treating with SABR around the world. By 2009, approximately 56% of centres in Japan were treating with SABR [26] and by 2010 64% of oncologists in the US were offering SABR [24]. More recent data show that in 2016, SABR was offered by 80% of North American practices [20], which is consistent with the 84% of centres offering SABR in NSW, suggesting that the number of centres practicing SABR in Australia is comparable with other countries.

The UK reported its first survey of SABR practice in 2012. At that time only 23% of centres were treating with a SABR technique, though low numbers could be attributed to the 'Commissioning through Evaluation' program where funding for SABR treatment is only available to a limited number of centres [28]. Since that report was published, a second survey was conducted which shows that in 2018 76% of centres now have active programs [27].

Data from both the US and UK show that lung is the most common SABR treatment and this agrees with our data for NSW. However, the NSW data show a much greater proportion of non-lung patients (58%) compared to the UK survey in 2018 [27] (15%) with the largest differences for node, spine, bone and adrenal treatments. The data from the US is not directly comparable, as it considers oncologists as opposed to patients or centres, however in 2010 only 7.9% of oncologists were treating prostate with SABR [24], whereas 33% of respondents to this survey indicated that prostate SABR was available at their centre. This suggests an increase in the prevalence of prostate SABR since the US survey coinciding with the publication of draft ASTRO Guidelines on hypofractioned radiotherapy [29] and the results from several large trials looking at prostate fractionation schemes [30–32].

Our survey indicates that SABR services are increasing across NSW and the number of clinical sites treated is also increasing. There is general interest in delivering liver SABR treatments, though this was identified as the site with least confidence indicating a potential need for further education and on-going peer review to improve this confidence. Further work will consider the benefits of a collaborative approach to reviewing procedural, training, prescribing, simulation and planning aspects of this treatment technique with the potential to share the resources and experience during the early development phase. This work will determine the optimal model of collaborative and educational activities for supporting safe and efficient implementation of SABR techniques across a range of clinical sites. The educational activities may resemble those which have been used for trials in the past but tailored to a wide audience [33]. The requirement for these activities will be guided by the areas of low confidence that have been identified in this survey, and may include planning comparison studies as suggested by the radiation therapists and activities to assist radiation oncologist with registration and contouring. Image guidance and motion management is often vendor dependent, therefore training packages to target specific vendor workflows may be required. It may be possible that the data collected in this survey can be used to create networks of centres with similar needs or to connect centres starting with a new site or technology with centres experienced in those areas.

Conclusion

The results of this survey have shown that SABR treatments are both prevalent and increasing within NSW. Comparisons with previous surveys show an increased use of technology, such as VMAT delivery, and a broadening of the utilisation of SABR. Whilst lung is still the most popular treatment site for SABR, the survey responses indicate an interest in implementing SABR for liver but highlight the lack of confidence in this treatment delivery.

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Compliance with ethical standards

Conflict of interest All the authors declared that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Appendix—Survey

NSW SABR/SBRT Evaluation and Improvement Initiative – Initial Questionnaire	
Background	
This project looks to improve the efficient and safe implementation of new technologies and techniques in NSW. We will initially look at the use of SBRT/SABR. This particular technique was chosen as it is technologically challenging and of interest to many NSW radiation oncology centres. In addition, experience with this technique is varied throughout NSW, with many centres still in the implementation phase	
The SBRT/SABR research project will be in several parts. We are collaborating with the ACDS for a dosimetric assessment of the technique. During a separate site visit, we also plan to investigate the procedural, training, simulation and planning aspects of this treatment technique	
SECTION 1	
Please complete the information below	If you have previously completed the TROG SABR questionnaire, this can be returned in place of Sect. 1
Date	
Email Address	
First Name	
Last Name	
Facility Name	
Site (if applicable)	
Contact phone number	
Does your facility currently treat using SBRT/SABR?	
Which, if any, sites do you currently treat with SBRT/SABR?	
Which techniques are used, or do you plan to use, for SBRT/SABR treatments?	
(delete responses which do not apply)	
3D conformal	Coplanar
	Non-Coplanar
IMRT: Static Gantry	Step and shoot
	Dynamic leaves
VMAT: Dynamic Gantry Arc	Single
	Multiple
	Hybrid
	Rapid
	Smart
	Tomotherapy
	Cyberknife
	Other (please specify)
Helical Tomotherapy	Yes
	No
	Comment
Cyberknife	Yes

SECTION 1	
	No
	Comment
How many patients were treated at your facility with SABR in the last year?	Lung
	Liver
	Spine
	Prostate
	Node
	Cranial
	Adrenal
	Bone
	Other (please specify tumour site and number of patients)
In what year did your facility start treatment these sites with SABR?	Lung
	Liver
	Spine
	Prostate
	Node
	Cranial
	Adrenal
	Bone
	Other (please specify tumour site and year)
Treatment Unit/s for SABR techniques	Manufacturer and model
	Local Linac Name
Image guidance for SABR techniques	CBCT
(delete responses which do not apply)	4D CBCT
	kV
	MV
	Other (please specify)
Please provide any further information which may be relevant to your participation	Open-Ended Response
SECTION 2	
Please complete the information below	Drop down options will appear for some questions
Radiation Oncologist	Name
SABR/SBRT Site:	Spine
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	

SECTION 1	
Current level of confidence in SABR/SBRT treatment dose accuracy	
SABR/SBRT Site with which you have the most confident:	Enter Site
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
SABR/SBRT Site with which you have the least confident:	Enter Site
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
Please describe any areas of SABR/SBRT treatment at your centre that you would like to improve	
Which, if any, additional sites would you like to be able to treat at your centre?	
Radiation Therapist	Name
SABR/SBRT Site:	Spine
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
SABR/SBRT Site with which you have the most confident:	Enter Site
Current level of confidence in SABR/SBRT technique overall	

SECTION 1	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
SABR/SBRT Site with which you have the least confident:	Enter Site
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
Please describe any areas of SABR/SBRT treatment at your centre that you would like to improve	
Which, if any, additional sites would you like to be able to treat at your centre?	
Medical Physicist	Name
SABR/SBRT Site:	Spine
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
SABR/SBRT Site with which you have the most confident:	Enter Site
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	

SECTION 1	
Current level of confidence in SABR/SBRT treatment dose accuracy	
SABR/SBRT Site with which you have the least confident:	Enter Site
Current level of confidence in SABR/SBRT technique overall	
Current level of confidence in SABR/SBRT contouring	
Current level of confidence in SABR/SBRT planning	
Current level of confidence in SABR/SBRT treatment position accuracy	
Current level of confidence in SABR/SBRT treatment dose accuracy	
Please describe any areas of SABR/SBRT treatment at your centre that you would like to improve	
Which, if any, additional sites would you like to be able to treat at your centre?	
Timeline	
If you are not using SBRT/SABR, when do you plan to begin?	

References

1. Uematsu M, Shioda A, Tahara K, Fukui T, Yamamoto F, Tsumatori G, Ozeki Y, Aoki T, Watanabe M, Kusano S (1998) Focal, high dose, and fractionated modified stereotactic radiation therapy for lung carcinoma patients: a preliminary experience. Cancer 82(6):1062–1070
2. Blomgren H, Lax I, Näslund I, Svanström R (2009) Stereotactic high dose fraction radiation therapy of extracranial tumors using an accelerator: clinical experience of the first thirty-one patients. Acta Oncol 34(6):861–870. https://doi.org/10.3109/02841869509127197
3. Fakiris AJ, McGarry RC, Yiannoutsos CT, Papiez L, Williams M, Henderson MA, Timmerman R (2009) Stereotactic body radiation therapy for early-stage non-small-cell lung carcinoma: four-year results of a prospective phase II study. Int J Radiat Oncol Biol Phys 75(3):677–682. https://doi.org/10.1016/j.ijrobp.2008.11.042
4. Guckenberger M, Andratschke N, Dieckmann K, Hoogeman MS, Hoyer M, Hurkmans C, Tanadini-Lang S, Lartigau E, Mendez Romero A, Senan S, Verellen D (2017) ESTRO ACROP consensus guideline on implementation and practice of stereotactic body radiotherapy for peripherally located early stage non-small cell lung cancer. Radiother Oncol 124(1):11–17. https://doi.org/10.1016/j.radonc.2017.05.012
5. Palma DA, Olson RA, Harrow S, Gaede S, Louie AV, Haasbeek C, Mulroy LA, Lock MI, Rodrigues G, Yaremko BP, Schellenberg D, Ahmad B, Griffioen G, Senthi S, Liu MC, Moore K, Currie S, Bauman GS, Warner A, Senan S (2018) Stereotactic ablative radiation therapy for the comprehensive treatment of oligometastatic tumors (SABR-COMET): results of a randomized trial. Int J Radiat Oncol Biol Phys 102(3):S3–S4. https://doi.org/10.1016/j.ijrobp.2018.06.105
6. Gomez DR, Tang C, Zhang J, Blumenschein GR, Hernandez M, Lee JJ, Ye R, Camidge DR, Skoulidis F, Doebele R, Gaspar LE, Gibbons DL, Karam J, Kavanagh BD, Palma DA, Louie AV, Tsao A, Sepesi B, Swisher SG, Heymach J (2018) Local consolidative therapy (LCT) improves overall survival (OS) compared to maintenance therapy/observation in oligometastatic non-small cell lung cancer (NSCLC): final results of a multicenter, randomized, controlled phase 2 trial. Paper presented at the 2018 ASTRO Annual Meeting, Oct 21 2018
7. Sprave T, Verma V, Forster R, Schlampp I, Bruckner T, Bostel T, Welte SE, Tonndorf-Martini E, Nicolay NH, Debus J, Rief H (2018) Randomized phase II trial evaluating pain response in patients with spinal metastases following stereotactic body radiotherapy versus three-dimensional conformal radiotherapy. Radiother Oncol 128(2):274–282. https://doi.org/10.1016/j.radonc.2018.04.030
8. Meier RM, Bloch DA, Cotrutz C, Beckman AC, Henning GT, Woodhouse SA, Williamson SK, Mohideen N, Dombrowski JJ, Hong RL, Brachman DG, Linson PW, Kaplan ID (2018) Multicenter trial of stereotactic body radiation therapy for low- and intermediate-risk prostate cancer: survival and toxicity endpoints. Int J Radiat Oncol Biol Phys 102(2):296–303. https://doi.org/10.1016/j.ijrobp.2018.05.040
9. Zilli T, Scorsetti M, Zwahlen D, Franzese C, Forster R, Giaj-Levra N, Koutsouvelis N, Bertaut A, Zimmermann M, D'Agostino GR, Alongi F, Guckenberger M, Miralbell R (2018) ONE SHOT - single shot radiotherapy for localized prostate cancer: study protocol of a single arm, multicenter phase I/II trial. Radiat Oncol 13(1):166. https://doi.org/10.1186/s13014-018-1112-0
10. Keall P, Nguyen DT, O'Brien R, Booth J, Greer P, Poulsen P, Gebski V, Kneebone A, Martin J (2017) Stereotactic prostate adaptive radiotherapy utilising kilovoltage intrafraction monitoring: the TROG 15.01 SPARK trial. BMC Cancer 17(1):180. https://doi.org/10.1186/s12885-017-3164-1
11. Quon HC, Ong A, Cheung P, Chu W, Chung HT, Vesprini D, Chowdhury A, Panjwani D, Pang G, Korol R, Davidson M, Ravi A, McCurdy B, Zhang L, Mamedov A, Deabreu A, Loblaw A (2018) Once-weekly versus every-other-day stereotactic body radiotherapy in patients with prostate cancer (PATRIOT): a phase 2 randomized trial. Radiother Oncol 127(2):206–212. https://doi.org/10.1016/j.radonc.2018.02.029
12. Mahadevan A, Blanck O, Lanciano R, Peddada A, Sundararaman S, D'Ambrosio D, Sharma S, Perry D, Kolker J, Davis J (2018) Stereotactic Body Radiotherapy (SBRT) for liver metastasis - clinical outcomes from the international multi-institutional RSSearch(R) Patient Registry. Radiat Oncol 13(1):26. https://doi.org/10.1186/s13014-018-0969-2
13. Moon DH, Wang AZ, Tepper JE (2018) A prospective study of the safety and efficacy of liver stereotactic body radiotherapy in patients with and without prior liver-directed therapy. Radiother Oncol 126(3):527–533. https://doi.org/10.1016/j.radonc.2018.01.004
14. Kim JW, Kim DY, Han KH, Seong J (2018) Phase I/II trial of helical IMRT-based stereotactic body radiotherapy for hepatocellular carcinoma. Dig Liver Dis. https://doi.org/10.1016/j.dld.2018.11.004
15. De Wolf K, Rottey S, Vermaelen K, Decaestecker K, Sundahl N, De Lobel L, Goetghebeur E, De Meerleer G, Lumen N, Fonteyne V, De Maeseneer D, Ost P (2017) Combined high dose radiation and pazopanib in metastatic renal cell carcinoma: a phase I dose

escalation trial. Radiat Oncol 12(1):157. https://doi.org/10.1186/s13014-017-0893-x
16. Siva S, Chesson B, Bressel M, Pryor D, Higgs B, Reynolds HM, Hardcastle N, Montgomery R, Vanneste B, Khoo V, Ruben J, Lau E, Hofman MS, De Abreu LR, Sridharan S, Brook NR, Martin J, Lawrentschuk N, Kron T, Foroudi F (2018) TROG 15.03 phase II clinical trial of Focal Ablative STereotactic Radiosurgery for Cancers of the Kidney - FASTRACK II. BMC Cancer 18(1):1030. https://doi.org/10.1186/s12885-018-4916-2
17. Videtic GMM, Donington J, Giuliani M, Heinzerling J, Karas TZ, Kelsey CR, Lally BE, Latzka K, Lo SS, Moghanaki D, Movsas B, Rimner A, Roach M, Rodrigues G, Shirvani SM, Simone CB 2nd, Timmerman R, Daly ME (2017) Stereotactic body radiation therapy for early-stage non-small cell lung cancer: executive Summary of an ASTRO Evidence-Based Guideline. Pract Radiat Oncol 7(5):295–301. https://doi.org/10.1016/j.prro.2017.04.014
18. Benedict SH, Yenice KM, Followill D, Galvin JM, Hinson W, Kavanagh B, Keall P, Lovelock M, Meeks S, Papiez L, Purdie T, Sadagopan R, Schell MC, Salter B, Schlesinger DJ, Shiu AS, Solberg T, Song DY, Stieber V, Timmerman R, Tome WA, Verellen D, Wang L, Yin FF (2010) Stereotactic body radiation therapy: the report of AAPM Task Group 101. Med Phys 37(8):4078–4101. https://doi.org/10.1118/1.3438081
19. Distefano G, Baker A, Scott AJ, Webster GJ, Group USCQA (2014) Survey of stereotactic ablative body radiotherapy in the UK by the QA group on behalf of the UK SABR Consortium. Br J Radiol 87(1037):20130681. https://doi.org/10.1259/bjr.20130681
20. Ford E, Dieterich S (2017) Safety considerations in stereotactic body radiation therapy. Semin Radiat Oncol 27(3):190–196. https://doi.org/10.1016/j.semradonc.2017.02.003
21. Rieber J, Abbassi-Senger N, Adebahr S, Andratschke N, Blanck O, Duma M, Eble MJ, Ernst I, Flentje M, Gerum S, Hass P, Henkenberens C, Hildebrandt G, Imhoff D, Kahl H, Klass ND, Krempien R, Lohaus F, Lohr F, Petersen C, Schrade E, Streblow J, Uhlmann L, Wittig A, Sterzing F, Guckenberger M (2017) Influence of institutional experience and technological advances on outcome of stereotactic body radiation therapy for oligometastatic lung disease. Int J Radiat Oncol Biol Phys 98(3):511–520. https://doi.org/10.1016/j.ijrobp.2016.09.026
22. Kirkbride (2011) National Radiotherapy Implementation Group Report Stereotactic Body Radiotherapy
23. Foote M, Bailey M, Smith L, Siva S, Hegi-Johnson F, Seeley A, Barry T, Booth J, Ball D, Thwaites D (2015) Guidelines for safe practice of stereotactic body (ablative) radiation therapy. J Med Imaging Radiat Oncol 59(5):646–653. https://doi.org/10.1111/1754-9485.12336
24. Pan H, Simpson DR, Mell LK, Mundt AJ, Lawson JD (2011) A survey of stereotactic body radiotherapy use in the United States. Cancer 117(19):4566–4572. https://doi.org/10.1002/cncr.26067
25. Dahele M, Hatton M, Slotman B, Guckenberger M (2015) Stereotactic body radiotherapy: a survey of contemporary practice in six selected European countries. Acta Oncol 54(8):1237–1241. https://doi.org/10.3109/0284186X.2014.1003961
26. Nagata Y, Hiraoka M, Mizowaki T, Narita Y, Matsuo Y, Norihisa Y, Onishi H, Shirato H (2009) Survey of stereotactic body radiation therapy in Japan by the Japan 3-D Conformal External Beam Radiotherapy Group. Int J Radiat Oncol Biol Phys 75(2):343–347. https://doi.org/10.1016/j.ijrobp.2009.02.087
27. Distefano G, Garikipati S, Grimes H, Hatton M (2019) Current status of stereotactic ablative body radiotherapy in the UK: six years of progress. BJR Open 1(20190022):1–12. https://doi.org/10.1259/bjro.20190022
28. Commissioning through Evaluation. NHS England. https://www.england.nhs.uk/commissioning/spec-services/npc-crg/comm-eval/
29. Morgan SC, Hoffman K, Loblaw DA, Buyyounouski MK, Patton C, Barocas D, Bentzen S, Chang M, Efstathiou J, Greany P, Halvorsen P, Koontz BF, Lawton C, Leyrer CM, Lin D, Ray M, Sandler H (2018) Hypofractionated radiation therapy for localized prostate cancer: an ASTRO, ASCO, and AUA evidence-based guideline. J Clin Oncol. https://doi.org/10.1200/JCO.18.01097
30. Dearnaley D, Syndikus I, Mossop H, Khoo V, Birtle A, Bloomfield D, Graham J, Kirkbride P, Logue J, Malik Z, Money-Kyrle J, O'Sullivan JM, Panades M, Parker C, Patterson H, Scrase C, Staffurth J, Stockdale A, Tremlett J, Bidmead M, Mayles H, Naismith O, South C, Gao A, Cruickshank C, Hassan S, Pugh J, Griffin C, Hall E, Investigators CH (2016) Conventional versus hypofractionated high-dose intensity-modulated radiotherapy for prostate cancer: 5-year outcomes of the randomised, non-inferiority, phase 3 CHHiP trial. Lancet Oncol 17(8):1047–1060. https://doi.org/10.1016/S1470-2045(16)30102-4
31. Catton CN, Lukka H, Gu CS, Martin JM, Supiot S, Chung PWM, Bauman GS, Bahary JP, Ahmed S, Cheung P, Tai KH, Wu JS, Parliament MB, Tsakiridis T, Corbett TB, Tang C, Dayes IS, Warde P, Craig TK, Julian JA, Levine MN (2017) Randomized trial of a hypofractionated radiation regimen for the treatment of localized prostate cancer. J Clin Oncol 35(17):1884–1890. https://doi.org/10.1200/JCO.2016.71.7397
32. Lee WR, Dignam JJ, Amin MB, Bruner DW, Low D, Swanson GP, Shah AB, D'Souza DP, Michalski JM, Dayes IS, Seaward SA, Hall WA, Nguyen PL, Pisansky TM, Faria SL, Chen Y, Koontz BF, Paulus R, Sandler HM (2016) Randomized phase III noninferiority study comparing two radiotherapy fractionation schedules in patients with low-risk prostate cancer. J Clin Oncol 34(20):2325–2332. https://doi.org/10.1200/JCO.2016.67.0448
33. Pham D, Hardcastle N, Foroudi F, Kron T, Bressel M, Hilder B, Chesson B, Oates R, Montgomery R, Ball D, Siva S (2016) A multidisciplinary evaluation of a web-based eLearning training programme for SAFRON II (TROG 1301): a multicentre randomised study of stereotactic radiotherapy for lung metastases. Clin Oncol (R Coll Radiol) 28(9):e101–108. https://doi.org/10.1016/j.clon.2016.03.005

3.3 POSTAMBLE

This chapter aimed to address Research Question 1 by investigating the implementation of SABR into NSW.

Research Question 1: Is stereotactic ablative body radiation therapy (SABR) available to all patients in NSW, has it been implemented in a timely manner and has the implementation of this technique across the state been equitable?
Key Findings from this Chapter: - By 2020, the number of centres treating SABR was on par with the USA and UK. However, the implementation initially lagged behind Japan and the US based on the surveys from 2009 and 2010 respectively. - The centres who had not introduced this new technique were all from regional areas. - While the first centre introduced SABR in 2007, the work in this paper predicts that this treatment technique would not be available at all centres until 2021.
Summary: The implementation of new technology in NSW radiation oncology centres is delayed compared to some other countries, particularly in regional NSW. SABR was not to be available to all patients in NSW which may have resulted in inequities.

To address these issues, the potential for knowledge sharing is explored in Chapters 5, 6, 7 and 8. More detailed information on the use of SABR in NSW is presented in Chapter 4, specifically looking at aspects of quality and safety. Additionally, Chapter 4 aims to identify barriers which may exist to the safe implementation of SABR into NSW.

CHAPTER 4

The Safety and Quality of SABR in New South Wales

4.1 PREAMBLE

In addition to investigating the availably of new techniques and technologies to radiation oncology patients in NSW, it is also important that treatments are delivered in a safe manner. This chapter again considers SABR in NSW, but evaluates the quality and safety of the treatments available against the 'Guidelines for safe practice of stereotactic body (ablative) radiation therapy', published in 2015 (159) by the Royal Australian and New Zealand College of Radiologist (RANZCR).

This chapter addresses research question 2:

- Has the implementation of SABR across NSW been in accordance with the RANZCR published recommendations?
- If not, in what areas are the recommendations not being met and what are the barriers to this? What can be done to address these barriers?

This work is the first study published looking at SABR-specific guideline compliance. In addition, this study aims to identify the specific areas of low compliance, barriers to compliance and potential future work which could address these issues.

Chapter 3 of this thesis is published as 'A survey of compliance with stereotactic ablative body radiotherapy quality recommendations' in the Journal of Medical Imaging and Radiation Oncology in 2023 (160).

4.2 PUBLICATION 2

A survey of compliance with stereotactic ablative body radiotherapy quality recommendations

RADIATION ONCOLOGY—ORIGINAL ARTICLE

A survey of compliance with stereotactic ablative body radiotherapy quality recommendations

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Conflict of interest: Dr. Nick Hardcastle is an Editorial Board member of JMIRO and a co-author of this article. To minimise bias, he was excluded from all editorial decision-making related to the acceptance of this article for publication. The authors declare no further conflicts of interest.

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Abstract

Introduction: Many publications have proposed quality standards for stereotactic ablative body radiotherapy (SABR). However, data on the level of compliance with these guidelines is lacking in the literature. This study aimed to understand how these guidelines are applied in the clinic and to identify barriers to implementing such recommendations.
Methods: Interviews were conducted with multidisciplinary staff at radiation oncology centres across New South Wales formulated around the RANZCR Guidelines for Safe Practice of Stereotactic Body (Ablative) Radiation Therapy. The interview responses were grouped into 20 topics, assessed against the guidelines and thematically analysed.
Results: Good compliance with the guidelines was found, with more than 80% of centres achieving satisfactory results in more than half the topics. The areas with the lowest compliance were auditing, risk assessment and reporting recommendations. Barriers to the quality of SABR treatments included limited training opportunities, low patient numbers and a lack of clear requirements on comprehensive auditing and reporting.
Conclusion: Overall, the centres surveyed reported good compliance with most of the RANZCR SABR guidelines. The tasks with the lowest compliance were those that monitor quality outcomes. Potential strategies for improvement include inclusion in clinical trials and the use of databases which link treatment parameters, dosimetry and outcomes. Further work will focus on the barriers identified in this survey and propose practical solutions to improve compliance in these areas.

Key words: guidelines; radiation oncology; SABR; survey.

Introduction

Quality healthcare can be defined as 'the degree to which health services for individuals and populations increase the likelihood of desired health outcomes'.[1] It should be safe, effective, patient-centred, timely, efficient and equitable.[2] Quality indicators in radiation oncology include clinical practice guidelines and consensus statements, systematic reviews and quality audits.[3–6]

With the increased use of stereotactic ablative radiation therapy (SABR),[7,8] many practice guidelines have been published in this area. Such guidelines can cover a specific area, such as contouring,[9,10] a particular treatment site[11,12] or they may be more general in nature,[13] covering a broad range of multidisciplinary areas. The Guidelines for Safe Practice of Stereotactic Body (Ablative) Radiation Therapy were published in 2015 by the Royal Australian and New Zealand College of Radiologists (RANZCR)[14] to assist the rapidly increasing number of centres implementing SABR techniques by ensuring best practice in the establishment and delivery of SABR programmes.

Several audit tools for general radiation oncology quality indicators exist such as the IAEA QUATRO audits[15] and the AAPM SPA.[16] In contrast, systematic auditing for specific SABR guidelines has not been published making it difficult to determine the quality of SABR in the real world. A SABR-specific audit tool would provide information on barriers to quality care, highlight areas for improvement and provide information on the quality priorities of radiation oncology centres.

Journal of Medical Imaging and Radiation Oncology

This study was performed within the Australian state of NSW. A state with a population of over 8 million, 30% of whom live in regional cities and isolated rural areas.[17] Australia's health system includes both public and private radiation therapy services. At the time of this study, there were 20 radiation therapy service providers operating in NSW: three private multi-centre radiation therapy providers; one private not-for-profit radiotherapy centre and 16 public radiotherapy centres operating as standalone sites or in small networks of up to three locations. These centres utilise 1–5 linacs, treating approximately 100–1700 radiotherapy courses per year.[18]

We present the results of a review of SABR practices within these New South Wales radiation therapy centres based on a series of interviews covering the RANZCR recommendations.[14] The study was designed to determine the level of compliance with the RANZCR recommendations in a real-world context and the barriers to compliance, to assist with the implementation of corrective strategies.

Method

Interview methods

Ethics approval for the study was granted by the University of Sydney Human Research Ethics Committee (2021/754).

All 20 radiation oncology service providers in NSW were invited to participate in this study and 19 agreed to take part. Interviews were conducted from November 2018 to December 2020. Some interviews were completed via phone or video call due to COVID-19 restrictions.

Based on the RANZCR Guidelines,[14] a list of 20 topics and guidelines was devised (Table 1). Some questions were broadened beyond the RANZCR guidelines to cover other published SABR recommendations.[19–22] Participants were asked to describe their SABR programme including the equipment used, how they current address each of the topics and were given the opportunity to.

Interviews were conducted by the first author, an experienced medical physicist, except at her workplace. In this case, the two remaining authors conducted the interviews. Extensive notes were recorded and where additional information was required, the centres were contacted by email with follow-up questions.

Following completion of the interviews, all responses were assessed using a rubric to classify the level of performance. The interviewers assessed the response to each question to determine to what degree the criterion had been satisfied. The level of performance was designated as 'At or exceeding recommended level', 'At or exceeding recommended level/Improvement possible', 'Improvement possible', 'Improvement possible/Significant work recommended' or 'Significant work recommended' with the first two levels indicating acceptable compliance. A thematic analysis of the recorded answers was performed and relevant information noted.

Radiation oncology centres in the cities of Sydney, Newcastle and Wollongong were classified as metropolitan, with all other centres classified as regional. Where the interviewees represented multiple sites across both metropolitan and regional areas, the interview responses were classified as mixed. Centres were classified as Public or Private based on the NSW Cancer Institute data.[18]

Analysis

Statistical analysis was performed in Microsoft Excel™ Version 2102. Where radiation oncology providers were part of a network, the interviews were conducted and reported either separately or together at the provider's request. Multiple interviews were conducted where required to accommodate staff availability.

The interviews resulted in 16 questionnaires completed by at least one radiation oncologist, radiation therapist and one physicist. In addition, one questionnaire was partially completed by radiation therapists and physicists, as a radiation oncologist was not available.

Each questionnaire may represent one or more centres and a variable number of professionals, so while the numerical values indicate trends in practice, they should not be taken to be an exact proportion of the centres or professionals within NSW. Percentages provided in the text are based on the number of recorded responses for that topic, and in some cases, multiple responses or no response may have been recorded for one centre. Centres were not specifically asked about difficulties in achieving the guidelines but often this information was provided and recorded.

Results

Study population

The data collection involved 11 on-site interviews and 14 phone or video calls, resulting in 17 questionnaires which captured data from 28 radiation oncology centres. There was input from 82 professionals including radiation oncologists, radiation therapists and medical physicists.

The majority of the responses (53%) represent metropolitan centres with a smaller proportion (35%) representing regional centres and (12%) mixed metropolitan/regional centres. A total of 76% of the questionnaires were from public centres, reflecting the higher number of public radiation therapy service providers in NSW. A total of 88% of centres had active SABR programmes at the time of the survey.

The number of questionnaires completed by staff using Varian and Elekta linear accelerators was nearly equal (53% and 47% respectively). Eclipse (Varian Medical Systems, Palo Alto, CA, USA) was the most commonly used treatment-planning system (43%) with Pinnacle (Philips

Table 1. A summary of the 20 topics and guidelines which formed the structure of the interviews and the basis for the assessments based on the RANZCR guidelines[14]

1	**Training**
	RO-specific SABR training (a relevant fellowship, a dedicated teaching course or mentoring)
	Specific competency-based training for radiation therapists (RT) in SABR particular for IGRT
	SABR-specific training course for radiation oncology medical physicists (ROMP)
2	**Protocols and Documentation**
	Utilise peer reviewed and evidence-based protocols that are regularly reviewed and date tracked. Simulation and planning procedures and protocols should be clearly documented and in place before starting SABR treatment
3	**Risk Assessment**
	A comprehensive, multidisciplinary risk assessment should be developed
4	**Contingency**
	Contingency plans should be in place in case of catastrophic machine breakdown allowing treatment courses to be completed
5	**Collaboration**
	Centres implementing SABR should seek collaborations with more experienced centres
6	**Audits**
	On-site external audit and review of processes prior to commencing SBRT recommended including imaging, planning and treatment processes per clinical site, equipment uses, QA programme and tolerances and end-to-end dosimetry
7	**Databases and Reviews**
	Databases linking patient treatment parameters, dosimetry and outcome are encouraged
	participation in trials, where available, is strongly encouraged
8	**Imaging for Planning**
	The most appropriate imaging to enable accuracy in target delineation should be used. Imaging should be performed at a similar time to radiation therapy planning in treatment position, if possible
9	**Motion Management for Planning**
	Tumour motion assessment must be accounted for at simulation. 4DCT simulation is recommended for lung and liver SABR
10	**Immobilisation**
	The entire length of the patient should be supported comfortably and effectively. Indexed patient positioning systems are recommended. Vacuum bags should be available
11	**Margins**
	Should be based on an understanding of SABR, as well as the natural history of the tumour, the limitations of in-house localisation and from information in the current literature
12	**Planning Technique**
	A range of planning options that include static beams, dynamic arcs and intensity-modulated beams or arcs and combinations of same should be available
13	**Dose Calculation**
	A superposition/convolution type dose algorithm and/or a Monte Carlo dose algorithm with a minimum grid resolution of 2 mm
14	**Reporting**
	Reporting should include Dmax, D95 and D98 for the PTV, Dmax and D99 for the GTV and site-specific OAR data
15	**Staffing for Treatment**
	RO, RT and Physics attend first fraction or trial setup and radiation oncologist (RO) must be present or immediately available for subsequent fractions. Once programme is established, RO and/or ROMP may not be required at each treatment but must be immediately available
16	**Image Guidance**
	Online correction and evaluation for intra-fraction errors is a minimum standard using volumetric or stereoscopic imaging. Imaging protocols are required that include consideration of tolerances, action levels and frequency of imaging, both intra- and inter-fractionally
17	**Treatment Unit**
	Treatment units should meet AAPM TG101[21] tolerances, have a high degree accuracy isocentre (<2 mm diameter), have high dose rates and monitor patient stability during treatment. MLC leaves should be ≤5 mm
18	**Linac QA Documentation**
	QA procedures and protocols should be documented and meet national and international guidelines.
19	**Linac Commissioning**
	From AAPM TG101,[21] commissioning should include immobilisation, localisation, small field measurements and verification. Several specific publications are referenced and particular mention is made to radiation and mechanical isocentre coincidence and end-to-end testing
20	**Patient-Specific QA**
	Initially, patient QA should include a relative and absolute measurement and calculation performed prior to treatment

Radiation Oncology Systems, Fitchburg, MA, USA), Monaco (Elekta, St. Louis, MO, USA) and iPlan (BrainLAB, Feldkirchen, Germany) making up the remainder.

As the responses may be influenced by the tumour sites being treated with SABR at each centre, data on this are provided in Figure 1.

Compliance with the RANZCR recommendations

Compliance for the 20 topics listed in the Guidelines for Safe Practice of Stereotactic Body (Ablative) Radiation Therapy[14] is shown in Figure 2. The recommendations with the lowest compliance were relating to audits, risk assessment and reporting. More than half the questionnaires showed scope for improvement in topics related to databases and clinical outcome/review. A summary of the results, reported solutions, barriers and issues related to compliance can be found in Table 2.

General barriers and requests

Analysis of all responses found that the most common barrier to compliance was staffing. Other common barriers were old or unsuitable equipment, issues with knowledge transfer, issues related to training and a lack of support from other centres. Several centres mentioned that collaborative rounds or peer review would be helpful. Others felt that pooling data or a coordinating group would be of assistance.

Discussion

The level of compliance in NSW with the RANZCR SABR recommendations has been determined in this study, providing for the first time information on how such guidelines are being applied in the real world. This has highlighted areas of low compliance and perceived barriers to compliance.

A lack of comprehensive, external auditing prior to the implementation of a SABR service was apparent during the interviews. Credentialling through clinical trials is available but limited to the specific clinical site. More than 50% of centres offering a SABR service had not participated in trials, and therefore, this form of credentialling would not have been available to them.

Dosimetry audits are available through the ACDS, but these do not cover other aspects required by the guidelines such as equipment quality assurance, so for many Australian centres, there is no formal mechanism for comprehensive external SABR audit. A recommendation of this study is that a framework for quality audits within Australia is established, preferably via a formal audit group or by a networked approach with other centres. Given that no centres satisfied this audit requirement, it is suggested that this remain as a recommendation with an additional statement acknowledging a formal mechanism does not currently exist and that a networked approach should be considered to address this recommendation.

Low levels of acceptable performance were also seen in the domain of risk assessment. These results agree with previously published quality and safety audit data.[15,23] In 2015, Ford *et al.*[23] proposed that this may be due to the newness of approaches such as Failure Modes and Effects Analysis, and our results suggest that this is still an area of poor performance and evidently not prioritised even for a new technique such as SABR.

Reporting was another area which showed low levels of acceptable performance. The requirements for reporting of SABR treatments are outlined in ICRU reports including report 91[24] and in the RANZCR guidelines.[14] References were made to a wide variety of reporting methods which suggest that there is confusion over how

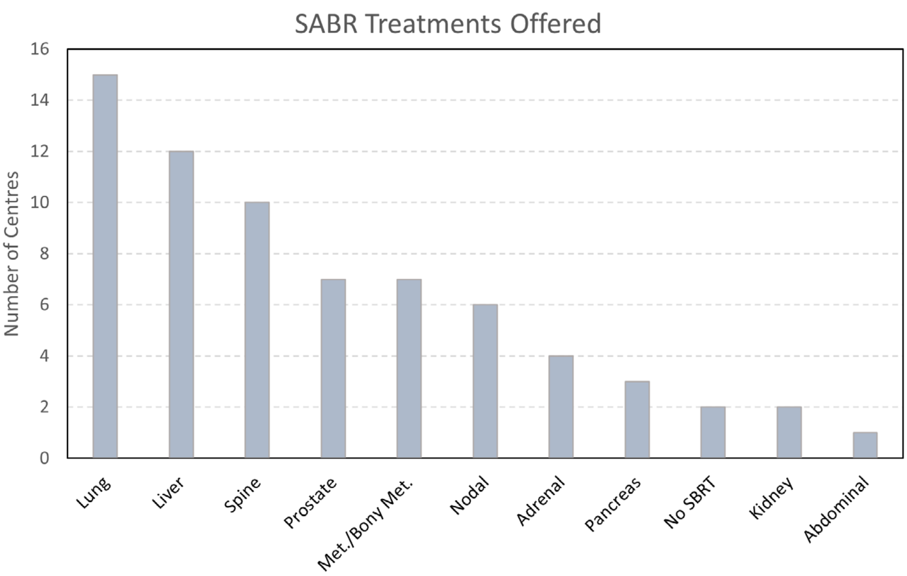

Fig. 1. The number of centres treating each tumour site with SABR.

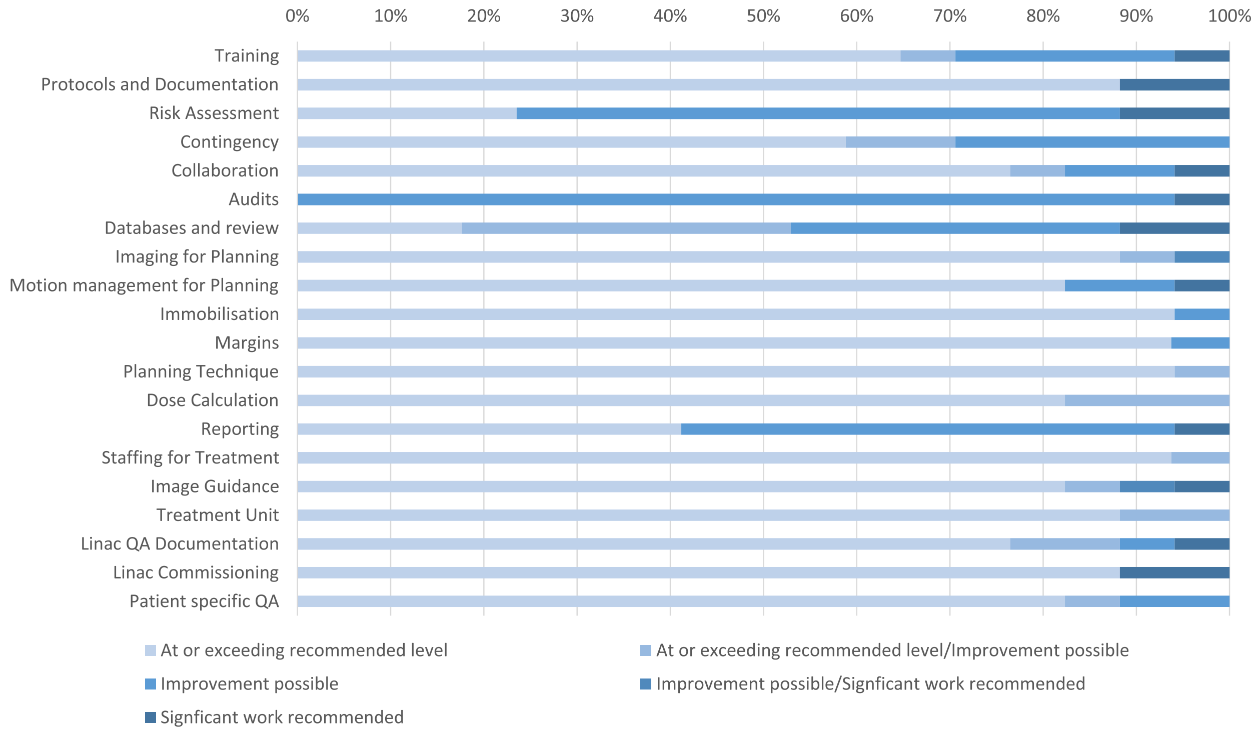

Fig. 2. Results of the evaluation against the RANZCR guidelines for the 20 topics.

to satisfy these requirements in practice. To clarify this, future recommendations should include not just the information which should be reported, but also the practical guidance on what constitutes a satisfactory format for the information being reported.

This study found that the use of databases and registries to monitor patient outcomes could be improved, which is particularly concerning for a complex technique such as SABR. The use of databases to monitor patient outcomes may be limited by financial resources, for example, to employ data managers or dedicate staff time. Efforts to increase automation and reduce the workload required to create such databases may assist in this area, as may longer term projects to assist with the pooling and linkage of outcomes data.

The deficiencies listed above are similar to those found in previous broader radiation oncology audits.[15,23] Following the quality standards decision tree outlined by Donaldson *et al.*,[25] the 20 topics evaluated in this article can be classified into categories. The only three topics classified as 'Outcome' were Audits, Risk Assessment, and Databases and Reviews, all of which have been discussed above as areas where improvement is needed. While the timely implementation of new techniques is important, effort should also be made to measure and report on appropriate quality metrics.

The positive impact of trials in the implementation of SABR was highlighted during the interviews. Trial protocols were often the basis for departmental protocols, even where the centre did not contribute patients to that particular trial. The SSBROC collaborative trial[26] in particular provided a framework which assisted the implementation of lung SABR into NSW. Interviewees mentioned that the trial increased consistency, made them feel safer about SABR, provided procedures to follow and included trial credentialling to validate their lung SABR delivery. This trial also included a registry for the collection of patient data to monitor outcomes. Unfortunately, barriers to trial participation were found and included a lack of support and the workload associated with trials, both of which have been previously identified by other studies.[27–30] While dedicated research staff have been suggested as a solution,[29] cost and funding issues were also identified as barriers. Alternative solutions, such as the use of technology to streamline processes,[31] may be more realistic.

The interviews highlighted the difficulty in training staff for early adopters of new techniques and for centres with low patient numbers. The issue of low patient numbers has been noted previously in Australia,[14] and large distances mean that limiting specialised treatments to major hospitals may not be equitable. Better collaborative efforts between radiation therapy centres, such as the regional networks recommended by the RANZCR[14] and virtual chart rounds,[32] may help to increase hands-on training opportunities when patient numbers are low. However, these opportunities may not be able to replace the experience gained in treating patients in one's own

Table 2. A summary of results, reported solutions, barriers and issues relating to compliance with the RANZCR Guidelines[14] based on the conducted interviews

Topic	General results and reported solutions	Barriers and issues
Training	• Theoretical and practical training for all staff and formal credentialing for staff. • International training or fellowships (88%) • National courses/workshops (88%), • Internal training programmes (76%) • Site visits (47%), • Recruiting experienced staff (47%) • Forming a specialist group for the implementation of SABR (41%)	• A lack of appropriate training for early adopters of SABR • Low patient numbers limiting internal training opportunities and the maintenance of skills
Protocols and Documentation	• Protocols based on trials (94%) • Protocols from another centre (59%) • Protocols based on the Sydney Stereotactic Body Radiotherapy Collaboration[26] lung trial (41%)	
Risk Assessment	• The AAPM TG100 report on risk analysis methods[36] (18%)	• A lack of radiation oncology-specific publications on the topic when implemented SABR
Contingency	• Back up linac available (88%) • Patient delays in the case of linac breakdown were accepted at 29% of centres • No published evidence as to whether a delay in a SABR treatment, which is both hypofractionated and ablative, would have a negative effect on patient outcomes	• The back up linac that has less technical capability than the primary linac (47%) • Staffing limitations, in relation to contingency planning (41%). • Linac breakdown required replanning, plan recalculation or transfer to another location (53%)
Collaboration	• Site visits (41%) • Trials-based collaboration (35%) • Collaboration facilitated by staff who came from other centres (35%) • Active recruitment of RTs with SABR experience • Most centres had actively sought out collaborative opportunities, particularly with centres using similar equipment	
Audits	• Trial credentialling (47%) • Australian Clinical Dosimetry Service (ACDS) SABR dosimetry audit[37] (35%) • Audits completed by other centres (17%) • Internal audits (11%)	• Of those currently treating SABR patients, 33% had not been externally audited • Of those currently treating SABR patients, 20% had not had a SABR-specific audit at all • External audit or trial credentialling were not comprehensive, covering only a particular treatment site or were performed as a dosimetry audit and did not include a review of processes or the QA programme
Databases and Review	• Trial participation was mixed (47% participation in any SABR trial) • Data were collected into a local or combined registry at 35% of centres	• A lack of an integrated, simple-to-use system was a barrier to systematic collection of data • A lack of support in the form of trial coordinators, to assist with the administrative burden and follow-up • Funding, workload, trial timelines and the requirement for experience were barriers to trials participation
Imaging for Planning	• Positron emission tomography (PET) utilisation (88%) • Magnetic resonance imaging (MRI) utilisation (82%)	• The centres not utilising MRI were all regional or mixed regional/metropolitan sites, most of which only treated lung SABR
Motion management for Planning	• Four-dimensional computed tomography (4DCT) used at 100% of sites treating SABR • Internal target volumes (ITV) (82%) • Maximum intensity projection (MIP) images (35%) • Formal assessment of tumour motion and motion-based action limits (64%) • Fluoroscopy for assessment (29%) • Breath-hold techniques (35%) • Abdominal compression (12%)	

Table 2. (continued)

Topic	General results and reported solutions	Barriers and issues
Immobilisation	• In-house studies to assess the immobilisation achieved • Vacuum bags (100%) • Full-body vacuum bags (82%) • Knee blocks (29%) • Indexing (29%)	
Margins	• All centres had well-documented, site-specific margins • Variable or adjustable margins (50%) • Trial-specific margins (25%) • Variation in margins based on the equipment used, in-house studies and individual patient assessments	
Planning Technique	• Volumetric modulated arc therapy (VMAT) (82%) • Dynamic conformal arc therapy (DCAT) (35%) • Planning techniques had changed since SABR was introduced at 35% of centres • General move from 3DCRT to VMAT • VMAT the most popular technique for lung SABR • Spine SABR evenly split between VMAT and intensity-modulated radiation therapy (IMRT)	
Dose calculation	• Several Eclipse centres were either using the Acuros XB algorithm or were changing to it from the AAA algorithm (44%) • 2 mm dose grid (65%) • 1 mm dose grid (53%)	• Improvement required where a 2.5 mm dose grid size was in use (with a 1 mm option available)
Reporting	• Treatment planning system specific reporting tools (29%)	• RANZCR-specific recommendations for SABR treatments[14] and the ICRU requirements for the reporting[24,38] not met (59%) • No formal process or template for reporting (18%) • Inconsistent reporting • A formal process was hampered by the lack of automation
Staffing for treatment	• A radiation oncologist attended at least the first treatment fraction, at times via video feed (100%) • Larger multidisciplinary team (MDT) attended treatments initially, with a move away from this over time (65%)	• Some oncologists would like to reduce their attendance
Image guidance	• Cone beam computed tomography (CBCT) (100%) • All Elekta centres using four-dimensional CBCT (4DCBCT) • Reduced need for mid-treatment imaging due faster VMAT (18%) delivery and flattening filter-free (FFF) beams (18%)	
Treatment unit	• Respiratory motion monitored using the Varian or Elekta systems (71%) • Surface guided radiation therapy (24%) • Using 6 degrees-of-freedom (6DoF) couch (29%) • 6 degrees-of-freedom (6DoF) couch available but not used for SABR (35%)	
Linear Accelerator QA	• Based on AAPM recommendations (91%) • AAPM TG142 (71%)[39] • Local adaptions to published recommendations (47%) • Testing of the kilovoltage isocentre coincidence with the megavoltage isocentre using a Winston–Lutz[40] style test performed daily (35%), weekly (29%) or monthly (24%)	
Equipment commissioning	• Measurements with a moving phantom (76%) • Small field measurements (71%) • ACDS audits (82%)	• End-to-end testing only mentioned in 35% of the interviews
Patient specific QA	• Film measurements (76%) • Three-dimensional arrays (76%) • The method used for patient-specific dosimetry measurement has changed or will soon change • Move away from film or towards portal imager-based dosimetry, with increased confidence in their SABR delivery and increasing patient numbers	• Unable to perform an independent dose verification calculation and were instead relying on in-phantom measurements for plan verification (12%)

centre. Increased use of multi-centre databases to monitor outcomes may also assist in monitoring quality where patient numbers are low at individual centres. Some centres used the SAFRON II e-learning course for lung SABR[33] and the ESTRO FALCON online training for contouring[34] and the recent proliferation of online training during the COVID-19 pandemic has increased access to international training opportunities.

Scope for the transfer of patients between linear accelerators varied widely across NSW, and prolonged linear accelerator breakdown at some centres would result in a significant delay in patient treatments. Recommendations or information on the scope for SABR patient delay would be useful to assess whether these contingency plans are appropriate.

The increasing use of SABR has gone hand-in-hand with technical improvements. Burton *et al*.[35] show that motion managed treatments now most often include the use of 4DCT and VMAT. This agrees with our results which additionally show that SGRT is becoming more prominent. As confidence with SABR increases the presence of a multidisciplinary team attending treatment is becoming less common. With these changes, the quality and safety processes such as risk analyses and end-to-end testing may need to be reviewed, or instigated where these have not been used previously. This may provide an opportunity for an increased focus on quality and safety.

In order to assess changes over time, this survey should be collected again in the future. However, a limitation of this study was the extended timeline required to visit and collect the data. Future work should aim to use faster and simpler methods of data collection such as online self-assessment and could be part of a larger project to simplify the collection of data within NSW radiation oncology centres.

In conclusion, data from across NSW showed good compliance with the recommendations regarding SABR treatments. Lower levels of acceptable performance were evident in the domains of auditing, risk assessment and reporting, which monitor quality outcomes but may not affect the quality of treatment. Allowance should be made for these tasks to ensure the quality as well as the speed of clinical implementation of a new technique. Some barriers to quality in SABR included the limited training opportunities in centres with low patient numbers, and a lack of comprehensive auditing options and clear reporting requirements. Barriers to risk assessment and the maintenance of patient databases were not identified in this study and will be addressed in future work. Meeting the requirements of clinical trials facilitated quality and safety in the implementation of SABR, even in centres who did not participate in those trials. Based on the results of this study, we recommend greater practical assistance be provided to radiation oncology centres in the areas mentioned. To achieve this, further work is currently being carried out to increase the use of prospective risk assessments and share practical training and resources.

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Ethical approval

This study was approved by the University of Sydney Human Research Ethics Committee.

Data availability statement

The data that support the findings of this study are not publicly available as it contains information that could compromise the privacy of research participants.

References

1. Organisation WH. Quality of care, 2020. Available from URL: https://www.who.int/health-topics/quality-of-care#tab=tab_1.
2. Crossing the Quality Chasm: A New Health System for the 21st Century. Washington (DC), 2001.
3. IAEA. Comprehensive Audits of Radiotherapy Practices A Tool for Quality Improvement: International Atomic Energy Agency, 2007.
4. Hayman JA. Measuring the quality of care in radiation oncology. *Semin Radiat Oncol* 2008; **18**: 201–6.
5. Albert JM, Das P. Quality indicators in radiation oncology. *Int J Radiat Oncol Biol Phys* 2013; **85**: 904–11.
6. Harden SV, Chiew KL, Millar J, Vinod SK. Quality indicators for radiation oncology. *J Med Imaging Radiat Oncol* 2022; **66**: 249–57.
7. Pan H, Simpson DR, Mell LK, Mundt AJ, Lawson JD. A survey of stereotactic body radiotherapy use in the United States. *Cancer* 2011; **117**: 4566–72.
8. Distefano G, Garikipati S, Grimes H, Hatton M. Current status of stereotactic ablative body radiotherapy in the UK: six years of progress. *BJR Open* 2019; **1**: 1–12.
9. Redmond KJ, Robertson S, Lo SS *et al*. Consensus contouring guidelines for postoperative stereotactic body radiation therapy for metastatic solid tumor malignancies to the spine. *Int J Radiat Oncol Biol Phys* 2017; **97**: 64–74.
10. Cox BW, Spratt DE, Lovelock M *et al*. International Spine Radiosurgery Consortium consensus guidelines for target volume definition in spinal stereotactic radiosurgery. *Int J Radiat Oncol Biol Phys* 2012; **83**: e597–605.

11. Oar A, Lee M, Le H *et al*. Australasian gastrointestinal trials group (AGITG) and trans-Tasman radiation oncology group (TROG) guidelines for pancreatic stereotactic body radiation therapy (SBRT). *Pract Radiat Oncol* 2020; **10**: e136–46.
12. Videtic GM, Donington J, Giuliani M *et al*. Stereotactic body radiation therapy for early-stage non-small cell lung cancer: executive summary of an ASTRO evidence-based guideline. *Pract Radiat Oncol* 2017; **7**: 295–301.
13. Potters L, Kavanagh B, Galvin JM *et al*. American Society for Therapeutic Radiology and Oncology (ASTRO) and American College of Radiology (ACR) practice guideline for the performance of stereotactic body radiation therapy. *Int J Radiat Oncol Biol Phys* 2010; **76**: 326–32.
14. Foote M, Bailey M, Smith L *et al*. Guidelines for safe practice of stereotactic body (ablative) radiation therapy. *J Med Imaging Radiat Oncol* 2015; **59**: 646–53.
15. Izewska J, Coffey M, Scalliet P *et al*. Improving the quality of radiation oncology: 10 years' experience of QUATRO audits in the IAEA Europe region. *Radiother Oncol* 2018; **126**: 183–90.
16. Dunscombe P, Brown D, Donaldson H *et al*. Safety profile assessment: an online tool to gauge safety-critical performance in radiation oncology. *Pract Radiat Oncol* 2015; **5**: 127–34.
17. Angus C. Regional NSW: A demographic and economic snapshot. NSW Parliamentary Research Service, 2020.
18. Currow D, Thomson W, Bailey K. *Radiotherapy Treatment Services to NSW Residents: 2017 Annual Report*. Cancer Institute of NSW, Sydney, 2018.
19. Das IJ, Dawes SL, Dominello MM *et al*. Quality and safety considerations in stereotactic radiosurgery and stereotactic body radiation therapy: an ASTRO safety White paper update. *Pract Radiat Oncol* 2022; **12**: e253–68.
20. Guckenberger M, Andratschke N, Dieckmann K *et al*. ESTRO ACROP consensus guideline on implementation and practice of stereotactic body radiotherapy for peripherally located early stage non-small cell lung cancer. *Radiother Oncol* 2017; **124**: 11–7.
21. Benedict SH, Yenice KM, Followill D *et al*. Stereotactic body radiation therapy: the report of AAPM task group 101. *Med Phys* 2010; **37**: 4078–101.
22. Kirkbride. National Radiotherapy Implementation Group Report Stereotactic Body Radiotherapy, 2011.
23. Ford EC, Brown D, Donaldson H *et al*. Patterns of practice for safety-critical processes in radiation oncology in the United States from the AAPM safety profile assessment survey. *Pract Radiat Oncol* 2015; **5**: e423–e9.
24. Seuntjens J. Prescribing, Recording, and Reporting of Stereotactic Treatments with Small Photon Beams, ICRU Report 91, 2017.
25. Donaldson H, Cao J, French J *et al*. Quality standards in radiation medicine. *Pract Radiat Oncol* 2014; **4**: 208–14.
26. Hau E, Hegi-Johnson F, Atkinson C *et al*. Collaborative implementation of stereotactic ablative body radiotherapy: a model for the safe implementation of complex radiotherapy techniques in Australia. *Asia Pac J Clin Oncol* 2020; **16**: 39–44.
27. Fayter D, McDaid C, Eastwood A. A systematic review highlights threats to validity in studies of barriers to cancer trial participation. *J Clin Epidemiol* 2007; **60**: 990–1001.
28. Ellis PM, Butow PN, Simes RJ, Tattersall MH, Dunn SM. Barriers to participation in randomized clinical trials for early breast cancer among Australian cancer specialists. *Aust N Z J Surg* 1999; **69**: 486–91.
29. Ross S, Grant A, Counsell C, Gillespie W, Russell I, Prescott R. Barriers to participation in randomised controlled trials: a systematic review. *J Clin Epidemiol* 1999; **52**: 1143–56.
30. Mahmud A, Zalay O, Springer A, Arts K, Eisenhauer E. Barriers to participation in clinical trials: a physician survey. *Curr Oncol* 2018; **25**: 119–25.
31. Haynes RM, Sirintrapun SJ, Gao J, McKenzie AJ. Using technology to enhance cancer clinical trial participation. *Am Soc Clin Oncol Educ Book* 2022; **42**: 1–7.
32. Fitzgerald R, Pryor D, Aland T *et al*. Quality and access – early experience of implementing a virtual stereotactic chart round across a national network. *J Med Imaging Radiat Oncol* 2020; **64**: 422–6.
33. Pham D, Hardcastle N, Foroudi F *et al*. A multidisciplinary evaluation of a web-based eLearning training Programme for SAFRON II (TROG 1301): a multicentre randomised study of stereotactic radiotherapy for lung metastases. *Clin Oncol (R Coll Radiol)* 2016; **28**: e101–8.
34. Eriksen JG, Salembier C, Rivera S *et al*. Four years with FALCON – an ESTRO educational project: achievements and perspectives. *Radiother Oncol* 2014; **112**: 145–9.
35. Burton A, Beveridge S, Hardcastle N, Lye J, Sanagou M, Franich R. Adoption of respiratory motion management in radiation therapy. *Phys Imaging Radiat Oncol* 2022; **24**: 21–9.
36. Huq MS, Fraass BA, Dunscombe PB *et al*. The report of Task Group 100 of the AAPM: application of risk analysis methods to radiation therapy quality management. *Med Phys* 2016; **43**: 4209.
37. Shaw M, Lye J, Alves A *et al*. Measuring the dose in bone for spine stereotactic body radiotherapy. *Phys Med* 2021; **84**: 265–73.
38. Report 83. *J ICRU* 2016; **10**: NP.
39. Klein EE, Hanley J, Bayouth J *et al*. Task Group 142 report: quality assurance of medical accelerators. *Med Phys* 2009; **36** (9 Pt 1): 4197–212.
40. Bissonnette JP, Moseley DJ, Jaffray DA. A quality assurance program for image quality of cone-beam CT guidance in radiation therapy. *Med Phys* 2008; **35**: 1807–15.

4.3 POSTAMBLE

This chapter aimed to address Research Question 2 by investigating the implementation of SABR into NSW.

Research Question 2: Has the implementation of SABR across NSW been in accordance with the RANZCR published recommendations? If not, in what areas are the recommendations not being met and what are the barriers to this? What can be done to address these barriers?
Key Findings from this Chapter: - Good compliance with the recommendations was found at NSW radiation oncology centres. - Areas with low compliance or potential for improvements were auditing, risk assessment, reporting and review of clinical outcomes. - Staffing levels, old or unsuitable equipment, knowledge transfer, training and a lack of support from other centres were identified as barriers to compliance. - The positive impact of clinical trials was highlighted along with the need for better pooling of data to assess clinical outcomes.
Summary: While compliance with recommendations was high, compliance could be improved in specific areas.

The work in this chapter was directly affected by the COVID-19 pandemic. In-person meetings with hospital staff had to be replaced by video calls and the staff of radiation therapy centres were busy maintaining a clinical service.

Several of the following chapters focus on addressing the findings of this chapter. Chapter 7 investigates how knowledge transfer and inter-centre cooperation can be used to expand the use of formalized risk assessments. Chapters 6 and 8 address the need for knowledge transfer and inter-centre support through focused workshops and online collaboration.

The work in Chapter 9 looks at how an existing research database can be used to implement automated and sustainable self-auditing and pool data to provide better information on current practice. Future work may include assessment of clinical outcomes using these same data.

The following chapter looks at a particular example of knowledge transfer and inter-centre collaboration.

CHAPTER 5

Collaborative Implementation of Knowledge-Based Planning

5.1 PREAMBLE

Knowledge-based planning (KBP) is a tool to rapidly generate high-quality radiation treatment plans. This planning technique involves estimating the dose to the organs-at-risk from the patient's anatomy and applies machine learning models based on data generated from a databased of previously created treatment plans. Modern radiation therapy planning utilizes a method called "inverse planning" where clinical goals and relative weighting factors (called priorities) are assigned to targets and normal tissues, and an optimized plan is created by minimizing a cost function. Traditionally, a template of appropriate goals and priorities is used and manually adjusted to achieve an acceptable plan for each patient. KBP instead uses previous patient data to estimate the dose distribution that should be achievable for a particular patient and sets the goals and priorities based on these estimates. This personalized approach aims to further reduce the dose to normal tissue for patients with favourable anatomy, whilst not trying to achieve physically unachievable results for others. As a result, KBP assists planners to achieve clinically acceptable plans more quickly than could be achieved starting with a template of objectives (161, 162) and is a valuable tool for less experienced planners (163).

Moving away from SABR, this chapter explores the implementation of knowledge-based planning in the form of the RapidPlan software from Varian Medical Systems (Palo Alto etc). A consortium of NSW radiation oncology centres was established in 2018 to look at the potential for collaboration with regards to RapidPlan. While the product vendor promoted the opportunities for sharing data models produced in RapidPlan between centres, the consortium felt that the benefits of this had yet to be established.

This chapter addresses research question 3:

Can knowledge-based planning models, created using the Varian RapidPlan software, be successfully shared between centres?

This work is the first study specifically investigating the benefits of sharing RapidPlan data models compared with creating centre specific models.

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SCIENTIFIC PAPER

A comparison of in-house and shared RapidPlan models for prostate radiation therapy planning

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Abstract

Knowledge-based planning (KBP) can increase plan quality, consistency and efficiency. In this study, we assess the success of a using a publicly available KBP model compared with developing an in-house model for prostate cancer radiotherapy using a single, commercially available treatment planning system based on the ability of the model to achieve the centre's planning goals. Two radiation oncology centres each created a prostate cancer KBP model using the Eclipse RapidPlan software. These two models and a third publicly-available, shared model were tested at three centres in a retrospective planning study. The publicly-available model achieved lower rectum doses than the other two models. However, the planning-target-volume (PTV) doses did not meet the local planning goals and the model could not be adjusted to correct this. As a result, the plans most likely to satisfy local planning goals and requirements were created using an in-house model. For centres without an existing in-house model, a model created by another centre with similar planning goals was found to be preferred. Variations in local planning practices including contouring, treatment technique and planning goals can influence the relative performance of KBP. The value of publicly available KBP models could be enhanced through standardisation of planning goals and contouring guidelines, providing information related to the planning goals used to create the model and increased flexibility to allow local adaptation of the KBP model.

Keywords RapidPlan · Knowledge-based planning (KBP) · Prostate · Radiation oncology · Shared models

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Introduction

Knowledge-based planning is a technique where knowledge from historical planning data is combined with patient anatomical information to inform achievable plan quality for the individual patient. The introduction of knowledge-based planning (KBP) for an automated, individualised approach for optimising modulated radiotherapy has been shown to increase plan quality and decrease inter-planner variation [1, 2]. Its implementation into the Eclipse treatment planning system, under the name RapidPlan (Varian Oncology Systems, Palo Alto, Ca, USA) has been validated in numerous studies [3–7]. RapidPlan uses dose-volume histogram (DVH) predictions based on previous plans to create individualised optimisation criteria.

The New South Wales RapidPlan Consortium was formed in late 2018 to investigate possible benefits which could be gained through collaboration between centres using RapidPlan. Whilst multiple publications have reported methods for optimising RapidPlan models for local use, few publications have reported potential benefits of model sharing across multiple institutes.

Schubert et al. [8], representing the German RapidPlan Consortium, distributed a model from a single centre to seven separate institutions and found that the model produced clinically acceptable plans at all centres. However, it was postulated that further fine tuning of the model at the local site may be beneficial given the differences between institutions in terms of contouring, planning techniques and planning goals. Ueda et al. [9] investigated the differences between models produced independently at 5 institutions and concluded that sharing models would require that the plan designs used for the DVH estimate match those used in the institution receiving the model. In contrast, rather than sharing models, the Victorian Public Sector RapidPlan Group created a prostate model jointly between eight separate radiotherapy centres [10]. When comparing the retrospective, manually produced plans with the Group-model generated plans, they found a general improvement in organ-at-risk doses and dose homogeneity. However, they also found that the introduction of a common automated model did not reduce the range of OAR doses (ie the minimum to maximum values) within each centre.

With the growing evidence of the benefits of using RapidPlan, many centres are looking to implement KBP. However, limited guidance on the best and most efficient ways to do this is provided in the literature. To investigate this, we designed a study to ask the following question: Is it better to develop an in-house model, use an externally developed model or modify an externally developed model? To answer this question, three centres evaluated two locally generated models and one publically available model. Each centre used the models to generate plans for a set of previously treated patients. Each centre evaluated the generated plans according to their standard (in-house) qualitative and quantitative planning goals.

Methods and materials

RapidPlan, implemented in the Eclipse Treatment Planning System (Varian Oncology Systems, Palo Alto, USA), was used for KBP model generation. For this study, three radiation therapy centres were enrolled, referred to as Centre A, B and C. Centre C had no prior KBP experience or local models. They aimed to determine from this study if an existing model would satisfy their requirements or whether they should instead create their own model. Centres A and B had existing prostate models which were included in the testing, referred to as Model A and Model B, respectively. Centres A and B aimed to determine whether an external model would better satisfy their planning requirements compared with their in-house models.

In addition to the in-house models from Centres A and B, the University of California, San Diego (UCSD) ‘UCSD Prostate’ [11] model was included in the testing as an example of a freely-available, shared model. Information regarding the 3 models is given in Table 1. Model A and B both include multiple target structures to allow the higher doses to be constrained to the central portion of the planning target volume (PTV).

At each of the three centres, 19–20 consecutive patients were selected after excluding those who would not normally be planned with a standard beam configuration, for example patients with bi-lateral hip prostheses. Each centre planned their selected cohort using each of the three KBP models. Planners were asked to use the prescription dose, beam configuration and energy they would normally use in their centre. All centres chose to plan using volumetric modulated arc therapy (VMAT). Patients were planned with a single-click optimisation with no adjustments made by the planner. Plans were completed in Eclipse V13 using the AAA algorithm (Centres A and B) or Eclipse V15 using the AXB dose-to-medium algorithm (Centre C). In line with current practise at each centre, Centre A plans used 10MV while plans at Centres B and C used 6MV.

In addition to the three initial models, Centres A and B created and applied an edited version of the UCSD model, labelled as UCSD Edit. This new model was created by adjusting the objectives, including both dose level and priority, in the UCSD model to better satisfy the planning goals of those centres.

Dose volume histogram (DVH) data were then extracted using the Eclipse Scripting API and compared to the

Table 1 Details of the initial KBP models

Model	Model A	Model B	UCSD
From	Centre A	Centre B	Downloaded from UCSD
Version	13.7.16	13.6.23	13.6.23
Number of patients	92	41	105
Number of targets	2	3	1
OARs	Bladder	Bladder	Bladder
	Femoral heads	Femoral heads	Left femur
	Rectum	Rectum	Right femur
		Small bowel	Rectum
			Penile bulb
Intended use	Intact prostate or prostate bed, VMAT technique	Intact prostate ± seminal vesicles, VMAT technique	Prostate, VMAT[a]

[a]The intent of this model is not explicitly stated, however the model is named ‘Prostate’ and ‘2-arc VMAT’ is listed as the beam configuration

centres’ own prostate planning goals for each patient’s dose prescription. The planning goals of the three centres for a 78 Gy prostate plan are presented in Table 2. In addition, the planning goals from the eviQ ‘Prostate adenocarcinoma definitive EBRT conventional high risk’ protocol [12] are listed for comparison. eviQ does not provide recommendations on target coverage. In addition to the values listed in Table 2, eviQ quotes planning goals from trial protocols.

Table 2 Prostate planning goals for 78 Gy prostate plans

Volume	DVH value	eviQ (12)	Centre A	Centre B	Centre C
CTV	V100%		> 99%		(> 99%)
PTV	V100%			> 99%	
	V95%		> 99%	> 99%	> 98%
	D1cc		< 107%		
	D2%				< 107%
	D99%				> 100%
	V107%			< 5%	
	Mean			> 102.4%	
	Mean			< 104.6 (104.4)%	
Bladder	V40	50%	50%		50%
	V50	50%	50%		
	V55			50%	
	V65	25%			25%
	V70		20%	30%	
	V78		5 cm^3		
	V80		0.1 cm^3		
Rectum	V40	35%	50%	60% (50%)	35%
	V60		35%	40% (35%)	
	V65	17%		25%	17%
	V70		20%	25% (20%)	
	V75	10%	10%	(15%)	5%
	V78		2cm^3		
Femoral heads	V30		60%		
	V35	100%		100%	
	V45	60%			
	V50		5%	5%	5%
	V60	30%			

Values in brackets indicate goals which are desirable but not required

These have not been included as they often differ from the eviQ recommendations. The eviQ protocol also includes constraints for the penile bulb, small intestines and large intestines. These are not listed as none of the centres in this study contour these organ-at-risk (OAR) structures.

To allow comparison between the models as well as between the centres, the following dosimetry parameters were evaluated: PTV V95% and D1cc, bladder V40Gy, V50Gy and V65Gy, rectum V40Gy, V65Gy and V75Gy and femoral heads V50Gy, where VxxGy refers to the volume receiving xx in Gy. For these parameters, the mean values for each centre were calculated and these data presented in graphical format for comparison.

Statistical comparisons of the results were performed using Matlab™ with an unpaired 2-sample t-test used where $P<0.05$ indicates significance in the difference of the mean values. The boxplots produced (Figs. 1, 2 and 3) to compare results display the interquartile range as a blue box with the median indicated by a red line and outliers shown as red '+' symbols.

Each centre was asked to provide feedback regarding the performance of the RapidPlan models and which model(s) that centre intended to use in the future.

Results

Overall model performance

Considering the plans against all the local planning goals at each centre, as shown in Table 3, all models gave similar results. Centres A and C found Model A more likely to meet the planning goals while the edited UCSD model resulted in the highest proportion of planning goals met for Centre B.

PTV model performance

Model B meet a higher proportion of PTV planning goals at Centres A and C, while the UCSD edit Model met the higher proportion of PTV metrics at Centre B. Figure 1 compares the PTV V95% and D1cc data, showing the 3 centres and the 3 or 4 different models used at each centre. Note that the UCSD Edit models in the presented graphs are unique to each centre based on the changes made by that centre. At Centres B and C, all models generally achieved V95% greater than 99%, whereas at Centre A, only the Models A and B consistently achieved this objective. Comparing PTV V95% between centres, the results from Centres B and C do not show a significant difference between any of the models. The Centre A data are significantly different from Centre C for the UCSD model ($P=0.007$) and also from Centre B for

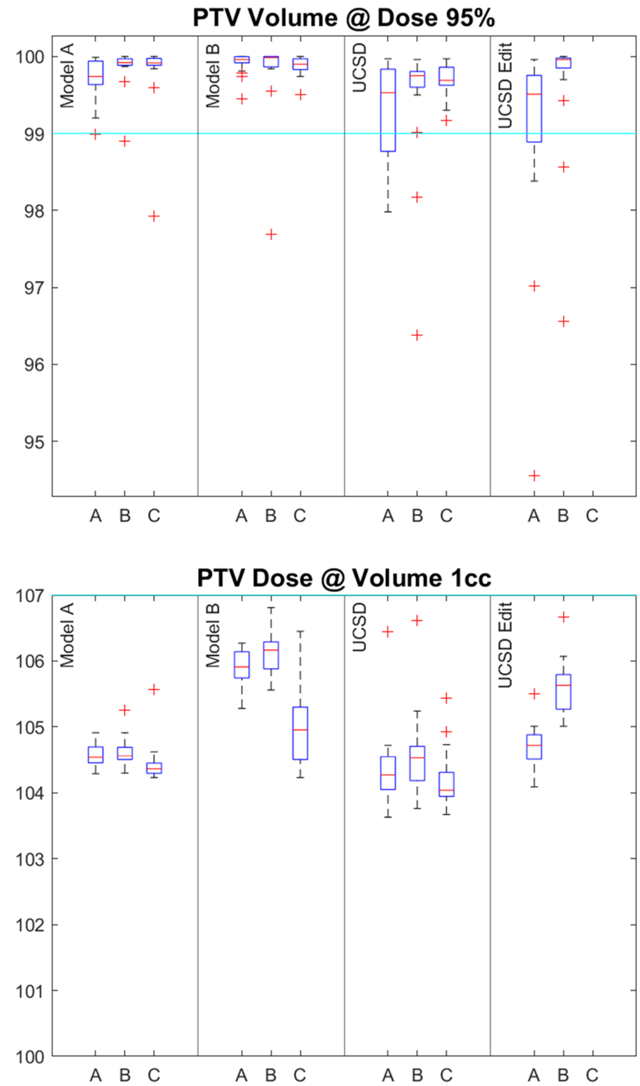

Fig. 1 **a** The volume of PTV receiving 95% of the prescription dose (V95%) for the three centres (A, B, C) and for the four models (Model A, Model B, UCSD and UCSD edit), shown as a percentage. The cyan line indicates the eviQ acceptable level. **b** Percentage dose received by 1 cc of PTV (D1cc) for the three centres (A, B and C) and for the four models (Centre A, Centre B, UCSD and UCSD edit)

Model A ($P=0.048$). Figure 1b shows the PTV D1cc for all centres. The 107% objective was meet by all plans. However, all centres found the mean D1cc to be higher with Model B ($P<0.001$).

OAR model performance

Model B achieved the lowest proportion of OAR planning goals at all centres while Model A, the UCSD model and the two UCSD edit models gave similar results. Figures 2 and 3 show the bladder and rectum V51.3% (equivalent

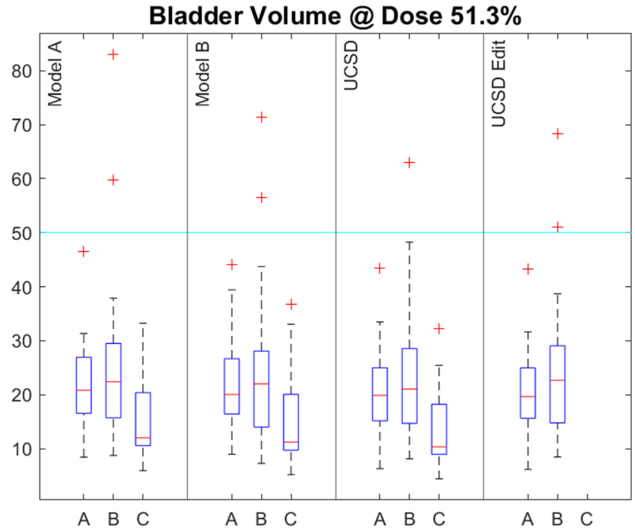

Fig. 2 The percentage of bladder receiving a dose of 51.3% or more (equivalent to V40Gy for a 78 Gy prescription) for the three centres (A, B, C) and for the four models (Centre A, Centre B, UCSD and UCSD edit). The cyan line indicates the 78 Gy prostate eviQ acceptable tolerance

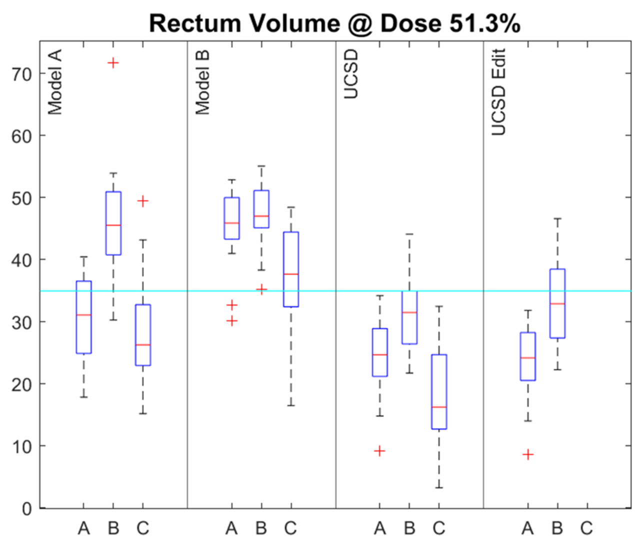

Fig. 3 The percentage of rectum receiving a dose of 51.3% or more (equivalent to V40Gy for a 78 Gy prescription) for the three centres (A, B, C) and for the four models (Centre A, Centre B, UCSD and UCSD edit). The cyan line indicates the 78 Gy prostate eviQ acceptable tolerance

to V40Gy for a 78 Gy prescription) DVH information for all centres and models. All models performed similarly with regard to the bladder doses. However, the dose to the rectum was lower with the UCSD model compared to both

Table 3 The average percentage of achieved local planning goals

	Model A	Model B	UCSD	UCSD edit
All local planning goals				
Centre A	80 ± 10%	72 ± 13%	76 ± 9%	76 ± 9%
Centre B	87 ± 3%	87 ± 3%	88 ± 2%	94 ± 6%
Centre C	92 ± 10%	88 ± 10%	86 ± 5%	
PTV local planning goals				
Centre A	75 ± 8%	99 ± 6%	57 ± 14%	57 ± 14%
Centre B	66 ± 4%	66 ± 4%	65 ± 5%	85 ± 16%
Centre C	93 ± 14%	97 ± 10%	67 ± 0%	
OAR local planning goals				
Centre A	81 ± 13%	64 ± 17%	82 ± 10%	82 ± 10%
Centre B	98 ± 5%	98 ± 5%	100 ± 0%	100 ± 2%
Centre C	91 ± 13%	84 ± 14%	94 ± 7%	

The values in the table are the average of the plans ± 1 standard deviation of these values

Models A and B ($P < 0.001$ for both Models A and B at Centres B and C and for Model B at Centre A).The UCSD Edit models also produced lower rectum doses than Model A and B. The increased rectal sparing of the UCSD model can be seen in Fig. 4 where the 50% isodose line covers less of the rectum posteriorly.

Centre A

Model A achieved the highest proportion of planning goals at Centre A. While PTV planning objectives were more likely to be meet by Model B, the lower performance against the OAR planning objectives meant that this model was unacceptable to Centre A. Conversely, the UCSD and UCSD Edit models provided better rectal sparing and met more of the planning goals but performed poorly against the PTV planning goals.

It can be seen from Figs. 1, 2, 3 and 4 that UCSD edit model managed to maintain the low rectal doses of the original model. However, Centre A felt that the PTV V95% dose coverage achieved was inferior, visible in Fig. 1, and they were not able to remedy this.

They noted that the UCSD model achieved lower rectal doses. Information about the plans used to create each model is included in Table 4 in Appendix. These data show that the mean rectum doses for the plans in the UCSD model are lower than the plans Model A and Model B leading to lower predicted DVH curves and a lower line dose optimisation objective. In addition, the UCSD model, which included a wider range of rectal volumes than those in Model A or B, contained a number of upper objectives on the rectum which were not present in Model A or B.

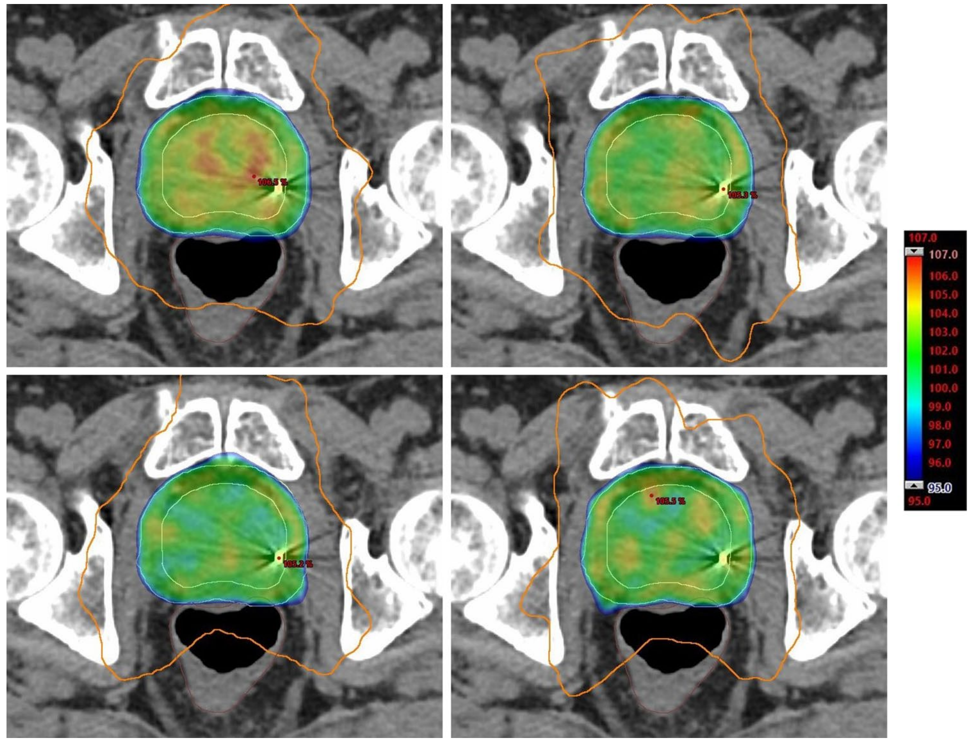

Fig. 4 The dose distribution of a patient from Centre B representative of the majority of patients. PTV shown in pink, CTV shown in orange, 50% isodose shown as orange, 100% isodose shown as cyan and the colour wash indicating 95–107% dose. Top Left—Model A. Top Right—Model B. Bottom Left—UCSD. Bottom Right—UCSD edit

The staff at Centre A found that the sharing of models was beneficial and discussed all models in a multi-disciplinary meeting. They chose to continue improving their in-house model (Model A) informed by the results of this study.

Centre B

For Centre B, the UCSD edit model achieved the PTV and OAR planning objectives more consistently than any of the other models performed. Despite this, Centre B did not select to use this model clinically.

Centre B is the only centre with a mean PTV dose goal. While the UCSD edit model satisfied more of the PTV planning goals than the other models, this particular goal was not satisfied for any patients using the UCSD and the UCSD Edit Models. In comparison, Model B achieved this objective for 95% of patients and Model A achieved this objective for 50% of patients. It is possible that renormalising the plans could have resulted in more plans satisfying this planning goal while still achieving better OAR doses. However, the planner at Centre B also noted that the global maximum dose with the UCSD and UCSD edit models was often outside the CTV (seen in 95% of plans using the UCSD model and 90% of plans using the UCSD edit model). While not a documented planning goal, the planner preferred the maximum dose to be in the CTV and this was achieved more often with the model developed in their own centre, Model B, with only 15% of plans using Model B having a global maximum dose outside the CTV. For Model A, which also uses multiple target structures, 75% of plans had the maximum dose outside the CTV.

Centre C

Model A achieved the most local planning goals at Centre C. The UCSD model fared poorly on the PTV planning goals and Model B was not able to satisfy as many OAR goals as Model A.

Based on their experience with the three models, Centre C expected that Model A would be the best model to adopt as their planning goals aligned better with Centre A, compared with Centre B. A lack of physics resources meant that the implementation of Model A was delayed and during this time an in-house model was developed by planning staff which was eventually implemented. The building of the in-house RapidPlan model at Centre C was informed by the other 3 models and hence participating in this project was considered beneficial.

Centre C reported that the sharing of models allowed them to become familiar with the software and to build a set of prostate plans to use in their own model. One of the main challenges at Centre C was finding agreement between their oncologists on the planning goals they should aim for. Centre C have implemented RapidPlan models for other treatment sites following this work.

Discussion

Creating a RapidPlan model requires multiple good quality treatment plans. Using an externally generated model has the potential to produce superior plans while reducing the repetition of work already performed by others. This study investigates this further by comparing in-house RapidPlan models with externally developed models. Our results, from both centres A and B, show that their in-house models produce plans which are more likely to satisfy the local planning goals compared to externally produced models. This is not surprising given these models were specifically created with the planning goals of their centres in mind.

However, the assessment of models based on the performance of plans against local planning goals was incomplete. This style of assessment failed to highlight the reductions in rectal dose achieved by the UCSD model and other considerations such as location of global maximum dose.

Knowledge-based planning, as implemented in RapidPlan, aims to predict the optimal OAR DVHs and, based on these, set realistic optimisation criteria. As the UCSD model creates plans with lower rectal doses, it could be argued that this is the model which should be adopted for planning at the three centres. However, it may be that the lower rectal dose predictions given by this model are not compatible with the PTV requirements of the centres involved and, even with editing, the UCSD model could not produce plans clinically acceptable at the centres.

The failure of either Centre A and B to create a satisfactory model from the UCSD model may indicate adjustment of a model created with different aims is limited. Consequently, the centres may be biased towards their own in-house models and were not invested in further developing the external model.

Also, the adjustments to the UCSD model were limited by the single target structure used in this model. While additional target structures can be added to a model for each patient, the addition of an extra target by default for all patients invalidates the model within Eclipse and renders it unusable. All centres in this study found the PTV doses from the UCSD model were unsatisfactory and, without additional control provided by an extra target structure, were not able to adjust the model to produce satisfactory plans.

The lower rectal doses achieved with the UCSD model indicate a potential for improvement of the in-house models. Utilising additional fixed objectives on the rectum, when producing plans in the future, may produce lower rectal DVH curves. New iterations of models using plans with lower rectal DVH curves would lead to lower model predicted DVH curves and the production of plans with lower rectal doses.

While the in-house models were selected for use by all centres, these results may not be true for other comparisons where the shared model is better suited to the centre involved and to customisation. In addition, situations exist where generating a local model may not be feasible e.g. if patient numbers are low or planning practises have recently changed (ie. using a new planning system or changing from an IMRT to VMAT technique).

This study has highlighted the differing planning goals which exist between centres but the data also shows that the same model can give different results at different centres. Our results show that, for all models, the bladder doses are lower at Centre C, that the rectum doses are higher at Centre B and that PTV coverage is lower at Centre A. The differences observed could be caused by differences in contours or differences in planning techniques. As all centres chose to use a 2-arc planning technique, this is unlikely to be the cause. Centres B and C used 6MV whereas Centre A used 10MV. This may contribute to the higher rectum doses at Centre B but higher doses were not seen at Centre C using the same energy, and this does not explain the lower bladder doses at Centre C or lower PTV coverage at Centre A. A review of the rectal contouring guidelines at the three centres shows that these are not well documented at Centre B. This may be contributing to the higher rectal doses. Additionally, the patients' prostate size as well as bladder and bowel preparation may also differ which could result in differing OAR and PTV contours.

While the shared models were not implemented clinically by the centres involve in this investigation, benefits were seen from the assessment of different models. All centres were able to benchmark in-house models against external models, determine areas of potential improvement for future model creation and learn by viewing the objectives set in other models.

Based on this work, an option to improve the success for future sharing of RapidPlan models and similar collaborative efforts is to work towards better agreement between centres, whereby planning goals and contouring guidelines are unified, prior to attempting to create a model. This option has several advantages in that it would incorporate external review of planning goals between centres, promote collaboration and discussion between centres and simplifies the task of creating a satisfactory model. This approach has been used successfully to create regional models in Germany and Victoria [8, 10]. In the Victorian model, plans from all centres were included in the creation of the model. This should ensure that the geometric range of patients at all centres is included. However, these models may need to exclude patient cohorts where systematic differences exist between target and OAR segmentations (eg potentially stratifying patients by use SpaceOAR gel to increase the space between the posterior prostate and rectum). When planning aims are agreed a-priori, for example in the context of a clinical trial, a share RapidPlan model has the potential to harmonise plan quality between centres and improve trial protocol compliance.

It has been seen in this study that considering only predefined planning metrics (i.e. DVH planning constraints) is not the only method used to assess plan quality. Even with prior agreement on planning goals, additional organ sparing following the as-low-as-reasonably-achievable (ALARA) [13] principal or improved PTV coverage may be achievable. The relative prioritisation and importance of these potential improvements may differ between radiation oncologists.

The success of sharing of RapidPlan models could be further improved by ensuring planning goals contained in the model are defined, and flexibility is built within the model. These features would allow wider sharing of models and would not require agreement or discussion prior to the creation of models. Centres could select a model which is most likely to align with their planning priorities and adapt this model in response to future changes in practice. In the specific context of RapidPlan, ensuring flexibly in shared models would mean including multiple PTV structures and a wide range of OAR structures to allow for the variation in planning goals between centres. This option would still require DVH predictions to be achievable in addition to the other added constraints, and hence all models need to be validated at the local level prior to clinical implementation.

A limitation of this study is that it only considered prostate radiotherapy. However, a comparison between an in-house created model and available shared models is likely to be beneficial for all treatment sites and ensure to best available RapidPlan model is used. Where the creation of an in-house model is not practical a flexible, shared model from a centre with similar planning goals is likely to be beneficial. However, internal testing and adjustment of the model are likely to still be required.

Conclusions

When comparing radiotherapy plans generated using an in-house model with an externally generated model, it was found that the in-house model would most likely achieve the local planning goals and satisfy the requirements of the radiation oncologist. When an in-house model is not available, the model most likely to be considered acceptable is a model that has been created by a centre with similar planning goals. While the UCSD prostate model was found to achieve the lowest rectal doses, a lack of flexibility in adjusting the model meant that it could not provide plans which were satisfactory to any of the centres.

Participating in a comparison of RapidPlan models was found to be beneficial for the centres involved, even when the centre chose not to adopt the new models for patient planning. Where possible, centres should consider a range of RapidPlan models to find the model that best suits their needs.

When developing RapidPlan models for sharing or for internal use, models should be designed to be flexible, in particular, multiple target structures should be included as well as all available OAR structures. This allows more adjustment of the model where additional boost regions or additional OAR limitations are required. Model documentation should include details of the planning goals and beam arrangements of the plans used to create the model. This allows centres to select the most compatible models and then adapted these models to different planning constraints or techniques. The success of shared RapidPlan models may be increased through standardisation of planning goals and contouring guidelines as this will ensure more consistently DVH predictions.

Appendix

See Table 4

Table 4 Data from the three models from the Varian Model Analytics program showing the optimisation objectives as well as minimum (min), mean, maximum (max) and standard deviation for the target and organs-at-risk both volumetrically and dosimetrically

	Model A	Model B	UCSD
Optimisation objectives			
PTV			D10% < 102% Priority 100
	D0% < 104% Priority 150	D0% < 102.5% Priority 110	D0% < 103% Priority 150
	D100% > 98% Priority 140	D100% > 100% Priority 130	D100% > 97% Priority 150
			D98% > 100% Priority 150
		D95% < 100% Priority 0*	
CTV or PTV inner		D0% < 106.5% Priority 140	
		D15% < 105% Priority 90	
	D100% > 101% Priority 160	D100% > 103% Priority 130	
Bladder	V99% < 0% Priority 90	V103.5% < 0% Priority 120	V95% < GV Priority 80
			V50% < GV Priority 80
			V25% < GV Priority 30
	Line Priority 60	Line Priority 65	Line GP
Femur_L/Femur_R			Line GP
Femoral Heads	Line Priority 60		
Penile Bulb			Line GP
Rectum	V99% < 0% Priority 90	V102% < 0% Priority 80	V100% < 0% Priority 150
			V95% < GV Priority 100
			V75% < GV Priority 90
			V50% < GV Priority 90
			V25% < GV Priority 80
			V10% < GV Priority 50
	Line Priority 60	Line GP	Line Priority 70
Input plan data			
Number of Targets	2	3	1
Number of OARs	3	3	5
Total number of plans	93	41	105
Targets	CTV	PTV inner	PTV
	PTV_High	PTV optimise	
		PTV low	
OARS	Bladder	Bladder	Bladder
	Rectum	Rectum	Rectum
	Femoral Heads	Femoral Heads	Femur_L
			Femur_R
			Penilebulb

Table 4 (continued)

	Model A	Model B	UCSD
PTV Target	PTV_High	PTV optimise	PTV
Volumetric [cm^3]			
Min	70.39	7.44	44.55
Max	402.73	462.92	387.32
Mean	163.93	197.45	135.54
Std	70.46	82.42	53.33
Mean Dose [Gy]			
Min	32.59	45.07	9.15
Max	79.59	80.77	83.71
Mean	67.25	76.83	55.37
Std	8.24	7.83	26.17
Mean Dose [%]			
Min	99.32	101.89	101.08
Max	102.77	103.55	103.56
Mean	101.09	102.67	101.86
Std	0.67	0.44	0.47
Central Target	CTV	PTV inner	
Volumetric [cm^3]			
Min	17.95	22.23	
Max	146.62	191.43	
Mean	54.59	69.47	
Std	21.50	37.21	
Mean Dose [Gy]			
Min	32.87	45.76	
Max	80.41	81.36	
Mean	68.17	77.52	
Std	8.40	8.11	
Mean Dose [%]			
Min	101.35	95.42	
Max	104.28	104.31	
Mean	102.46	102.98	
Std	0.64	1.42	
Bladder			
Volumetric			
Total min [cm^3]	68.71	42.24	76.72
In-field min [cm^3]	30.11	17.49	55.26
In-field min [%]	19.57	33.72	16.43
Out-of-field min [cm^3]	0	0	0
Out-of-field min [%]	0	0	0
Overlap with target min [cm^3]	1.84	2.61	2.9
Overlap with target min [%]	1.04	2.88	1.16
Total max [cm^3]	632.26	546.2	685.52
In-field max [cm^3]	261.84	358.76	555.6
In-field max [%]	87.25	94.93	94.15
Out-of-field max [cm^3]	249.11	162.08	437.94
Out-of-field max [%]	52.2	45.37	66.49
Overlap with target max [cm^3]	137.44	65.46	42.64
Overlap with target max [%]	60.63	66.28	22.7
Total mean [cm^3]	236.83	192.06	265.39
In-field mean [cm^3]	112.08	133.92	145.72
In-field mean [%]	53.23	71.2	60.75

Table 4 (continued)

	Model A	Model B	UCSD
Out-of-field mean [cm^3]	41.2	26.95	50.41
Out-of-field mean [%]	11.77	10.5	13.25
Overlap with target mean [cm^3]	24.4	20.56	13.04
Overlap with target mean [%]	12.04	13.8	5.67
Total std [cm^3]	125.16	105.86	142.72
In-field std [cm^3]	43.56	69.86	71.01
In-field std [%]	18.12	13.92	19.45
Out-of-field std [cm^3]	64.59	40.20	88.80
Out-of-field std [%]	15.52	12.94	17.53
Overlap std [cm^3]	22.47	12.17	8.95
Overlap std [%]	10.51	11.93	3.99
Mean Dose [Gy]			
Min	7.12	16.25	1.59
Max	58.99	60.66	40.51
Mean	26.10	38.23	16.93
Std	13.05	11.58	10.85
Mean Dose [%]			
Min	11.89	20.84	7.39
Max	89.38	81.97	55.77
Mean	38.92	50.99	29.83
Std	18.26	14.78	11.25
Rectum			
Volumetric			
Total min [cm^3]	27.65	34.36	34.27
In-field min [cm^3]	21.76	28.31	19.47
In-field min [%]	61.59	63.95	37.76
Out-of-field min [cm^3]	0	0	0
Out-of-field min [%]	0	0	0
Overlap with target min [cm^3]	0	0.22	0
Overlap with target min [%]	0	0.44	0
Total max [cm^3]	111.58	145.84	226.16
In-field max [cm^3]	101.4	108.79	134.92
In-field max [%]	97.79	94.83	98.35
Out-of-field max [cm^3]	8.51	38.55	81.98
Out-of-field max [%]	18.67	26.44	46.33
Overlap with target max [cm^3]	13.87	23.86	8.99
Overlap with target max [%]	22.25	29.98	12.61
Total mean [cm^3]	56.19	69.68	74
In-field mean [cm^3]	47.53	57.07	55.92
In-field mean [%]	84.82	83.41	78.22
Out-of-field mean [cm^3]	0.36	4.24	6.28
Out-of-field mean [%]	0.57	4.73	6.47
Overlap with target mean [cm^3]	4.85	6.5	2.76
Overlap with target mean [%]	8.6	9.46	3.97
Total std [cm^3]	18.3	27.57	31.6
In-field std [cm^3]	15.92	20.26	20.44
In-field std [%]	6.89	8.94	13.93
Out-of-field std [cm^3]	1.39	8.37	13.58
Out-of-field std [%]	2.35	6.82	9.65
Overlap std [cm^3]	3.24	4.3	1.75
Overlap std [%]	5.25	5.63	2.49

Table 4 (continued)

	Model A	Model B	UCSD
Mean Dose [Gy]			
Min	18.59	18.75	3.7
Max	44	48.63	36.24
Mean	32.43	42.44	19.02
Std	6.73	5.58	10.06
Mean Dose [%]			
Min	30.99	42.62	16.83
Max	66.01	70.2	48.58
Mean	48.64	56.2	34.27
Std	8.3	5.75	6.84
Femoral Heads/Femur			Left, Right
Volumetric			
Total min [cm^3]	50.41	113.12	46.38, 46.26
In-field min [cm^3]	41.42	102.78	32.17, 31.71
In-field min [%]	57.38	59.55	48.84, 49.37
Out-of-field min [cm^3]	0	0	0, 0
Out-of-field min [%]	0	0	0, 0
Overlap with target min [cm^3]	0	0	0, 0
Overlap with target min [%]	0	0	0, 0
Total max [cm^3]	120.6	291.3	269.29, 266.21
In-field max [cm^3]	120.52	271.62	196.92, 211.32
In-field max [%]	100	100	100, 100
Out-of-field max [cm^3]	15.76	47.5	73.47, 75.49
Out-of-field max [%]	16.47	26.21	27.28, 28.36
Overlap with target max [cm^3]	0	0	0, 0
Overlap with target max [%]	0	0	0, 0
Total mean [cm^3]	77.94	177.92	69.02, 69.85
In-field mean [cm^3]	74.63	147.54	63.87, 64.8
In-field mean [%]	95.97	83.39	94.49, 94.63
Out-of-field mean [cm^3]	0.51	8.57	2.29, 2.14
Out-of-field mean [%]	0.58	4.53	1.54, 1.41
Overlap with target mean [cm^3]	0	0	0, 0
Overlap with target mean [%]	0	0	0, 0
Total std [cm^3]	14.88	27.4	35.91, 35.1
In-field std [cm^3]	15.05	23.08	26.65, 26.06
In-field std [%]	8.56	8.47	10.53, 10.54
Out-of-field std [cm^3]	1.95	10.69	10.79, 10.74
Out-of-field std [%]	2.25	5.37	5.29, 5.05
Overlap std [cm^3]	0	0	0, 0
Overlap std [%]	0	0	0, 0
Mean Dose [Gy]			
Min	4.85	5.18	1.32, 1.17
Max	32.57	29.25	27.99, 24.05
Mean	17.58	17.17	12.03, 11.95
Std	6.17	4.61	7.36, 7.27
Mean Dose [%]			
Min	7.39	6.64	5.21, 3.28
Max	49.34	38.53	35.74, 32.85
Mean	26.37	23.19	21.88, 21.75
Std	8.54	6.52	6.99, 6.94

G generated, *D* dose, *V* volume, *P* priority

[a]Objective affects normal tissue objective

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Declarations

Conflict of interest No potential conflicts of interest exist for any of the authors with respect to this research and manuscript.

Ethical Approval This study has been reviewed and approved by the St Vincent's Hospital human ethics committee (2019/ETH12120) and has therefore been performed in accordance with the ethical standards in accordance with the Declaration of Helsinki.

References

1. Scaggion A, Fusella M, Roggio A, Bacco S, Pivato N, Rossato MA et al (2018) Reducing inter- and intra-planner variability in radiotherapy plan output with a commercial knowledge-based planning solution. Phys Med 53:86–93. https://doi.org/10.1016/j.ejmp.2018.08.016
2. Fogliata A, Reggiori G, Stravato A, Lobefalo F, Franzese C, Franceschini D et al (2017) RapidPlan head and neck model: the objectives and possible clinical benefit. Radiat Oncol 12(1):73. https://doi.org/10.1186/s13014-017-0808-x
3. Hussein M, South CP, Barry MA, Adams EJ, Jordan TJ, Stewart AJ et al (2016) Clinical validation and benchmarking of knowledge-based IMRT and VMAT treatment planning in pelvic anatomy. Radiother Oncol 120(3):473–479. https://doi.org/10.1016/j.radonc.2016.06.022
4. Fogliata A, Belosi F, Clivio A, Navarria P, Nicolini G, Scorsetti M et al (2014) On the pre-clinical validation of a commercial model-based optimisation engine: application to volumetric modulated arc therapy for patients with lung or prostate cancer. Radiother Oncol 113(3):385–391. https://doi.org/10.1016/j.radonc.2014.11.009
5. Chang ATY, Hung AWM, Cheung FWK, Lee MCH, Chan OSH, Philips H et al (2016) Comparison of planning quality and efficiency between conventional and knowledge-based algorithms in nasopharyngeal cancer patients using intensity modulated radiation therapy. Int J Radiat Oncol Biol Phys 95(3):981–990. https://doi.org/10.1016/j.ijrobp.2016.02.017
6. Foy JJ, Marsh R, Ten Haken RK, Younge KC, Schipper M, Sun Y et al (2017) An analysis of knowledge-based planning for stereotactic body radiation therapy of the spine. Pract Radiat Oncol 7(5):e355–e360. https://doi.org/10.1016/j.prro.2017.02.007
7. Kubo K, Monzen H, Ishii K, Tamura M, Kawamorita R, Sumida I et al (2017) Dosimetric comparison of RapidPlan and manually optimized plans in volumetric modulated arc therapy for prostate cancer. Phys Med 44:199–204. https://doi.org/10.1016/j.ejmp.2017.06.026
8. Schubert C, Waletzko O, Weiss C, Voelzke D, Toperim S, Roeser A et al (2017) Intercenter validation of a knowledge based model for automated planning of volumetric modulated arc therapy for prostate cancer. The experience of the German RapidPlan Consortium. PLoS ONE 12(5):e0178034. https://doi.org/10.1371/journal.pone.0178034
9. Ueda Y, Fukunaga JI, Kamima T, Adachi Y, Nakamatsu K, Monzen H (2018) Evaluation of multiple institutions' models for knowledge-based planning of volumetric modulated arc therapy (VMAT) for prostate cancer. Radiat Oncol 13(1):46. https://doi.org/10.1186/s13014-018-0994-1
10. Panettieri V, Ball D, Chapman A, Cristofaro N, Gawthrop J, Griffin P et al (2019) Development of a multicentre automated model to reduce planning variability in radiotherapy of prostate cancer. Phys Imaging Radiat Oncol 11:34–40. https://doi.org/10.1016/j.phro.2019.07.005
11. Kevin Moore (2016) UCSD RapidPlan Models San Diego, UC San Diego Department of Radiation Medicine and Applied Sciences. http://ucsd.knowledgebasedrt.org/ucsdmodels. Accessed 4 Feb 2019
12. EviQ (2016) Prostate adenocarcinoma definitive EBRT conventional high risk: Cancer Institute NSW. https://www.eviq.org.au/radiation-oncology/urogenital/prostate/235-prostate-adenocarcinoma-definitive-ebrt-conven#organs-at-risk. Accessed 30 Nov 2018
13. ICRP (1991) 1990 recommendations of the International Commission on Radiological Protection. Ann ICRP 21(1–3):1–201

5.3 POSTAMBLE

This chapter aimed to address Research Question 3 by assessing the benefits of sharing knowledge-based planning models between NSW radiation oncology centres.

Research Question 3: Can knowledge-based planning models, created using the Varian RapidPlan software, be successfully shared between centres?
Key Findings from this Chapter: - While centre-specific 'in-house' models were more likely to produce clinically acceptable plans, there was potential to use shared models where in-house models cannot be created. - The process of sharing allowed for internal benchmarking and identified potential areas for improvement. - The creation of multi-centre consensus models would require collaborative replanning. Such models could be used for benchmarking plan quality
Summary: Sharing the implementation of technology has the potential to increase uptake and use but limitations may exist.

This work established both barriers to successful collaboration but also identified areas where collaboration would be most beneficial to enhance the speed of the implementation of this new technology and, potentially, the quality of radiation therapy plans produced. Based on the findings of this chapter, the consortium focused its efforts on creating shared models for less common treatment sites, for which many centres would not be able to create their own models. COVID-19, a lack of empowerment amongst NSW radiation oncology staff and the responsibilities and obligations associated with sharing have meant that no models have yet been shared through the NSW RapidPlan Consortium.

While the majority of the work in this chapter was not affected by the COVID-19 pandemic, continued work with the NSW RapidPlan Consortium was not possible as in-person meetings could not occur, not yet been replaced by online meetings, and the priorities and workload of hospital employees changed, allowing less time for quality improvement projects.

Following this work, Chapters 6 and 8 consider alternative approaches to collaboration and sharing. Chapter 8 specifically addresses the issues of responsibility as a barrier to sharing. This project allows for a much broader range of shared resources and assesses the utilisation of these shared resources.

CHAPTER 6

A Knowledge-Sharing Workshop on Motion Management

6.1 PREAMBLE

Chapter 3 demonstrated that the rate at which SABR was implemented across NSW centres varied, with regional centres more likely to delay clinical roll-out. That work highlighted the need for improved knowledge transfer and inter-centre support, and the desire to improve motion management for SABR treatments amongst survey participants.

One potential way to address these and similar issues is through online workshops focused on new technology or techniques, as the need arises. This chapter describes the outcomes from a workshop that was designed to share knowledge about motion management in the treatment of moving targets. The online workshop was run in 2022 as a collaboration between the ACPSEM and the University of Sydney. It was multi-disciplinary and focused on motion management in radiation oncology. The outcomes of this study were informed by the workshop activities and the accompanying questionnaires, which examined current motion management practice in Australia and New Zealand and the impact of the workshop.

This chapter addresses research question:

- What is the current usage of radiation therapy motion management in Australia and New Zealand and what benefits can be gained by running a workshop focused on motion management techniques?

Chapter 6 of this thesis is published as 'Improving motion management in radiation therapy: findings from a workshop and survey in Australia and New Zealand' in Physics and Engineering Sciences in Medicine in 2024 (165).

6.2 PUBLICATION 4

Improving motion management in radiation therapy: findings from a workshop and survey in Australia and New Zealand

Physical and Engineering Sciences in Medicine
https://doi.org/10.1007/s13246-024-01405-0

SCIENTIFIC PAPER

Improving motion management in radiation therapy: findings from a workshop and survey in Australia and New Zealand

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Abstract
Motion management has become an integral part of radiation therapy. Multiple approaches to motion management have been reported in the literature. To allow the sharing of experiences on current practice and emerging technology, the University of Sydney and the New South Wales/Australian Capital Territory branch of the Australasian College of Physical Scientists and Engineers in Medicine (ACPSEM) held a two-day motion management workshop. To inform the workshop program, participants were invited to complete a survey prior to the workshop on current use of motion management techniques and their opinion on the effectiveness of each approach. A post-workshop survey was also conducted, designed to capture changes in opinion as a result of workshop participation. The online workshop was the most well attended ever hosted by the ACPSEM, with over 300 participants and a response to the pre-workshop survey was received from at least 60% of the radiation therapy centres in Australia and New Zealand. Motion management is extensively used in the region with use of deep inspiration breath-hold (DIBH) reported by 98% of centres for left-sided breast treatments and 91% for at least some right-sided breast treatments. Surface guided radiation therapy (SGRT) was the most popular session at the workshop and survey results showed that the use of SGRT is likely to increase. The workshop provided an excellent opportunity for the exchange of knowledge and experience, with most survey respondents indicating that their participation would lead to improvements in the quality of delivery of treatments at their centres.

Keywords Motion management · Australia · New Zealand · Australasia · Workshop · Survey

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Introduction

Strategies to control, limit or correct for the motion of targets and organs-at-risk (OAR) during radiation therapy can be broadly considered as motion management. While motion management is often focused on respiratory motion, it may also be applied to digestive, cardiac and other physiological motion [1].

Motion management in the form of deep inspiration breath-hold (DIBH) has been shown to reduce cardiac toxicity for breast radiation therapy patients [2]. As a result, this technique is recommended for left-sided breast radiation therapy patients and is widely utilised [3, 4].

Motion management using techniques such as gating and breath-hold is used in other thoracic and upper abdominal treatments to minimise tumour motion and associated target margins, to spare adjacent OARs. This is particularly pertinent in stereotactic ablative body radiotherapy (SBRT), where escalated target doses are used. The use of SBRT is

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increasing in Australia [5] and it is recognized as an emerging standard of care for a range of early stage or metastatic cancers in the thorax and upper abdomen [6–8]. Management of respiratory motion has come to be recognized as a key requirement for these treatments [9, 10].

With the uptake of various methods of motion management increasing, the NSW/ACT branch of the ACPSEM collaborated with the University of Sydney to host a two-day workshop on motion management. The workshop was designed to identify and communicate emerging trends, and to facilitate the sharing of practical experience. To address these aims, the workshop invited speakers to present an overview of their experience in using a range of motion management equipment and techniques, including the advantages and disadvantages. In addition, radiation therapy centres were surveyed to identify equipment and methods currently in use and opinions on their effectiveness. Following the workshop, participants were again surveyed to identify any changes in opinion resulting from the information and panel discussions presented.

Here we present an executive summary of the motion management techniques that were in common use at the time of the workshop and the opinions of the participants regarding the practical advantages and limitations of each. This summary is intended to promote further discussion across the community.

Method

The workshop was hosted virtually on the 27th and 28th of July 2022, in two 5 h sessions. This format was chosen to facilitate participation from the ACPSEM membership around clinical duties, and mitigate difficulties associated with travel required for in-person meetings. Invitations to the workshop were sent via the ACPSEM email list, the Australian Society of Medical Imaging and Radiation Therapy (ASMIRT) NSW/ACT email list and the University of Sydney, Institute of Medical Physics email list, and the event was advertised on the ACPSEM website, on the Better Healthcare Technology Foundation website, on social media and in the ACPSEM newsletter.

The program was devised by an organizing committee of experienced radiation oncology medical physicists with topics covered in Table 1. To ensure broad applicability, invited speakers with experience using a diverse range of motion management equipment and techniques were selected from radiation therapy centres around Australia. They were encouraged to focus on the practicalities and limitations of specific motion management techniques, as well as the underlying principles. The program included dedicated time for discussion and facilitated questions using the online chat.

Table 1 Summary of the topics covered in the workshop

The current use of motion management
Motion management aspects of simulation and planning
Surface guided monitoring
Imaging and monitoring on treatment
Practical experience of radiation oncology centres in NSW/ACT
Motion management for clinical trial
Motion management into the future

Three online surveys were developed using Survey Monkey (www.surveymonkey.com) to accompany the workshop: a current practice survey (Survey A), an initial opinions survey (Survey B), and a post-workshop opinions survey (Survey C). Survey A was targeted at clinical departments at an organizational level, focused on the utilisation of motion management and availability of equipment for motion management. In contrast, Surveys B and C were aimed at gaining the opinions of individuals prior to and following the workshop to look at differences and determine if the workshop changed individual's opinions on different topics. The survey questions were developed collaboratively by the organizing committee and are shown in Appendix 1. Surveys A and B were sent with the invitation to register for the workshop and Survey C was sent to all registered participants following the workshop.

All survey responses were collected anonymously. Respondents were asked to nominate a single representative from their centre to complete Survey A, and to indicate the name of their centre, to avoid duplication of data. This information was not used in the analysis. The surveys utilised logic to remove or skip irrelevant questions based on previous responses, thereby minimizing the time for respondents, and preventing the collection of unneeded data. Due to this logic filtering, some questions only received a small number of responses. To ensure anonymity, only questions with 5 or greater responses are reported. Analysis was performed using Microsoft Excel (Microsoft Corporation. (2018) Version 2301).

Results

The online workshop attracted over 300 participants (the most well attended workshop ever hosted by the ACPSEM at the time), demonstrating a high level of interest in motion management. While time was allocated for discussion and questions, it was often insufficient to answer all the questions from attendees.

The results from Survey C indicated 54% of survey respondents felt that the workshop did change their opinions about motion management and 83% felt that, as a result of attending the workshop, changes could be made at their centre to improve treatment quality (Survey C, 24 responses).

At the workshop conclusion, the session on surface guided radiation therapy (SGRT) was rated the most valuable (Survey C, 24 responses).

Several questions were repeated in both Survey B and Survey C in order to measure the effect of the workshop on opinions. Only small differences were seen in the responses to these questions, so they did not provide quantitative evidence that the workshop had an impact on participants' opinions.

High response rates were received to both Survey A and B. Survey A received 66 responses, each representing a separate radiation therapy centre. Of these, 3 respondents indicated that they do not currently work in a radiation therapy centre and 4 people choose not to list their workplace. All workplaces were unique locations and from Australia or New Zealand. This represents a response rate of at least 60% of the 99 radiation therapy centres in Australia and New Zealand [11, 12]. For Survey B, 97 responses were received with the largest number of responses from radiation oncology medical physicists (83%) with 14% from radiation therapists and 3% from radiation oncologists. For Survey C, 33 responses were received, all from radiation oncology medical physicists.

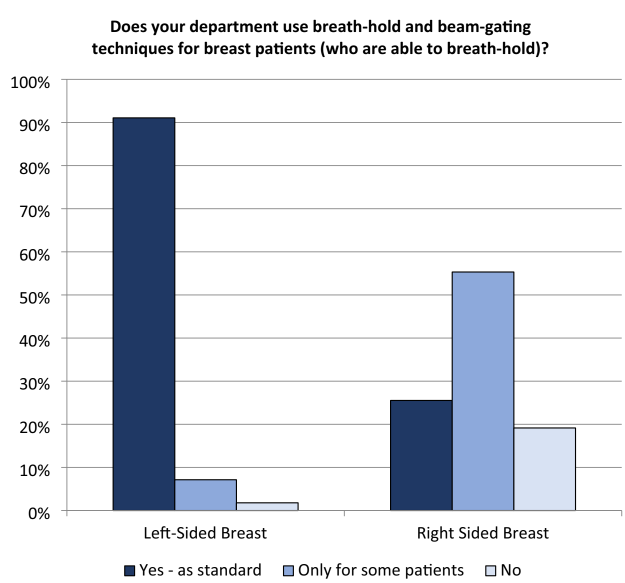
Table 2 Responses to "Does your department use motion management for any of the following sites?" 66 responses recorded

Site	Responses (%)
Breast	94
Lung	91
Liver	56
Prostate	44
Pancreas	33
Kidney	30

Deep inspiration breath-hold and surface guided radiation therapy

Motion management is most commonly used for breast treatments (Table 2, Survey A) with 98% of centres using breath-hold and beam gating treatment delivery for left-sided breast treatments and 91% considering it as standard practice (Fig. 1). This technique is also commonly used for right-sided breast treatments with 91% of centres using this form of motion management for at least some right-sided breast radiation therapy patients. These results are higher than those reported in international studies such at the POP-ART RT survey conducted by ESTRO in 2019 [13] where 63% of respondents indicated that deep inspiration breath-hold (DIBH) was used for breast cancer at their centre, and the AAPM Task Group 324 survey in 2020 [14] where 84% of respondents indicated the use DIBH for left-sided breast radiation therapy.

With the expansion of DIBH, many questions at the workshop were focused on the practicalities of providing this service, such as infection risks and consumable costs for a range of technologies. These concerns have led some centres to move from using semi-invasive active breathing control systems to SGRT systems for breath-hold gating. This shift in practice was also evident in survey A that showed 25% of centres are using SGRT for motion management, with 40% indicating that such an approach was currently being procured, implemented, or was being considered for the future



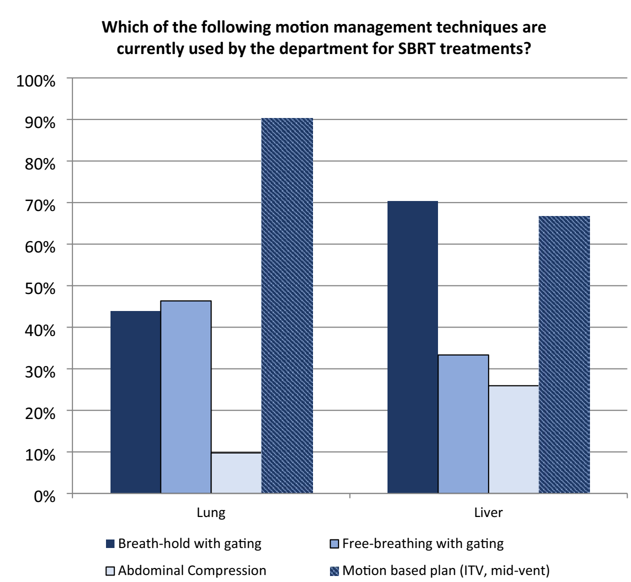


Fig. 1 (Left) Application of breath-hold and beam-gating for breast patients by laterality (Survey A, 56 responses). (Right) Methods of motion management by site for SBRT (Survey A, 42 responses), responses only from centres treating SBRT for these sites

(Survey A, 48 responses). Compared to the recent SGRT survey results from Batista et al. [15], an international survey, where 49% of institutions were using SGRT clinically, the lower usage locally shows the potential for future growth.

The panelists at the SGRT session agreed that surface guidance is unlikely to replace x-ray based positional verification imaging. However, by allowing better initial patient positioning and on-going monitoring, it has the potential to reduce the number of x-ray images taken and to reduce setup times once the staff become familiar with the system. Panelists discussed the steep learning curve and the need to ensure radiation therapist training and credentialing is incorporated into implementation planning to ensure efficient and accurate patient treatment.

Patient focused motion management

Many of the workshop presentations demonstrated the clear benefits of motion management for patients resulting from the reduced dose to OARs, but discussion also indicated that it is important to consider the needs of the individual patient to ensure the motion management approach used is appropriate [16]. For example, some patients feel more comfortable in voluntary breath-hold compared with active breath-hold, but if an SGRT based system is used to monitor the breath-hold, this may lead to different issues, as some patients may not wish to be uncovered for treatment. Another comment regarded the sensitivity around marketing of motion management, since patients may feel disappointed, or concerned about the quality of their treatment if they are assessed to be unsuitable for breath-hold or another motion management technique.

When deciding on a motion management strategy, 87% of centres stated that they perform some form of patient screening to assess suitability. Breathing assessments were performed at simulation at 83% of all centres (Survey A, 46 responses), motion assessments were performed at simulation at 94% of all centres (Survey A, 46 responses) and patient breathing assessments were performed prior to simulation at 42% of all centres (Survey A, 40 responses). Screening of patients was considered to be important or very important by 96% of respondents (Survey B, 57 responses). Breathing assessments are most commonly performed using the Varian RPM (Varian Medical Systems, Palo Alto, CA, USA) system (Survey A, 67% of 43 responses) and target motion assessments are most often based on the treatment planning CT images (Survey A, 83% of 40 responses).

During the workshop, presenters showed tools used for determining the appropriate motion management technique for each patient, similar to the decision tree shown in a recent publication from a large Australian cancer centre [17]. For this institution, abdominal compression is only selected if exhale breath-hold and free-breathing gating are not suitable, and where it reduces liver dome motion. This results in only 20% of patients being treated with abdominal compression. For smaller centres, such a proportion of patients may be too small to justify the continued use of abdominal compression as staff skill and knowledge would be difficult to maintain.

Practicalities

The workshop featured a session on the experiences of radiation oncology centres in NSW/ACT. This provided information on the full range of motion management techniques currently in use as well as the opportunity to discuss practical considerations such as the additional on-going cost or time required for particular motion management techniques, infection control considerations, contingency plans to allow patients to continue treatment in the case of breakdown and the potential burden of additional quality assurance requirements for new motion management equipment.

Survey C asked participants if any motion management techniques had once been used in their department but were now superseded. Abdominal compression, visual feedback and gating were all noted, with abdominal compression the most popular response (55%, 21 responses).

The additional burden of quality assurance should be assessed against the value to the patient, and incorporated into staffing models. An example of this additional quality assurance is end-to-end testing of motion management systems. The majority of those surveyed felt this testing should be performed at commissioning, post-upgrade and annually (Fig. 2, Survey B).

SBRT

With motion management an integral part of SBRT, many of the presentations and much of the discussion at the workshop addressed this treatment technique. Discussion was focused on two main areas, motion management for free-breathing patients and for patients treated in breath-hold with gating. Both techniques are commonly used, with 95% of centres using either a free-breathing gated technique or internal target volume (ITV)-based planning for lung SBRT patients and 70% of centres using a breath-hold technique for liver SBRT patients (Fig. 1, Survey A, as a percentage of centres treating with these techniques).

For both free-breathing and breath-hold treatments, workshop attendees were interested in which images should be used for the dose calculation. The advice from the workshop panelists aligns with previous published work, that small changes in the CT data set due to tumour position make little difference to the plan dosimetrically [18]. However, it is important to consider which image is more appropriate to be matched to the CBCT or 4DCBCT image on treatment.

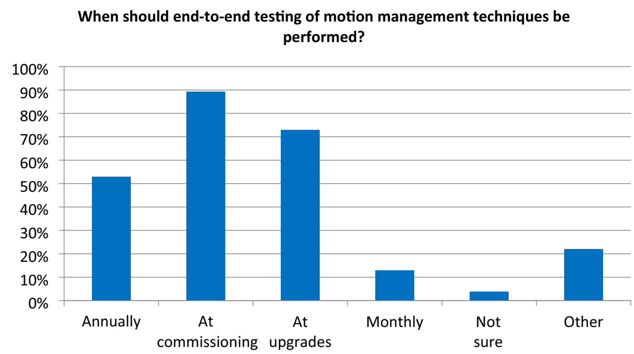


Fig. 2 Opinions on the need for end-to-end testing of motion management techniques (55 responses)

An example was provided for breath-hold treatments, where three or more breath-hold CT data sets may be used to create an ITV, acquired for the purpose of quantitating uncertainty in target position during breath-hold, with the most appropriate image the one showing the median tumour position. Another challenge identified at the workshop is matching of CBCT images to planning images. This can be difficult due to artifacts caused by fiducial markers or clips in the CBCT and differing methods of reconstruction and binning between the planning CT and the CBCT. The relevance of markers distant from the tumour was also questioned given recent publications [19].

Free-breathing motion management

Motion management for free-breathing patients starts at simulation with acquisition of a 4DCT. Workshop participants were interested in the options available if a patient is breathing too slow, too fast or in an irregular way such that the image acquired are unreliable or technically can't be acquired. Several options were discussed including coaching the patient to breath differently at simulation with the potential draw back that the patient's breathing may not be the same at treatment. Monitoring breathing traces and using gating, either with a wide window around the patient's normal breathing amplitude or focused around a part of the breathing cycle, were discussed as options that some centres have found help to ensure the target stays within the targeted region at treatment.

Practical issues associated with free breathing motion management were highlighted during the workshop. For example, that the tumour may not be completely visible on all phases of the 4DCT and that a review of the images is required to ensure the ITV is not compromised. This was also seen in Survey A where 98% of respondents agreed that 4DCT images require review due to the potential for compromised 4DCT imaging data (55 responses). A summary of approaches to manage artifacts in 4DCT images is presented in Fig. 3.

From Survey A, 93% of centres use 4DCT and 97% use ITV-based planning. Figure 3 shows the methods used to create an ITV, with most people using all individual image phases. The use of maximum intensity projection (MIP) CT to create an ITV was more popular in the AAPM survey [14], (73% AAPM and 51% this work). The delineation of targets using a MIP dataset has been shown to be faster [20] and result in a smaller target volume compared with contouring the tumour on all individual phases but it can also result in inadequately target coverage [20–25]. In addition to the planning images, workshop discussions indicated that, in addition to the simulation CT, diagnostic imaging may also be used as a source of information about tumour movement at a different time point.

Emerging trends

The potential to reduce the irradiated normal tissue by using mid-ventilation based targets [26, 27] was presented at the workshop including practical steps towards implementation.

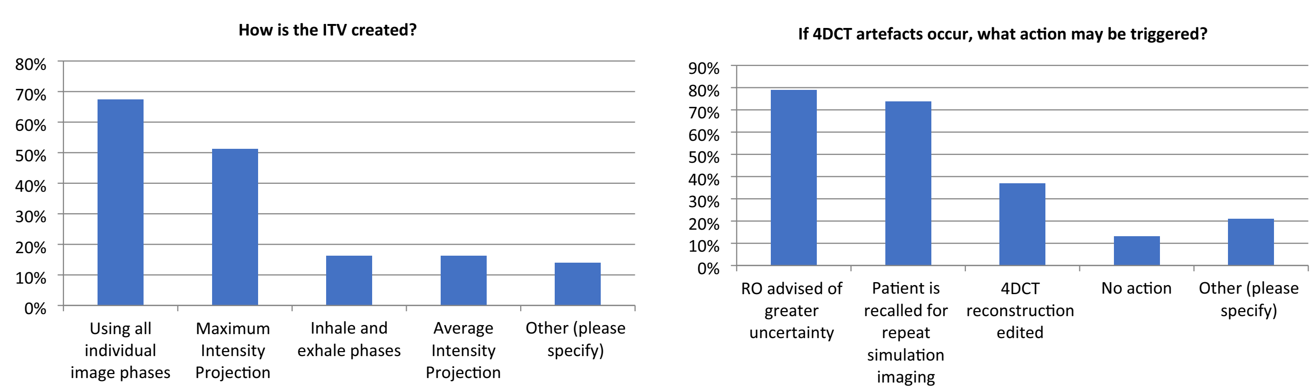


Fig. 3 Survey A results showing how the ITV is created (left, 43 responses) and actions which may be triggered when an artifact occurs in a 4DCT image (right, 38 responses). Multiple responses were allowed for these questions

Based on Survey A, this is yet to be implemented clinically in Australia and New Zealand.

New developments in motion management were discussed, including the potential for tumour tracking and dose-guided motion management to replace external surrogates and improve dosimetric accuracy. When asked about external surrogates, only 11% of survey respondents felt that these were sufficient for SBRT liver treatments compared to 78% for breast treatments, where the target is usually more superficial (Survey B, 55 responses).

Discussion

The high attendance rate and range of presentations at the motion management workshop provided an opportunity for professionals to share practical experience and engage in collaborative learning without leaving their clinics. The high uptake of motion management, particularly for breast radiation therapy, and increasing interest in SGRT mean that additional sharing and learning opportunities may be required in the future. Organisers of future workshops should consider additional options to ensure all audience questions are addressed. These could include allocation of more time for questions, distribution of written responses after the workshop or facilitating private discussion between the attendees and presenters. Workshops could be viewed as a starting point for future work and discussion rather than a conclusion [28, 29].

One of the challenges identified by clinical physicists during the final session of the workshop was finding people with experience and knowledge. This workshop, and particularly the practical experience session, was designed to assist with and to facilitate knowledge-sharing. A physicist from a regional centre commented that 'The forum has been a really good way to share and learn from other people's experiences.' A common theme was the need to adapt motion management approaches to the needs of individual patients. This may require new motion management options to become available. Increasing the range of techniques available to patients may present additional challenges in terms of training and resourcing.

Looking to the future, a minority of respondents felt that external surrogates were sufficient for SBRT liver (11%) with the remainder unsure or indicating that external surrogates were an inadequate surrogate for estimating internal motion. This may lead to the introduction or expansion of tumour and fiducial marker tracking more broadly.

Based on the workshop discussion and survey results, a move away from technologies that require expensive, non-environmentally friendly disposable items and particularly equipment that poses an infection risk [30] was identified. SGRT and x-ray based tumour tracking may have a role to play.

Despite the progress made in motion management, technological challenges remain: the quality of CBCT images for soft tissue structures was identified, as was the difficulty in acquiring adequate quality 4DCT images for some patients. Additionally, the fast pace of improvements in motion management also lead to training challenges and the risk that centres may not have the resources to implement and maintain a wide range of newly available technologies and techniques, particularly if patient numbers are small. Collaborative methods of working and learning may need to be explored to address these needs, with events such as this workshop to provide opportunities for sharing of knowledge, experience and ideas.

Limitations of this work

A limitation of this work as a means to determine the current state-of-play in motion-management in Australasia is the reliance on workshop presentations, discussions, and surveys. These sources may introduce bias, as individuals with a particular interest in and knowledge of motion management are more inclined to participate in workshops and respond to surveys on this topic. While the survey response rate was high, obtaining current practice data through established reporting channels could enhance future research by mitigating response bias. For future work aiming to compare pre- and post-workshop opinions, the methodology could be improved by linking the two opinion surveys based on the respondent, focusing the survey questions, and encouraging the completion of the post-workshop opinions survey.

While this study presents the opinion of the participants, these opinions may not be linked to clinical outcomes data as such data may not exist. Linking technology to clinical outcomes is challenging due to the number of incremental changes that can occur over a protracted period. However, we suggest that the value of the workshop is in providing an opportunity to reflect on current practices, receive external peer review and develop a collaborative network to provide on-going peer review and support for the efficient and safe introduction of new technologies.

Conclusion

Motion management is now seen as integral to the radiation therapy of many patients. The workshop presentations and the survey results show that motion management techniques for breast and lung radiation therapy are routinely incorporated as part of the standard of care in Australasia. However, further work is required to address the barriers to implementation and training which were highlighted during the workshop. Future trends in motion management may include an increase in the use of SGRT and the use of X-ray based monitoring and tracking where external surrogates are not sufficient to account for tumour motion. Additional training and collaboration opportunities may be required to address the needs of the radiation therapy community.

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Declarations

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Keall PJ, Mageras GS, Balter JM, Emery RS, Forster KM, Jiang SB et al (2006) The management of respiratory motion in radiation oncology report of AAPM task group. Med Phys 33(10):3874–3900. https://doi.org/10.1118/1.2349696
2. Korreman SS, Pedersen AN, Aarup LR, Nottrup TJ, Specht L, Nystrom H (2006) Reduction of cardiac and pulmonary complication probabilities after breathing adapted radiotherapy for breast cancer. Int J Radiat Oncol Biol Phys ;65(5):1375–1380
3. Desai N, Currey A, Kelly T, Bergom C (2019) Nationwide trends in heart-sparing techniques utilized in radiation therapy for breast cancer. Adv Radiat Oncol 4(2):246–252. https://doi.org/10.1016/j.adro.2019.01.001
4. Smith BD, Bellon JD, Blitzblau R, Freedman G, Haffty B, Hahn C et al (2018) Radiation therapy for the whole breast: executive summary of an american society for radiation oncology (ASTRO) evidence-based guideline. Pract Radiat Oncol 8(3):145–152. https://doi.org/10.1016/j.prro.2018.01.012
5. Claridge Mackonis ER, Hardcastle N, Haworth A (2020) Stereotactic ablative body radiation therapy (SABR) in NSW. Phys Eng Sci Med 43(2):641–650. https://doi.org/10.1007/s13246-020-00866-3
6. Harrow S, Palma DA, Olson R, Gaede S, Louie AV, Haasbeek C et al (2022) Stereotactic radiation for the comprehensive treatment of oligometastases (SABR-COMET): extended long-term outcomes. Int J Radiat Oncol Biol Phys 14(4):611–616. https://doi.org/10.1016/j.ijrobp.2022.05.004
7. Siva S, Sakyanun P, Mai T, Wong W, Lim A, Ludbrook J et al (2023) Long-term outcomes of TROG 13.01 SAFRON II randomized trial of single-versus multifraction stereotactic ablative body radiotherapy for pulmonary oligometastases. J Clin Oncol 41(19):3493–3498. https://doi.org/10.1200/JCO.23.00150
8. Gomez DR, Tang C, Zhang J, Blumenschein GR, Hernandez M, Lee JJ et al (2018) Local Consolidative Therapy (LCT) Improves Overall Survival (OS) Compared to Maintenance Therapy/Observation in Oligometastatic Non-Small Cell Lung Cancer (NSCLC): Final Results of a Multicenter, Randomized, Controlled Phase 2 Trial. ASTRO Annual Meeting; Presented October 21, 2018
9. Guckenberger M, Andratschke N, Dieckmann K, Hoogeman MS, Hoyer M, Hurkmans C et al (2017) ESTRO ACROP consensus guideline on implementation and practice of stereotactic body radiotherapy for peripherally located early stage non-small cell lung cancer. Radiother Oncol 124(1):11–17. https://doi.org/10.1016/j.radonc.2017.05.012
10. Foote M, Bailey M, Smith L, Siva S, Hegi-Johnson F, Seeley A et al (2015) Guidelines for safe practice of stereotactic body (ablative) radiation therapy. J Med Imaging Radiat Oncol 59(5):646–653. https://doi.org/10.1111/1754-9485.12336
11. Australian Institute of Health and Welfare. Radiotherapy in Australia (2018–2019) Canberra: AIHW (2020) Available from: https://www.aihw.gov.au/reports/radiotherapy/radiotherapy-in-australia-2018-19
12. The Royal Australian and New Zealand College of Radiologists. Radiation Oncology Accredited Training Site Listing Sydney: RANZCR (2023) ; [updated 6/2/2023. Available from: https://www.ranzcr.com/college/document-library/radiation-oncology-accredited-training-site-listing
13. Anastasi G, Bertholet J, Poulsen P, Roggen T, Garibaldi C, Tilly N et al (2020) Patterns of practice for adaptive and real-time radiation therapy (POP-ART RT) part I: intra-fraction breathing motion management. Radiother Oncol 153:79–87. https://doi.org/10.1016/j.radonc.2020.06.018
14. Ball HJ, Santanam L, Senan S, Tanyi JA, van Herk M, Keall PJ (2022) Results from the AAPM Task Group 324 respiratory motion management in radiation oncology survey. J Appl Clin Med Phys 23(11):e13810. https://doi.org/10.1002/acm2.13810
15. Batista V, Gober G, Moura M, Webster A, Oellers M, Ramtohul M et al (2022) Surface guided radiation therapy: an international survey on current clinical practice. Tech Innov Patient Support Radiat Oncol. https://doi.org/10.1016/j.tipsro.2022.03.003
16. Lievens Y, Ricardi U, Poortmans P, Verellen D, Gasparotto C, Verfaillie C et al (2019) Radiation oncology. optimal health for all, together. ESTRO vision, 2030. Radiother Oncol 136:86–97. https://doi.org/10.1016/j.radonc.2019.03.031
17. Hardcastle N, Gaudreault M, Yeo AU, Ungureanu E, Markham C, Barnes R et al (2023) Selection of motion management in liver stereotactic body radiotherapy and its impact on treatment time. Phys Imaging Radiat Oncol 25:100407. https://doi.org/10.1016/j.phro.2022.12.004

18. Zvolanek K, Ma R, Zhou C, Liang X, Wang S, Verma V et al (2017) Still equivalent for dose calculation in the Monte Carlo era? A comparison of free breathing and average intensity projection CT datasets for lung SBRT using three generations of dose calculation algorithms. Med Phys 44(5):1939–1947. https://doi.org/10.1002/mp.12193
19. Seppenwoolde Y, Wunderink W, Wunderink-van Veen SR, Storchi P, Mendez Romero A, Heijmen BJ (2011) Treatment precision of image-guided liver SBRT using implanted fiducial markers depends on marker-tumour distance. Phys Med Biol 56(17):5445–5468. https://doi.org/10.1088/0031-9155/56/17/001
20. Tibdewal A, Bushra S, Mummudi N, Kinhikar R, Ghadi Y, Agrawal JP (2021) Maximum intensity projection an optimal approach for internal target volume delineation in lung cancer? J Med Phys 46(2):59–65
21. Park K, Huang L, Gagne H, Papiez L (2009) Do maximum intensity projection images truly capture tumor motion? Int J Radiat Oncol Biol Phys 73(2):618–625. https://doi.org/10.1016/j.ijrobp.2008.10.008
22. Muirhead R, McNee SG, Featherstone C, Moore K, Muscat S (2008) Use of maximum intensity projections (MIPs) for target outlining in 4DCT radiotherapy planning. J Thorac Oncol 3(12):1433–1438. https://doi.org/10.1097/JTO.0b013e31818e5db7
23. Wang G, Zhu X, Zhang F, Liu J, Yue L, Deng L et al (2020) Applied research of a four-dimensional CT localization technique in radiotherapy and treatment planning for early lung cancer. Transl Cancer Res 9(11):7227–7235. https://doi.org/10.21037/tcr-20-2800
24. Borm KJ, Oechsner M, Wiegandt M, Hofmeister A, Combs SE, Duma MN (2018) Moving targets in 4D-CTs versus MIP and AIP: comparison of patients data to phantom data. BMC Cancer 18(1):760. https://doi.org/10.1186/s12885-018-4647-4
25. Underberg RW, Lagerwaard FJ, Slotman BJ, Cuijpers JP, Senan S (2005) Use of maximum intensity projections (MIP) for target volume generation in 4DCT scans for lung cancer. Int J Radiat Oncol Biol Phys 63(1):253–260. https://doi.org/10.1016/j.ijrobp.2005.05.045
26. Wolthaus JW, Schneider C, Sonke JJ, van Herk M, Belderbos JS, Rossi MM et al (2006) Mid-ventilation CT scan construction from four-dimensional respiration-correlated CT scans for radiotherapy planning of lung cancer patients. Int J Radiat Oncol Biol Phys 65(5):1560–1571. https://doi.org/10.1016/j.ijrobp.2006.04.031
27. Peulen H, Belderbos J, Rossi M, Sonke JJ (2014) Mid-ventilation based PTV margins in stereotactic body radiotherapy (SBRT): a clinical evaluation. Radiother Oncol 110(3):511–516. https://doi.org/10.1016/j.radonc.2014.01.010
28. Physics Workshop (2023) Science in development ESTRO avenue marnix 17, 1000 brussels: the european society for radiotherapy and oncology. Available from: https://www.estro.org/Workshops/2023-Physics-Workshop-Science-in-Development
29. Vandewinckele L, Claessens M, Dinkla A, Brouwer C, Crijns W, Verellen D et al (2020) Overview of artificial intelligence-based applications in radiotherapy: recommendations for implementation and quality assurance. Radiother Oncol 153:55–66. https://doi.org/10.1016/j.radonc.2020.09.008
30. Song AJ, Manukian G, Taylor AK, Anne PR, Simone NL (2020) Concerns for active breathing control (ABC) with breast cancer in the era of COVID-19: maximizing infection control while minimizing heart dose. Adv Radiat Oncol 5(4):573–574. https://doi.org/10.1016/j.adro.2020.03.009

6.3 POSTAMBLE

This chapter aimed to address Research Question 4.

Research Question 4: What is the current usage of radiation therapy motion management in Australia and New Zealand and what benefits can be gained by running a workshop focused on motion management techniques?
Key Findings from this Chapter: - Motion management was found to be used extensively in Australia and New Zealand, particularly breath-hold techniques for left sided breast irradiation. - The workshop was found to be an excellent opportunity for the exchange of knowledge and experience - Participants felt the workshop would improve the quality of treatment delivery - The online format allowed for sharing of practical experience without travel and allowing for COVID restrictions. However, the workshop attracted the largest number of participants of any other ACPSEM workshop demonstrating this method of knowledge sharing is feasible and well supported.
Summary: Focused online workshops facilitate knowledge sharing, without disadvantaging regional centres, and may improve the quality of radiation therapy treatments.

At the time this workshop was run, motion management was of interest to many professionals working in radiation oncology. This meant that radiation oncology professionals were motivated to both organize and attend the workshop and ultimately lead to the success of the workshop. However, this method of knowledge sharing may not be suitable where interest in the topic is staggered or the content not suited to a workshop. Online workshops should therefore be viewed as one aspect of a multi-pronged approach to knowledge sharing.

Other approaches which facilitate knowledge sharing are considered in Chapter 7 and 8. In Chapter 8, an online platform is used, providing a longer-term solution for the sharing of resources. In Chapter 7, a shorter, more informal and interactive approach is used to facilitate the sharing of knowledge and skills where previous efforts had not been effective.

However, to ensure the provision of quality healthcare, knowledge-sharing must be complimented by other activities. The comparison of current practices to quality standards described in Chapter 4 is one such example. This work, like the workshop described in this chapter, required significant organisation and time commitment from individuals, and may not present a sustainable model. Instead, it may be better to provide tools and baselines against which centres can compare their performance. Examples of this are presented in Chapter 9.

CHAPTER 7

Increasing Prospective Risk Assessments through a Novel Training Program

7.1 PREAMBLE

Safety is a part of quality within health care and can be defined as freedom from accidental injury (166). In radiation oncology, additionally this can be interpreted as avoiding unintended radiation exposure to patients and staff (167).

A number of reports have been published containing recommendations for safety in radiation oncology. Two of these publications categorize the recommendations into 12 areas (168, 169) with the common categories of training, staffing/human resources, documentation, incident learning, safety culture, communication, check lists, quality control of equipment, accreditation/audits, minimizing interruptions and prospective risk assessment.

As mentioned in Chapter 2, formal audits covering safety may not always be available or practical, particularly when a new technique or technology is being introduced. Performing a prospective risk assessment may provide an alternative safety framework. Prospective risk assessment is a process whereby potential risks are identified and categorizes proactively (170). This involves a systematic review of the proposed processes and an assessment of each risk. Risks can then be prioritized, weighed against benefits and minimized. This type of risk assessment is important to ensure the safe implementation of new techniques, technologies and processes (171, 172), where retrospective incident data may not be relevant and accidents are more likely (12).

Chapter 4 of this thesis showed that, although prospective risk assessments were recommended prior to the implementation of SABR, most centres were not performing them. The work presented in Chapter 7 was designed to address this problem. A training program was developed based around a simple prospective risk assessment and project management tool. This training was then offered to radiation therapy centres across NSW. A series of surveys were designed to assess the effectiveness of the training program. Information about the training program and the survey results are included in this chapter.

This chapter addresses research question:

- Can focused risk assessment training increase the use of prospective risk assessment for new technologies and techniques in NSW radiation oncology centres?

Chapter 7 of this thesis is published as 'Increasing the use of prospective risk assessment through training' in Physica Medica in 2025 (173).

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Original paper

Increasing the use of prospective risk assessment through training

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ABSTRACT

Purpose: Whilst a formal prospective risk assessment is an important part of risk management in the implementation of new techniques and technologies, a lack of time and practical knowledge can prevent its use. Here we present an innovative training program aiming to increase the knowledge and practical skills of radiation oncology professionals in using prospective risk assessment.
Methods: The training program explained the need for prospective risk assessment and provided practical experience in the use of an easy-to-use prospective risk assessment and project management tool. Participants were surveyed before the training and 12-months post-training to determine current risk assessment processes and whether the training affected participants views and behaviours in this area.
Results: A time-efficient training program in prospective risk assessment was created and successful delivered to multi-disciplinary groups from 12 radiation therapy providers. In the 12-months post-training, the number of centres completing prospective risk assessments increased from 8% to 30%. The training removed many of the perceived barriers, with insufficient time remaining the largest barrier.
Conclusions: The training was found to be useful and applicable by all respondents. Future work needs to focus on how to expand the reach of the training program while maintaining its success, and how to ensure prospective risk assessments are seen as an essential part of implementation of new techniques and technologies in radiation therapy centres.

1. Introduction

Prospective risk assessment (PRA) forms an important part of safety in modern radiation therapy [1–3] and should be part of the education and training of all professions involved [4]. It is recommended by the International Atomic Energy Agency in its safety standards SSG-46 [5], which is consider best practise by the Australian Radiation Protection and Nuclear Safety Agency [6], and is required when commissioning new equipment by the Radiation Oncology Practice Standards [7]. PRA is particularly important, and has been argued should be mandatory, when implementing changes in practise, equipment or procedures [4,8]. For this reason, it is recommended that PRAs be performed prior to the implementation of new stereotactic ablative body radiotherapy (SABR) techniques [9–10], however, a recent study showed that less than 25 % of radiation therapy centres in Australian centres in New South Wales (NSW) performed a PRA as part of implementing SABR [11].

Potential barriers to the utilisation of PRA are staff time and knowledge [12–13], with some published risk assessments noting many hours of work [14] and/or the services of people with specific risk management training [15–18]. In this work, we aimed to address these potential barriers, by providing training for 12 multi-disciplinary radiation therapy teams using a time-efficient PRA method.

The training incorporated PRA through the use of the Risk and Benefit Balance Impact Template (RABBIT). The RABBIT is a document designed to guide multi-disciplinary teams through radiation oncology implementation projects and includes PRA. This tool was selected because it is user-friendly and has been successfully implemented in one New South Wales (NSW) hospital [12–13,19] for regular clinical use.

This work presents an new program designed to educate radiation therapy professionals in prospective risk assessment and the practical application of the RABBIT for a clinical implementation project. By running small multi-disciplinary training sessions focused on real-world examples, this work aimed to increase the use of PRA as part of the implementation of new techniques and technologies through targeted training. We report on the training provided and the results of a survey designed to evaluate the training and to test the study aims.

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2. Methods

Ethics approval for the study was granted by the University of Sydney Human Research Ethics Committee (Project Number 2023/214).

A. The RABBIT template

Developed at the St George Cancer Care Centre (STGCCC), the RABBIT is a project management tool which incorporates prospective risk assessment. Practically, the RABBIT is a Microsoft Word template covering project scope, preparation, risk–benefit review and multidisciplinary team decision making. It was developed to facilitate rapid and safe implementation of new techniques and technologies and has been extensively used at STGCCC [12–13,19].

B. Prospective risk assessment training

The training program was developed and delivered by two physicists from STGCCC with experience in risk management and the use of the RABBIT, with the assistance of the first author who was trained beforehand. The first part of the training consisted of a prerecorded presentation with contents as described in Fig. 1. This video is publicly available on the University of Sydney, Institute of Medical Physics Website.

The second part of the training was interactive, with the trainers and trainees working together to complete the RABBIT template. The training sessions were booked for one hour. The actual time for the training ranged from one hour to 90 min, depending on the availability of the participants and the number of questions they had regarding the RABBIT process.

All sixteen radiation oncology providers in NSW were invited to participate in the training program. Twelve centres confirmed availability and willingness to participate, and four centres declined the invitation. Training was provided to nominated staff at each centre via video conference and a recording of the training was provided to that centre. Additional support was offered to all participants immediately following the training and at 3-months post-training.

C. Quantifying the effectiveness of the training

To evaluate the effectiveness of the training and to gain feedback from participants, three surveys were conducted using Qualtrics (Provo, UT, Versions June 2023 – Dec 2024). All three surveys used skip logic to ensure that only relevant questions were presented. The first and third surveys presented questions on the number and type of risk assessments which had been performed in the preceding 12-month period, the type/s of risk assessments performed, the participants previous experience in performing risk assessments, the barriers to performing risk assessments and the participants opinions about risk assessments. A link to the first survey was provided prior to the risk assessment training. A link to the third survey was provided 12-months after the risk assessment training. The second survey was designed to provide feedback which could be used to improve the training in the future. A link to this survey was provided immediately following the risk assessment training. The three

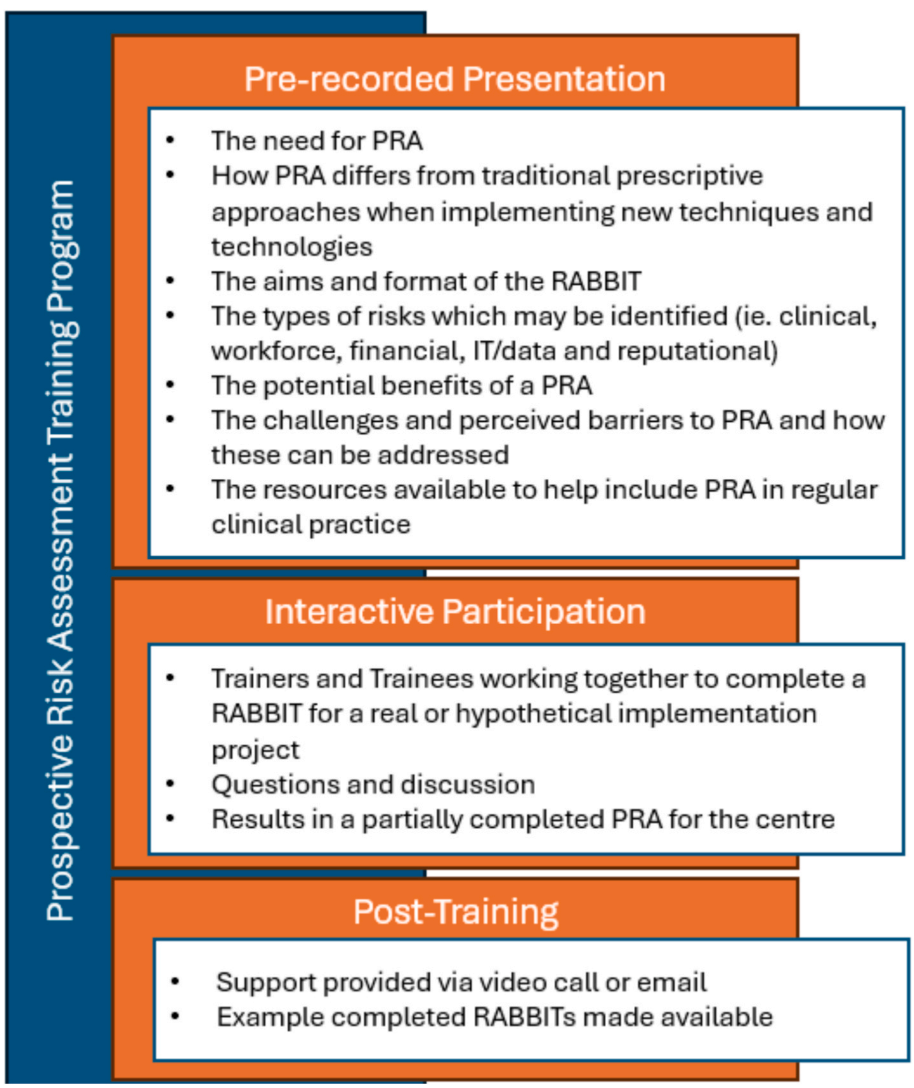

Fig. 1. The content of the PRA assessment training.

surveys are available in appendices 1 to 3.

D. Analysis

The data were extracted from Qualtrics and analysed in Microsoft Excel (Redmond, WA, Version 2504). The data are presented as individual responses or grouped into centres as appropriate, and labelled as such.

3. Results

PRA training was provided to multidisciplinary groups from 12 radiation therapy providers between June and December 2023. All training sessions were delivered via video call, avoiding travel time, and were completed within 90 min.

A. Feedback from the training

Feedback on the training received through the post-training survey was positive, with 69 % of respondents strongly agreeing with the statement "The risk assessment training was useful and applicable to my centre" (12 responses received), and the remaining respondents somewhat agreeing. Based on the received responses, the most helpful parts of the training were the background about and justification for PRA and the worked example using the RABBIT template.

Initially, the training sessions included completing a RABBIT template as a group. However, feedback from the post-training survey showed that participants wanted to see a completed example of a RABBIT template. The feedback was taken on board and later training sessions included a review of a completed RABBIT template instead. Where possible, the example RABBIT was based on an implementation project relevant to the centre. Additional example RABBITs were made available to participants through an online collaboration website, COPPER [20], hosted by the University of Sydney.

B. PRA in NSW radiation oncology centres – Pre and 12-months post-training

From the 12 participating institutions, a total of 31 responses to the pre-training survey were received from professionals within the multidisciplinary teams. The 12-months post-training survey received 14 responses representing 10 radiation oncology centres, with 2 centres failing to complete this survey. Both surveys received responses from radiation oncologists, radiation therapists and radiation oncology medical physicists from across both metropolitan and regional areas (Pre- and 12-month post training surveys had 55 %:16 %:29 % and 43 %:14 %:43 % responses from Physicists: Radiation Oncologists: Radiation Therapists respectively).

The percentage of centres who had completed a PRA in the previous 12-months are shown in Fig. 2, with the percentage of centres completing a PRA increasing after training. Fig. 3 shows the responses from individual centres including those who did not respond to the final survey.

Prior to the training, 75 % of the centres who reported completing a

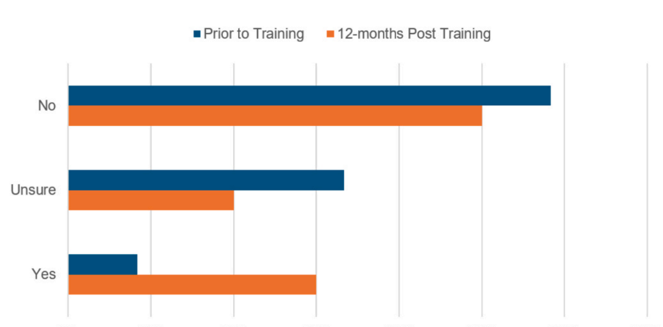

Fig. 2. Responses to the survey question "Has your centre completed any form of multi-disciplinary risk assessment of a radiotherapy technology or technique (not just SABR) in the last 12-months?" Twelve centres responded to this question in Survey 1, prior to the training, and ten centres responded to the question in Survey 2, 12-months post training.

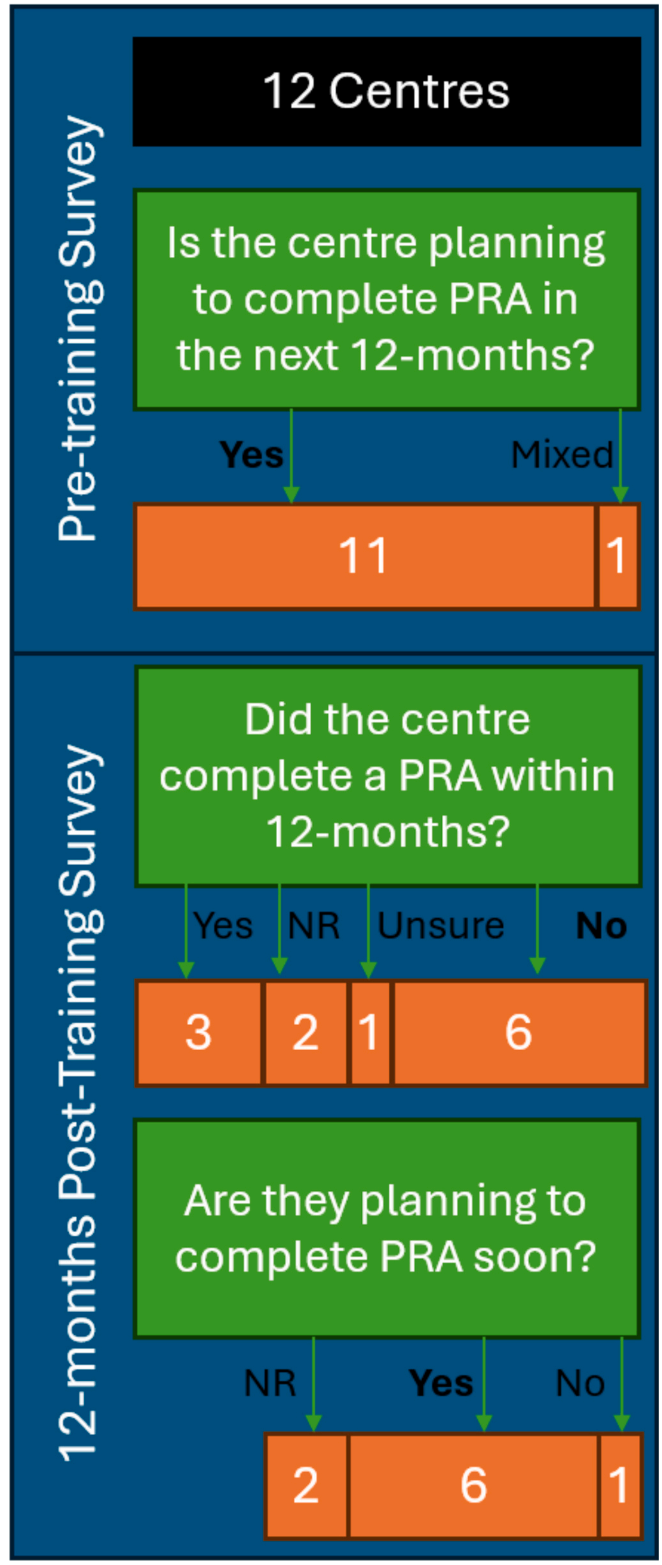

Fig. 3. Whether centres intend to complete a PRA in the following 12-months, from the pre-training survey, whether they completed a PRA in the following 12-months and, for those who did not complete a PRA in that time, their intention for the next 12-months. 'Mixed' indicates different responses received from the same centre. 'NR' indicates no response received.

PRA previously used a tool, other than the RABBIT. In the 12-month post training results, of those who completed a PRA or were unsure, 75 % used the RABBIT alone or included in a mix of risk assessment tools.

The reasons for selecting the applied PRA tool are shown in Fig. 4, with of the majority of respondents selecting a specific tool because it was recommended to them.

When asked if the risk assessments performed found any unique or new hazards that would not have been identified otherwise, 75 % and 83 % of respondents agreed that they had in the pre and 12-month post training surveys, respectively.

Respondents were asked which current or future project they planned to complete a risk assessment for. Fifty percent of the centres planned to perform a risk assessment for a specific new technique or the use of a new piece of technology, with the specific topics including stereotactic ablative radiotherapy, AI contouring, tattooless-setup and total body irradiation. The remaining centres either planned to perform a PRA for new projects in general (23 %) or did not specify their intent. All the centres who completed a PRA in the 12-months following the training had mentioned a specific technique or technology in their response. The motivations mentioned included improving quality and safety for both staff and patients, having a formalised process, identifying and managing risks and assessing the benefits of the process.

The pre-training and 12-months post-training surveys asked respondents about the barriers which prevented them from completing a PRA or completing more PRAs in the previous 12-months. These results are shown in Fig. 5. In the 12-month post-training survey, fewer respondents perceived a 'lack of knowledge or training' (−30 %), 'scepticism about the benefits and/or effectiveness' (−14 %), 'no interest' (−17 %) or 'too hard or overwhelming' (−5%) as a barrier, but with more respondents who perceived 'insufficient time' as a barrier (+22 %).

Unlike the perceived barriers to PRA, the perceptions of respondents about PRA, in response to the statements in the pre-training and 12-months post-training survey were similar. Fig. 6 shows that the majority of participants agree that formal risk assessments can improve safety and quality. Formal risk assessments were seen to require too much time and effort by more than one third of participants in both surveys.

4. Discussion

Both before and after the training, over 90 % of respondents believed that PRA can improve quality and safety. The challenge, therefore, is not to convince the radiation therapy workforce that PRA is required but instead to address other barriers which prevent PRA for being performed. The innovative training provided as part of this study was successful in reducing barriers, particularly those stemming from a lack of knowledge and practical experience, and it succeeded in increasing the number of centres completing PRA as part of project implementation.

However, while the training removed some of the barriers at some centres, time then became the largest barrier to the implementation of PRA, as shown in Fig. 5. These results also fail to include the centres who chose not to participate in the offered training at all due to a lack of available staff. Surveys of pharmacists in Europe and the UK have also identified insufficient knowledge and time as barriers to the use of PRA [21–22].

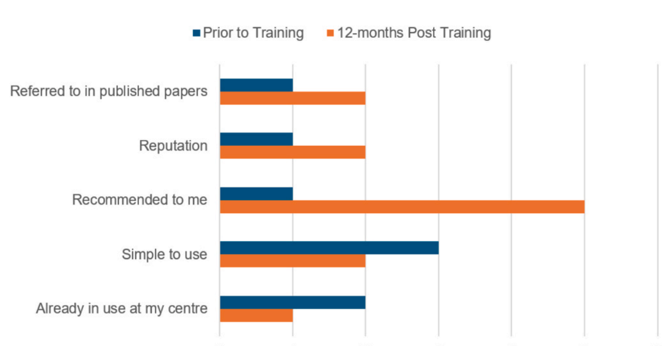

Fig. 4. Reasons for selecting the risk analysis method/tool used given by survey respondents (multiple answers allowed).

Comments from respondents highlighted staffing shortages as an issue, and certainly any understaffing should be addressed to ensure safe and high-quality treatments are available to patients. However, it is also possible that PRA is not seen as an essential part of implementation, instead prioritising the fast implementation of the constant technological improvements now available. PRA should be strongly encouraged when implementing new techniques or technologies, and mandatory for high-risk projects. When PRA is not applied during the implementation of a new technique or technology, this should be clearly justified. Any future iterations of this training should emphasise this.

The training, as it was presented, was time efficient for the participants taking less than 90 min to complete and, importantly, did increase the use of PRA in NSW radiation therapy centres. Increasing participant's knowledge, demonstrating practical examples and providing a simple-to-use tool overcame many of the barriers which existed prior to the training. Most centres in NSW were able to participate due to the low amount of time required for this training. By focussing on a specific topic, the training itself could be performed quickly. By delivering the content via video call, unnecessary travel time could be avoided, which is particularly important for regional centres located many hours' drive from Sydney.

For the centres who did perform a PRA, unique and new hazards were identified at least 75 % of the time, further demonstrating the potential utility of PRA. For example, one centre used the RABBIT for the implementation of tattooless treatment. They identified a risk that patients may be positioned incorrectly for treatment. This was mitigated through pre-treatment imaging, written procedures, staff training and gaining experience at other centres.

Unfortunately, not all NSW radiation therapy centres were able to participate in this program, and not all the participating centres were able to complete a PRA in the following 12-month period. This program was run in the early post-Covid pandemic phase with many centres still recovering from staff shortages and low rates of project development. The training program described here should be set up as a periodic event with centres more likely to participate as they commence the planning stage of a new project. Future versions of the program could involve each hospitals risk management team which may allow for better data collection and broader implementation of PRO within the hospital. No recommendation was made to the participants to involve their hospital's risk management team in the study, and no data collected about whether this was done or not, as this was considered outside the scope of this project.

No other publications could be identified focused on training or education in prospective risk assessment or in risk assessment in radiation oncology. Schuller et al [23] refer to training in failure modes effects analysis (FMEA) by the American Association for Physicist in Medicine in 2013 and describes the department level training provided to staff in their practice. To our knowledge, this is the first publication outlining a prospective risk assessment training program, and the first assessing the impact of such training on practice.

This training program was designed to provide hands-on training and practical examples to small groups of professionals. This helped to ensure engagement and multi-disciplinary participation. We believe the success of this project came from working with small multidisciplinary groups of professionals who were open to working as a team.

To replicate the success of this project within and outside Australia, we would recommend development of regional programs which are customised to local conditions and methods of implementation of new techniques and technologies.

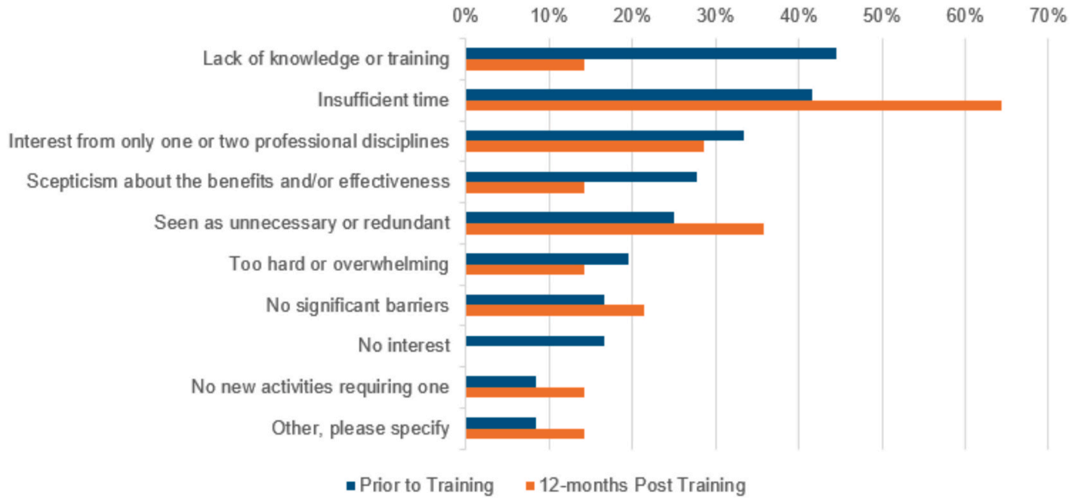

Fig. 5. Barriers to Completing a PRA in the last 12-months.

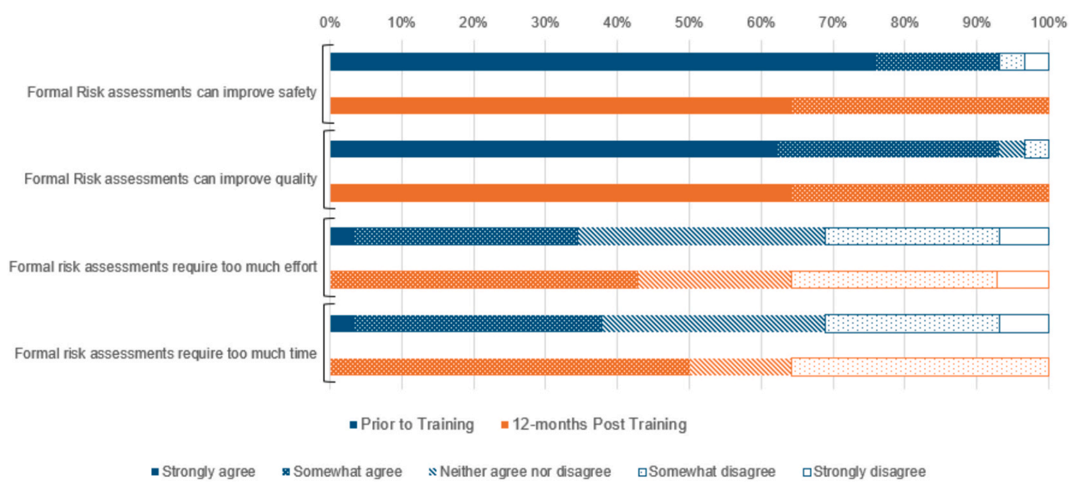

Fig. 6. Perceptions Regarding Formal Risk Assessments from the pre-training and 12-months post-training surveys.

5. Conclusion

We performed targeted, time-efficient prospective risk assessment training at 12 radiation therapy centres across NSW. The program increased knowledge and the use of PRA within NSW, with an increase of more than 20 % in the number of centres using prospective risk assessment in the 12-months following the training and the potential for further increases in the future. Future work should focus on ensuring prospective risk assessment is seen as an essential part of implementing new techniques and technologies into radiation therapy centres and on assisting others to offer similar training programs in other locations.

Author Contribution Statement: E. Claridge Mackonis analysed the data and wrote the first draft manuscript. All authors contributed to the design of the work, the interpretation of data from the work, revision of the draft manuscript and approved the final version of the manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Data availability statement

Data will not be available under the current Ethics Committee approval.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejmp.2025.105213.

References

[1] Dunscombe P. Recommendations for safer radiotherapy: what's the message? Front Oncol 2012;2:129. https://doi.org/10.3389/fonc.2012.00129.

[2] Pardo Masferrer J, Del Cerro Penalver E, Contreras Martinez J, Ferrer Albiach C, Patient S, Quality Working Group of the Spanish Society of Radiation O.. Patient safety in radiation oncology in Spain: a need to change. Clin Transl Oncol May 2020;22(5):751–8. https://doi.org/10.1007/s12094-019-02184-x.

[3] World Health Organization. Radiotherapy risk profile: technical manual. Geneva, Switzerland: World Health Organization; 2008.

[4] European Commission, Directorate-General for Energy. *General guidelines on risk management in external beam radiotherapy*. Publications Office; 2015.

[5] IAEA. *Radiation protection and safety in medical uses of ionizing radiation*. vol SSG-46. IAEA Specific Safety Guide Series International Atomic Energy Agency 2018.

[6] A. Licence conditions - Codes and standards applicable to controlled facilities (ARPANSA-SUP-1782). Updated 29/9/2023. Accessed 24/6/2025, 2025. https://www.arpansa.gov.au/regulation-and-licensing/licensing/information-for-licence-holders/regulatory-guides/licence-conditions-codes-and-standards-0.

[7] The Royal Australian and New Zealand College of Radiologists 2023.

[8] Yuen J, Batool M, Baldock C. Proactive risk management should be mandatory for the setup of new techniques in radiation oncology. Phys Eng Sci Med Sep 2024;47(3):783–7. https://doi.org/10.1007/s13246-024-01446-5.

[9] *Guidelines for Safe Practice of Stereotactic Body (Ablative) Radiation Therapy*. Faculty of Radiation Oncology, The Royal Australian and New Zealand College of Radiologists; 2015.

[10] Das IJ, Dawes SL, Dominello MM, et al. Quality and Safety Considerations in Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy: an ASTRO Safety White Paper Update. Pract Radiat Oncol Jul-Aug 2022;12(4):e253–68. https://doi.org/10.1016/j.prro.2022.03.001.

[11] Claridge Mackonis ER, Hardcastle N, Haworth A. A survey of compliance with stereotactic ablative body radiotherapy quality recommendations. J Med Imaging Radiat Oncol Mar 30 2023. https://doi.org/10.1111/1754-9485.13526.

[12] Ralston A, Graham P, Poder J, Yuen J. The RABBIT risk-based approach to clinical implementation of new technology: SRS as a case study. Tech Innov Patient Support Radiat Oncol Jun 2020;14:51–60. https://doi.org/10.1016/j.tipsro.2020.04.003.

[13] Ralston A, Yuen J. Use of the AAPM Safety Profile Assessment Tool to Evaluate the Change in Safety Culture after Implementing the RABBIT prospective Risk Management System. Adv Radiat Oncol Jan-Mar 2019;4(1):150–5. https://doi.org/10.1016/j.adro.2018.08.015.

[14] Gilmore MDF, Rowbottom CG. Evaluation of failure modes and effect analysis for routine risk assessment of lung radiotherapy at a UK center. J Appl Clin Med Phys May 2021;22(5):36–47. https://doi.org/10.1002/acm2.13238.

[15] Vidali C, Severgnini M, Urbani M, Toscano L, Perulli A, Bortul M. FMECA Application to Intraoperative Electron Beam Radiotherapy Procedure As a Quality Method to prevent and Reduce Patient's risk in Conservative Surgery for Breast Cancer. Front Med (Lausanne) 2017;4:138. https://doi.org/10.3389/fmed.2017.00138.

[16] Kluter S, Schrenk O, Renkamp CK, et al. A practical implementation of risk management for the clinical introduction of online adaptive magnetic Resonance-guided radiotherapy. Phys Imaging Radiat Oncol Jan 2021;17:53–7. https://doi.org/10.1016/j.phro.2020.12.005.

[17] Mancosu P, Signori C, Clerici E, et al. Critical Re-Evaluation of a failure Mode effect Analysis in a Radiation Therapy Department after 10 Years. Pract Radiat Oncol May-Jun 2021;11(3):e329–38. https://doi.org/10.1016/j.prro.2020.11.002.

[18] Morabito A, Mercadante E, Muto P, et al. Risk Management Activities in a Lung Cancer Multidisciplinary Team at a Comprehensive Cancer Center: results of a prospective Analysis. JCO Oncol Pract Mar 2023;19(3):e315–25. https://doi.org/10.1200/OP.22.00358.

[19] Poder J, Brown R, Howie A, et al. A risk-based approach to development of ultrasound-based high-dose-rate prostate brachytherapy quality management. Brachytherapy Sep-Oct 2018;17(5):788–93. https://doi.org/10.1016/j.brachy.2018.05.005.

[20] Collaborative Online Platform for Physics Experts in Radiation The University of Sydney. Updated 9/12/2024. Accessed 18/02/2025, 2025. https://unisyd.sharepoint.com/sites/COPPER/SitePages/Home.aspx.

[21] Miljković N, Van Overbeeke E, Godman B, et al. Practical implications from European hospital pharmacists on prospective risk assessment for medicine shortages. Front Med 2020;7:407.

[22] Shebl N, Franklin B, Barber N, Burnett S, Parand A. Failure mode and effects analysis: views of hospital staff in the UK. J Health Serv Res Policy 2012;17(1):37–43.

[23] Schuller BW, Burns A, Ceilley EA, et al. Failure mode and effects analysis: a community practice perspective. J Appl Clin Med Phys 2017;18(6):258–67.

7.3 POSTAMBLE

This chapter aimed to address Research Question 5.

Research Question 5: Can focused risk assessment training increase the use of prospective risk assessment for new technologies and techniques in NSW radiation oncology centres?
Key Findings from this Chapter: - Focused training can increase the use of prospective risk assessment - Barriers to prospective risk assessment such as a lack of knowledge or training and scepticism about the benefits were reduced by the training, while insufficient time remained a barrier. - This training should be offered periodically to best align with the new projects and could be replicated internationally.
Summary: A time-efficient training program was delivered to NSW radiation therapy centres and has increased the use of prospective risk assessment. Ongoing access to training needs to be considered to build on this.

This project has demonstrated the effectiveness of knowledge sharing within the NSW radiation therapy context. In this case, the training program was focused on a deficiency which had been identified in Chapter 4. By focusing in this way, the scope of the training could be limited and the success of the project evaluated. The legacy of this project is a training program which can be delivered as required by centres in NSW, and a template which can be used nationally and internationally to increase the use of prospective risk assessments, or address other identified deficiencies.

To complement this training, example prospective risk assessments were made available to participants via the COPPER file sharing platform, discussed in the following chapter. This chapter looks at a less focused but more flexible approach to collaboration within the radiation therapy community.

Following on from this, Chapter 9 looks to establish a template for utilising an existing research platform to assess current practice against guidelines. This would facilitate self-assessment, inter-comparisons and establish current practice as a reference for other centres.

CHAPTER 8

Improving the Implementation of New Techniques and Technologies through the Introduction of a Collaborative Online Platform

8.1 PREAMBLE

This work is designed to address research question 6.

Will the facilitation of file sharing between NSW (and Australasian) radiation oncology centres be utilized to increase speed and safety when implementing new technologies and techniques?

8.2 INTRODUCTION

Chapters 2, 3 and 4 of this thesis identified a number of issues relating to the introduction of new techniques and technologies into radiation oncology centres. In Chapter 3, the introduction of the new SABR technique was found to be delayed in some centres compared to others, particularly in regional areas. Chapter 4 highlights issues with training staff in new techniques, which potentially could be addressed by the sharing of practical training and resources. In Chapter 5, it was reported that professionals are keen to work together and share resources within the radiation oncology community.

From this previous work, a project was devised which would allow centres to share resources and experience, thereby avoiding time-consuming duplication of work and allowing knowledge of new technologies and techniques to be shared.

8.2.1 Current Examples of Resource Sharing in Radiation Oncology Medical Physics

Traditionally, the sharing of expertise between radiation oncology medical physicists has been facilitated through the publication of recommendations and guides by professional colleges. These documents provide an avenue for experienced physicists to share their expertise and help clinical physicists by combining existing evidence and information into a format which can be easily applied.

For example, the American Association of Medical Physicists (AAPM) Task Group 142 publication on linear accelerator quality assurance is widely used and has been referenced 556 (as of 10/6/2025) times. However, these documents are often written by committees and as a result can take years to be published. In addition, formal publications may not contain practical information about a particular piece of equipment or scenario and this can be useful when implementing a new technique or technology.

Information sharing can also occur through educational and training programs. One example is the EMERALD project which was developed in Europe to provide medical physics education to low and middle-income countries (LMI) (174). The IAEA has also developed medical physics education resources for LMI countries (174) and their website includes useful videos demonstrating standard medical physics tasks (175). These groups target LMI countries as these countries often lack formal training programs. However, because of their target audience, the material is often too basic for qualified Australian medical physicists and not focused on advanced technology. In Australia, the Training, Education and Assessment Program (TEAP) is run by the ACPSEM and provides training for medical physicists. It focuses on standard medical physics tasks and, while this program does get updated regularly, a training program cannot have the agility to include up-to-date and cutting-edge technologies or advanced treatment techniques.

To share information on recent developments, medical physics colleges, such as the ACPSEM and AAPM, run webinars and meetings such as the Motion Management Workshop discussed in Chapter 6. These meetings can provide up-to-date information and an opportunity for discussion. Often a recording of the meeting or presentation slides will be available to members following the meeting. These can provide a helpful resource, but the information provided can be limited by time constraints and the format. The usefulness of these resources may be improved by supplementing them with other file-based resources.

Resource sharing in radiation oncology medical physics can also occur through multi-disciplinary forums. In Canada, a community-of-practice approach was implemented to rebuild the radiotherapy community focusing on in-person meetings, in-person interactions, emails and phone calls (176). The approach has potential in the NSW setting but, like the webinars and meetings previously discussed, could be complimented by a file-based sharing solution.

Current File-Based Sharing

In the AAPM publication by Task Group 100 (172), the authors recommend that "The AAPM establish a website with model process maps, FMEAs, FTAs, and the resultant quality management program for various procedures as those analyses are developed." In 2020, four years after the task group made this recommendation, a repository for TG-100 tools was established. Unfortunately, its use has been limited and it currently contains only 7 files including only one example process map (as of Dec 2024).

Vendors have also looked to provide resource sharing opportunities. One example of file-based sharing was established by Varian Medical Systems, as a customer-only website. They encourage customers to share RapidPlan knowledge-based planning models (See Chapter 4) via this website. In this case, the sharing may have a financial benefit to Varian, as it may increase the sales of the RapidPlan product and increase the usefulness of this product for customers who have already purchased it.

Elekta, another radiation therapy vendor, provides the BrachyAcademy to its customers. The platform provides peer-to-peer education by facilitating on-site visits and vendor sponsored clinical workshops and webinars. Published papers are shared on the website but no other file sharing is provided.

Another web-based platform was established in the Netherlands concurrent to the work presented in this chapter. Their web-based platform was established in 2022 by a group of Dutch radiation therapy centres aiming to improve the implementation of innovations in radiation oncology (177). This platform facilitates the sharing of formal innovation project reports between radiation oncology centres.

This project

The project presented here has similar aims to the Dutch project but a different approach. In this work, an online platform is used to allow the sharing of files and other resources between medical physicists. This should reduce the duplication of effort and allow experienced centres to share what they have learnt about new techniques and technologies, thereby helping other centres to implement improvements more quickly and safely. The testable hypothesis for this work is that an online platform for collaborative file-sharing will be used by the medical physics community and, specifically, used in the areas of new technology and techniques.

8.3 METHOD

8.3.1 Steering Committee

The creation of an online sharing platform was proposed in October 2022. The decision was made to aim the platform at medical physicists rather than the wider radiation oncology community initially. A steering committee was formed later in 2022 to provide support, guidance and oversight for the project. As chairperson of this committee, I recruited committee members including six clinical medical physicists from NSW and one academic.

8.3.2 Legal Advice and Risk

The committee established that a significant obstacle to the success of the project was the perceived risk to the individual or organization sharing content on the website. Legal advice was therefore obtained from the Office of General Council at the University of Sydney. This established that the risk could be significantly reduced by ensuring that the contents of the website were only available to trained health professionals. A trained health professional is expected to have sufficient knowledge to understand and assess the content before using it in practice.

Based on this advice, the steering committee decided that the content of the website must be only available to Australian and New Zealand radiation oncology healthcare professionals (with an email address associated with a registered healthcare provider).

A disclaimer was also created to further mitigate perceived risks. This was later expanded in consultation with the representatives of a local health district to alleviate their concerns.

8.3.3 Technological Structure

The technical requirements for the project were established as follows:

- Accessible only to those granted permission
- Able to host files of various formats
- Records utilisation information of visitors.

In consultation with University of Sydney Information and Communications Technology (ICT) team, the Microsoft SharePoint platform (Microsoft Corporation, WA, USA) was selected. This software was already available at the university and allows the creation of intranet sites incorporating document storage and secure login capabilities (178). The platform was available to host content from April 2023.

8.3.4 Communication and Initiatives

For a collaborative project to be effective, the relevant population need to know of its existence and how to refer to it. The steering committee selected the name COPPER for the platform, an acronym for Collaborative Online Platform for Physics Experts in Radiation. Once established, a number of communication pathways were used to maximize awareness amongst radiation oncology medical physicists.

- Information was presented about the project at the EPSM2023 Conference and at the NSW Research and Development Workshops hosted at the University of Sydney in 2023, 2024 and 2025.
- Regular updates were included in the University of Sydney, Institute of Medical Physics newsletter.
- In April 2024, a promotional video was produced with a link emailed to all members of the ACPSEM NSW branch.
- In the latter half of 2024, an effort was made to contact speakers from conferences and workshops, requesting a copy of their slides for sharing on COPPER. This provided a low-effort opportunity for people to contribute.
- In February 2025, the project was presented at the Varian Summit to a multi-disciplinary group of Varian customers from Australia and New Zealand.
- In June 2025, based on feedback from users, a quarterly update was instigated containing a list of new content available on COPPER and highlighting the contributions of specific centres.

8.3.5 Assessment of use

To assess the ultilisation of COPPER, the site visits and unique site visits were recorded from January 2024. Information on the number and type of files uploaded was assessed to provide an indication of the willingness of registered users to share content. The viewing histories of these files were collected and analysed as an indication of what content was of most interest and what the content is likely to be used for.

8.4 RESULTS

8.4.1 Membership

Access to COPPER was granted based on an email request from a recognized health domain within Australia or New Zealand. In April 2024, 12 months after COPPER was launched, 56 health care professionals had registered for access. As of November 2025, there were 137 registered uses with 116 unique users having visited the website. The majority of users are medical physicists from NSW. However, access has been granted to physicists and radiation therapists from across Australia and New Zealand.

8.4.2 Content

An initial group of documents were shared on COPPER at launch. These included procedural documents from Chris O'Brien Lifehouse, an editable document profiling radiation oncology department (number and type of linacs, ancillary equipment, treatment planning system etc.) and a document with useful links for scripting. Additional content was then added over the following 12-months including a document with links to commercially available AI-contouring products, information on scripts centres were using, editable spreadsheets for sharing beam modelling data, presentation slides from a workshop held at the University of Sydney and RABBIT risk assessment templates (Chapter 7). Physicists added department specific information to the department profiles document and data to the beam modelling spreadsheet.

Figure 24 shows the amount of content uploaded to COPPER and the centres providing content. The three large increases in content correspond to the contribution of presentations from the NSW Research and Development days in 2023, 2024 and 2025.

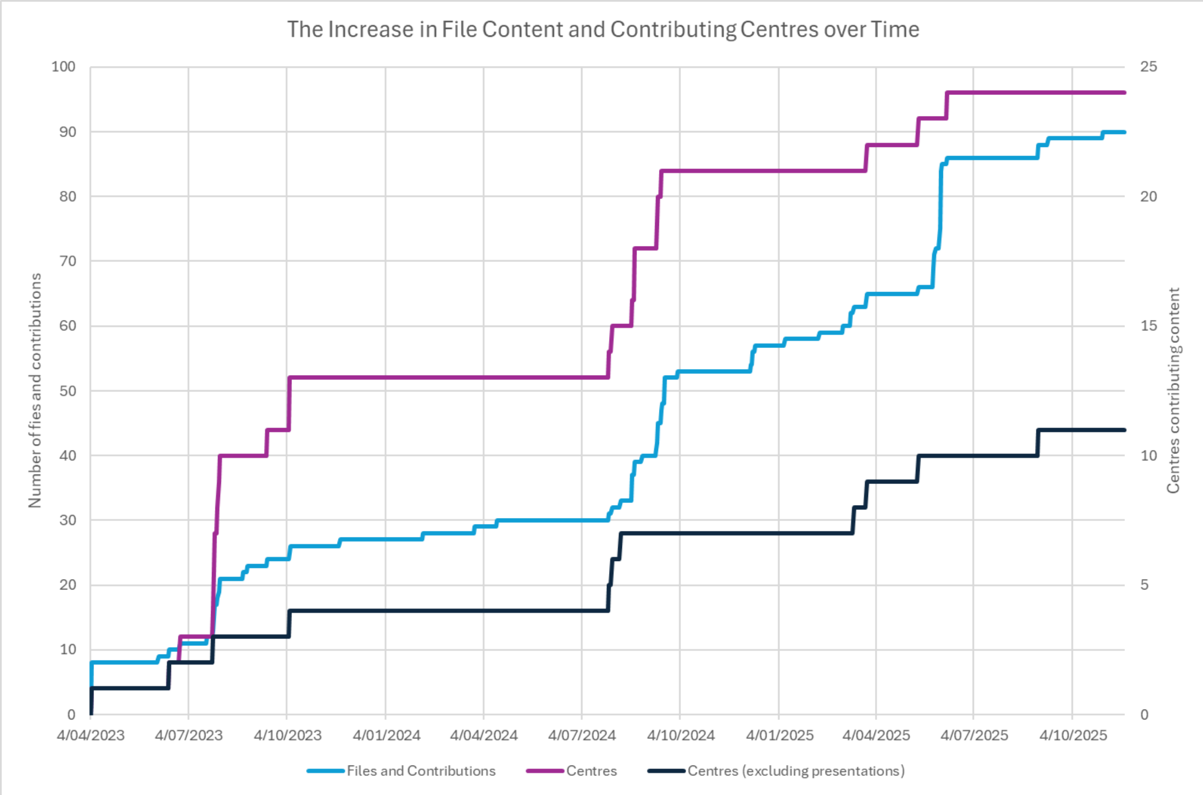

Figure 24: The number of files uploaded to COPPER, the number of centres contributing to COPPER & the number of centres contributing content other than slides from presentations.

An assessment of the unique views of the content on COPPER shows a total of 456 unique content views up to June 2025. The most popular content is shown in Table 13.

Six of the top 10 most popular pieces of content were editable content such as the Department Profiles and lists of links to useful scripting content. The Department Profiles content provides a place for users to provide and view information on the equipment, software and techniques used at radiation oncology centres and may improve communication between centres facing similar challenges. This was the most popular piece of content on COPPER. Four of the top 10 pieces of content were documents related to scripting. Unfortunately, Sharepoint does not provide information on the number of times files are downloaded. So, the popularity of the actual script files shared on COPPER could not be determined. The most popular non-editable document on COPPER has been an SGRT commissioning plan, which provided a list of tests and timeframes used in the commissioning of a new SGRT system.

Table 13: Most popular content on COPPER as of June 2025

Item	Type	Unique Viewers	Total Views
Department profiles	Editable	36	166
MegaCheck: Eclipse plan checking script description	Script	27	62
ESAPI script list	Editable	24	63
Eclipse DLG and leakage prior to V18	Editable	18	70
Eclipse V18 MLC parameters	Editable	18	119
Fault log: Script example description	Script	16	31
AI contouring products: Internet links to vendors	Editable	14	32
Scripting links: Internet links	Editable	14	24
COPPER information	Administrative	13	33
SGRT commissioning plan	Document	13	27

8.4.3 Usage

In 2024, the committee decided to more actively pursue content which had been presented at a workshop or conference, as registered users appeared more comfortable sharing this style of content. Figure 25 shows the site traffic for 2024-5, Institute of Medical Physics newsletters mentioning COPPER and relevant workshops and conferences.

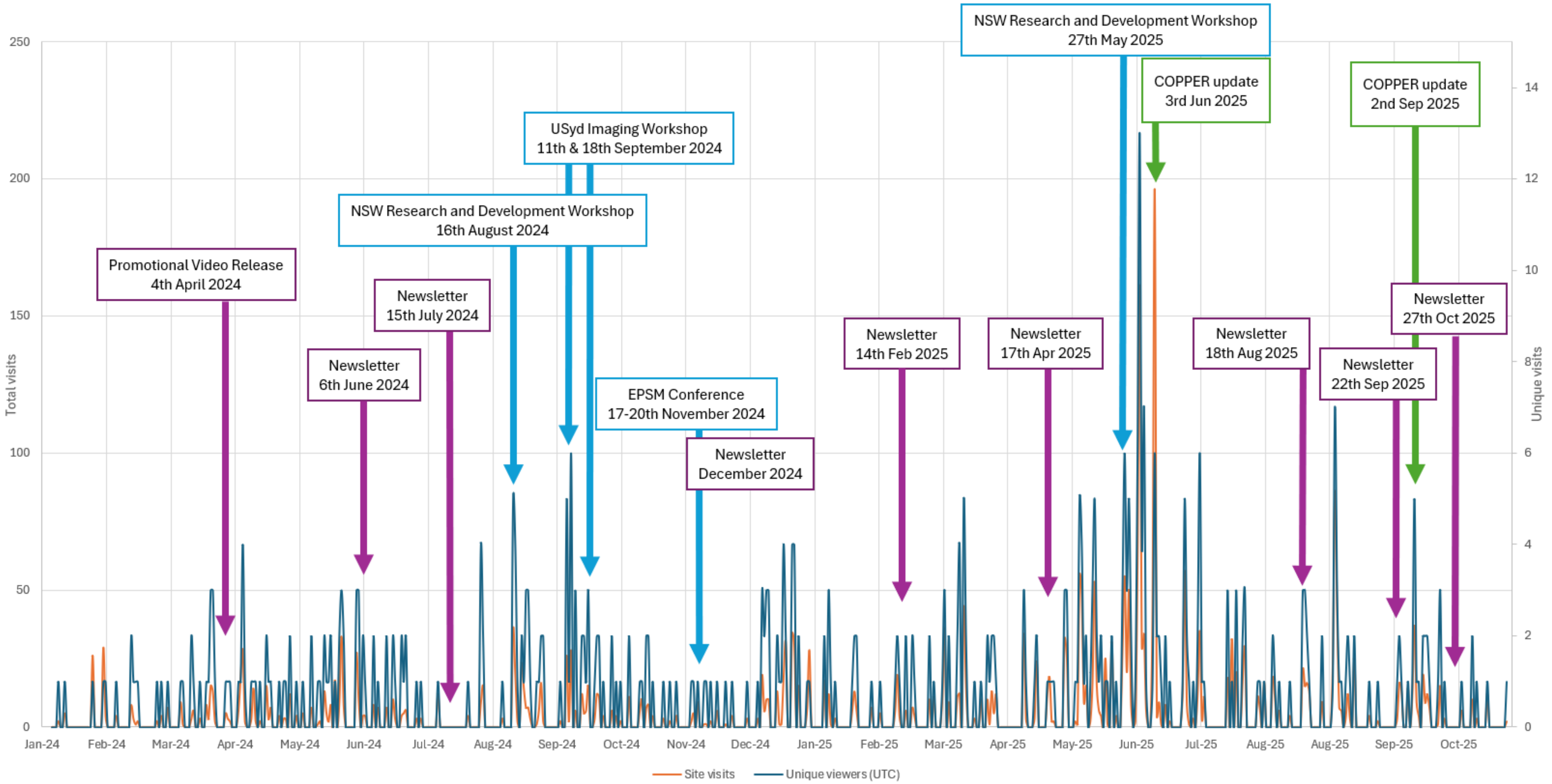

Figure 25: COPPER site visits, total and unique from January 2024 to Nov 2025. Note that the time scale is in UTC time, not AEST, and therefore some increasing in traffic may appear one day before the event

8.5 DISCUSSION

The work presented here is part of an ongoing project envisaged to facilitate sharing between radiation therapy centres, particularly regarding new technology and techniques, to reduce duplication of work, increase safety and reduce delays in implementation. To evaluate the success of this project, the utilisation of the COPPER platform has been assessed using information on the users, content and activity on the website.

The increasing number of users and volume of content on COPPER demonstrate that the platform is being used by the radiation oncology community and that this use is increasing. The number of centres contributing content to COPPER has also increased, however many centres have only contributed presentations. There are a number of possible reasons for this. Physicists may be unsure if their manager or employer would allow them to upload other content, they may have been told not to upload content or they may not wish to spend time contributing.

Potentially managers may be concerned about the risk to their centre if the content is incorrect or misused. Others may be reluctant to share content for free when the content cost their centre time to produce. Another issue is that physicists may be unsure what would be of interest to others or reluctant to put their work on display for fear of criticism. Physicists may also be hesitant to submit multi-disciplinary files due to the site's focus on physics or the broader authorship of these documents. These are issues which will need to be addressed to ensure COPPER continues to grow.

The recent changes to the disclaimer and input of content from one centre may indicate that the community are becoming more comfortable with the idea of sharing, and these contributions may help others to overcome their concerns about risk. However, changing these attitudes may take time. Other possible strategies to overcome these concerns could be to work with recognized government or professional organisations and to inform the broadener radiation oncology community about COPPER, as currently the initiative has been focussed on medical physicists. However, established organisations can, themselves, be risk adverse and slow-moving.

The most popular files currently on COPPER are those relating to new techniques (SGRT), technological improvements (scripting) and providing information about the equipment at other centres (potentially for the purposes of implementation and collaborative improvements). This demonstrates that the project is being used by the medical physics community for the implementation of new techniques and technologies.

Future work should continue to focus in these areas and should include providing users with feedback about which content has been shown to be most popular. However, Figure 25 demonstrates increases in site visits following an upload of workshop presentations. These presentations, while not as popular as other content, do lead to user engagement, reminding people about the project and providing a simple method for centres to contribute to COPPER.

This work can be compared to the recent work in the Netherlands (177), where a national taskforce was established to improve the implementation of innovation in radiotherapy. Their work was motivated by a study which showed slow implementation of innovations (177). Like this work, it aimed to increase collaboration on implementation projects and uses a website to host shared content. It differed in that it was driven by a multi-disciplinary task force and was much more prescriptive about the content to be shared. The template used for sharing content has the potential to ensure health care professionals feel comfortable sharing but does create additional work for centres to contribute and would require significant resources from participating centres. The multi-disciplinary approach has the potential advantage of allowing for more complete content regarding a new technique or technology to be shared.

This work has demonstrated that an online platform for collaborative file-sharing will be used by the medical physics community. The most popular content has been the editable content, particularly the department profiles, which are aimed at facilitating collaboration between similarly equipped centres. Potentially synergistic relationships have been established between centres.

Content relating to scripting was also popular. Sharing scripts should reduce the workload across the healthcare system by minimising the repetition of work. SGRT commissioning list was the most popular document. This shows another way that centres can collaborate in the implementation of new technologies. In order to continue the success of COPPER, the project should focus on content that facilitates collaboration, that reduces the workload of healthcare professionals and that relates to new techniques and technologies. It will also be important to continue working with departments to address concerns and obtaining content from workshops and conferences to fuel engagement.

The usefulness of COPPER relies on new and relevant content being provided by members. It is therefore vital that the lessons learnt so far be applied to ensure the continuing success of this project. Options to work with recognized organisation and the expansion to include content from other professions should be explored in the future.

8.6 CONCLUSIONS

A collaborative file-sharing platform was established for the use of the medical physics community in Australia and New Zealand. The platform has an increasing number of users and shared content, with the most popular content focused on new techniques and technologies. The availability of this content is designed to reduce the risk of duplication of work allowing centres to offer up-to-date treatments more quickly and safely. Continuing work is required to ensure concerns and barriers to contribution are addressed and engagement remains high.

This chapter aimed to address Research Question 6 by assessing the use of a file sharing platform for medical physicists.

8.7 POSTAMBLE

Research Question 6: Will the facilitation of file sharing between NSW (and Australasian) radiation oncology centres be utilized to increase speed and safety when implementing new technologies and techniques?
Key Findings from this Chapter: - File sharing via the COPPER platform is being utilized by radiation oncology medical physicists. - The most popular content was related to collaboration, scripting and new techniques. - Providing workshop and conference presentations allows for continued and low effort engagement. - Continuing work is required to address barriers to contributing and ensure engagement of all centres. - Expansion to a multi-disciplinary platform or collaboration with a professional organization or government body could be explored. - The project may have increased the speed and safety of the implementation of new technologies and techniques but further work would need to be required to verify this.
Summary: Facilitated file-sharing was successfully implemented for NSW radiation oncology centres potentially leading to safer and quicker implementation of new techniques and technologies.

CHAPTER 9

Implemented Automated Auditing using Existing Research Infrastructure for Spine SABR

9.1 PREAMBLE

This work is designed to address research question 7.

Can the ACDN Distributed Learning Network be used to automatically audit radiation therapy treatments against published standards?

9.2 INTRODUCTION

Radiation therapy outcomes depend on the quality of the treatment. This is demonstrated in multiple studies where compliance with trial protocols is associated with improved clinical outcomes (179-182).

Similarly, clinical audits can assess compliance with current treatment recommendations. Multicentre clinical audits, which retrospectively assess the quality of radiation therapy treatments have been shown to identify areas for improvement and differences in practice between centres (183). Given that higher quality treatments lead to improved outcomes in a trial setting, it is reasonable to assume that, if audits can lead to higher quality treatments, they will also lead to improved outcomes for all patients.

Despite this, recent publications have shown that centres in New South Wales have limited opportunities to participate in external or multicentre audits (160), and that, when audits are performed, they show low levels of protocol compliance (184). More auditing opportunities need to be made available. Unfortunately, manual auditing practices can be time consuming, resource intensive and may not include up-to-date treatment techniques (35, 46, 185, 186). Automated methods of auditing may provide an alternative, reducing the manual labour involved and allowing faster feedback on the adherence to recommendations and the quality of patient treatments.

This work aims to pilot the use of the Australian Cancer Data Network (ACDN) Distributed Learning Network (18) to automatically audit radiation therapy treatments against recommended practice. The ACDN is a data network designed to enable multi-hospital cancer research and data analysis. The network links clinical and registry data to allow machine learning and assessment of clinical practice. This pilot study looks specifically at spine stereotactic ablative body radiotherapy (SABR) treatments where previous work has shown that deviations from consensus contouring guidelines can lead to inferior local control (187).

In this study, radiation therapy treatments at two large cancer hospitals are compared to the recommendations in a consensus guideline published by the Cancer Institute of New South Wales on the use of spine SABR (20). In addition, dosimetric information from spine SABR plans was extracted and summarised providing information on the prescriptions, target coverage and organ-at-risk sparing, allowing inter-centre practice comparisons.

9.3 METHOD

The Cancer Institute of New South Wales provides consensus and evidence-based treatment protocols to support the delivery of cancer treatment (188). In this work, radiation therapy treatments were assessed against the Spinal bone metastases palliative EBRT stereotactic protocol, ID:4098 v. 1 published via the Cancer Institute of New South Wales eviQ webpage (20). This protocol is for the treatment of oligometastatic disease in the form of a spinal metastasis from a solid primary tumour and excludes patients who have had previous radiation therapy to the region being treated.

The scope of the audit was limited to objectively accessible data which could be readily extracted from the electronic patient record. For example, the protocol recommends that analgesia be optimised prior to radiation therapy. As this is subjective and difficult to extract, this was not assessed as part of this audit. In comparison, the protocol states that patients should be in a supine position for treatment. This datum is non-subjective, simple to extract and was therefore included in the audit.

The data extraction and collation were performed using the ACDN under the network ethics approval (18) (Ethics approval granted by the NSW Population and Health Services Ethics committee 2019/ETH01550). The inclusion criteria in this study were patients receiving stereotactic treatments to a spinal bone target in the period 2021-2024. Patients were included from two large metropolitan hospitals with a mature spine SABR program. This study is intended as a pilot for this audit process, with the aim to broaden the study to all centres in the ACDN network. Where the presented data are separated by centre, the centres have been reidentified.

9.3.1 Data Extraction

Patients meeting the inclusion criteria were identified based on prescription information, treatment site and relevant checking tasks, based on the practice at each centre. Following the identification of suitable patient treatments, the data extraction was performed using similar but not identical processes at each centre without individual patient data leaving the centre. The extracted data are shown in Table 14 and include the simulation, magnetic resonance (MR) imaging and first treatment date, computed tomography (CT) slice thickness, patient scan orientation, MR imaging protocol, extension of the CT scan beyond the target, prescription dose, fractionation, beam energy, whether the multileaf collimators (MLCs) moved dynamically during treatment, the dose calculation algorithm, the dose grid resolution, the treatment verification imaging used, the target contours for assessment and dose-volume information.

At each centre, Digital Imaging and Communications in Medicine (DICOM) format versions of the treatment plans were exported into a directory for analysis. At Centre 1, individual plans were manually exported from the Eclipse treatment planning system. At Centre 2, plans were extracted from a Picture Archiving and Communication System (PACS) using DICOMweb services(189). A python script using the PyDicer (190) python library extracted both dosimetric and non-dosimetric information from the DICOM files. This included information about the contours, dose distribution, treatment fields and other meta data.

Additional information, which could not be extracted from the DICOM files, such as the treatment start date and prescription dose, were extracted from the treatment planning system or oncology information system (OIS) using SQL queries or custom scripts. The extraction methods used for this work as well as potential future methods are shown in Table 14.

The target volume contours were visually assessed against the contouring guidelines in the eviQ protocol, Cox et al (191) and Dunne et al (192). An image file was produced for each planning target volume (PTV) showing three orthogonal views through the centre of the PTV. An example of this is shown in Figure 26. The assessment did not include a review of other available imaging. The clinical target volume (CTV) to PTV margin was assessed separately by calculating the difference in the bounding box for each structure.

A summary of the data was produced including statistical data and the percentage of plans passing each criterion for the years 2021-2022 and the years 2023-2024, with the data split into two cohorts to allow a comparison between the two time periods and an assessment of changes in practice following the release of the eviQ protocol in November 2022.

The number of plans included was reported for each value as some data could only be assessed for some plans, for example the time from MRI imaging to treatment could only be assessed for patients who had an MRI image. Also, as the spinal cord planning organ at risk volume (PRV) and oesophagus tolerances in the eviQ protocol are different for different dose fractionation schedules, plans for each schedule are grouped and summarised together.

The ACDN is designed to perform multi-centre research projects without patient data leaving each centre, and this is a requirement of the ethics approval for projects using this network. To ensure no individual patient data was shared, summary data were only calculated when two or more plans were available. Further, a 'near median' value was reported rather than a true median to avoid reporting individual patient data. For an odd number of values, the near median was equal to the average of the three central data points. For even number of values the near median was the average of the two central data points, equal to the median value.

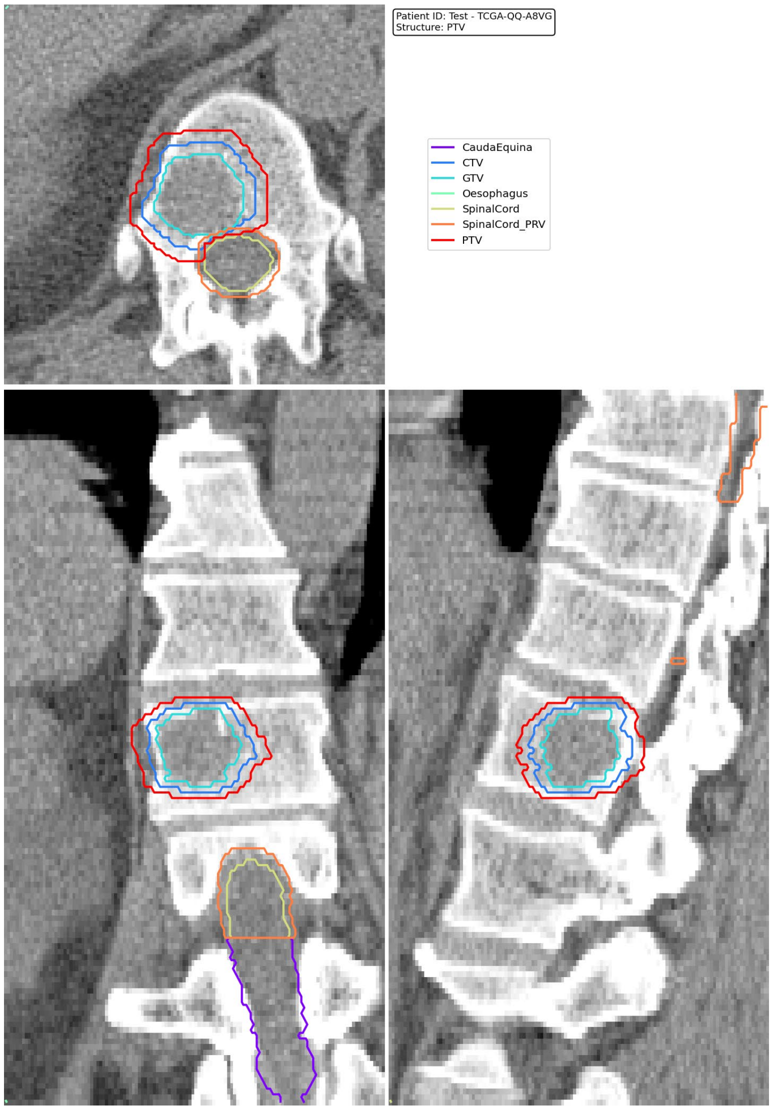

Figure 26: An example of the image produced for contour review. The ethics approval for this work does not allow images from study patients to be displayed. This CT image is taken from the Cancer Image Archive (193).

To simplify the assessment process, the cauda equina structures were grouped with the spinal cord PRV and assessed against the same dosimetric criteria. Where both structures were present in a structure set, the structure with the highest dose was assessed.

Table 14: Data extracted and where the data was extracted from at each centre. DICOM header extraction and dosimetric calculations performed by PyDicer. Future Centres denotes alternative data extraction methods which could be used for data extraction for future studies. Abbreviations: Treatment planning system (TPS), Structured query language (SQL)

Data items	Centre 1	Centre 2	Future Centres*
Simulation Date	CT image DICOM header	CT image DICOM header	CT image DICOM header
Treatment start date	Eclipse TPS script	SQL query of Victorian Radiotherapy Minimum Data Set (194)	SQL query of OIS
CT patient position	CT image DICOM header	CT image DICOM header	CT image DICOM header
CT slice thickness	CT image DICOM header	CT image DICOM header	CT image DICOM header
Extension of CT beyond the target	Structure set PTV and external contour extensions	Structure set PTV and external contour extensions	Structure set PTV and external contour extensions
Existence of MRI or CT myelogram registered to planning images	Eclipse TPS script	Not extracted	SQL query of OIS
MRI protocol used	Eclipse TPS script	Not extracted	SQL query of OIS
MRI date of scan	Eclipse TPS script	Not extracted	SQL query of OIS
Prescription dose (Gy)	Plan DICOM header	SQL query of Victorian Radiotherapy Minimum Data Set (194)	SQL query of OIS
Beam energy	Plan DICOM header	Plan DICOM header	Plan DICOM header
Robotic treatment or dynamic MLC used for treatment	Plan DICOM header	Plan DICOM header	Plan DICOM header
Algorithm	Eclipse TPS script	Manually entered	Custom scripts
Dose grid resolution	Dose DICOM header	Dose DICOM header	Dose DICOM header

Treatment verification images used for the patient treatment	Plan DICOM header	SQL query of Victorian Radiotherapy Minimum Data Set (194)	SQL query of OIS
Whether this treatment is a reirradiation (if available)	Not available	Not extracted	Centre dependent
Target contours	DICOM structure set	DICOM structure set	DICOM structure set
Structure dosimetry	DICOM structure set and DICOM dose file	DICOM structure set and DICOM dose file	DICOM structure set and DICOM dose file

9.4 RESULTS

All eligible treatment plans were able to be audited and have been included in the analysis, 83 from Centre 1 and 187 from Centre 2. Dosimetric and contouring compliance could not be assessed for 5 plans at Centre 1 and 5 plans at Centre 2 as the DICOM plan files were not compatible with the analysis package, but other information was assessed for these plans.

Through digitally extracted data, 23 metrics at Centre 1 and 20 metrics at Centre were able to be assessed. The metrics assessed and the percentage of plans which satisfied each metric are shown in Table 15.

In addition to the assessment against metrics, dosimetric data were extracted for each plan and summarised using the mean, near median and standard deviation. The GTV and PTV dosimetry data are show in Figure 27. The eviQ recommendations for organs-at-risk (OARs) are given in absolute dose and are specific to the planned fractionation. For two fraction plans, the dosimetric results for the spinal cord PRV are shown in Figure 28 and the oesophagus results are shown in Figure 29. For the other fractionation schedules, one or both hospitals had insufficient plan numbers for comparison.

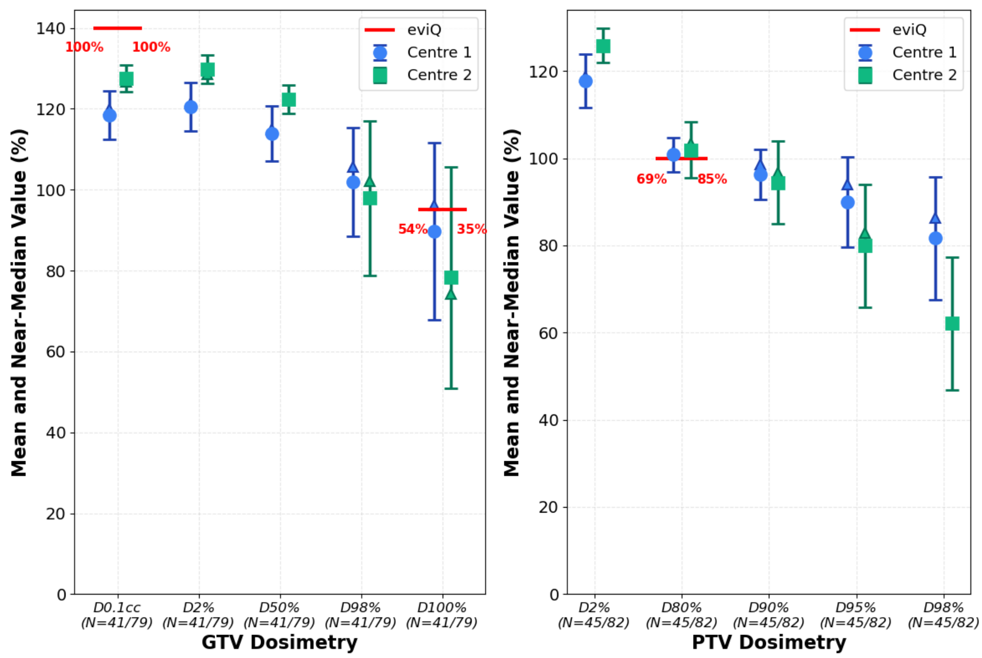

Figure 27: GTV and PTV data from Centres 1 and 2 for 2023-2024. Mean values are shown as a circle (Centre 1) and a square (Centre 2), lines representing 1 SD and a triangle showing the near median. The red lines indicate the eviQ recommended level and the percentages of plans from each centre satisfying that requirement are shown in red.

Table 15: Percentage of plans at Centres 1 and 2 satisfying the eviQ recommendation for 2021-2022 and 2023-2024. The recommendations require that GTV D100% optimal value is >100% with >95% a minor deviation (both are listed), and that PTV D80-90% should equal 100% (both 80% and 90% are listed). Abbreviations: Gross tumour volume (GTV), Linear Boltzmann Transport Equation (LBTE), Flattening filter free (FFF), Cone beam computed tomography (CBCT) Spinal cord (SC)

Spine SABR Results

	Centre 1				Centre 2			
	2021-2022		2023-2024		2021-2022		2023-2024	
Metrics assessed	Plans (%)	Plans Assessed	Plans (%)	Plans Assessed	Plans (%)	Plans Assessed	Plans (%)	Plans Assessed
Scanned with slice thickness ≤2 mm	77	35	85	46	98	103	100	84
Scanned supine	100	35	100	46	98	103	100	84
Targets contoured following consensus guidelines	42	31	44	45	93	90	96	78
Treated with a superposition/convolution or Monte Carlo or LBTE dose algorithm	100	35	100	46	100	103	100	84
With MRI images using T1 or T2 sequence	66	35	87	46				
With MRI or CT myelogram taken less than 4 weeks prior to simulation CT	91	23	100	40				
Treated within 14 days of simulation	20	35	26	46	30	92	28	79
With MRI or CT myelogram taken less than 8 weeks prior to the start of treatment	91	23	100	40				
Treated with 6-10MV	100	35	100	46	100	103	100	84
Treated with FFF	14	35	80	46	100	103	100	84

Treated robotically or with dynamic MLCs.	100	35	100	46	100	103	100	84
With a dose grid ≤2mm	94	35	100	46	97	103	100	84
Treated with CBCT imaging	86	35	100	46	100	98	100	83
PTV-CTV margin 2-3 mm (inclusive)	48	27	51	41	77	95	82	82
CT scans with ≥10 cm from target to scan end	94	31	87	45	85	96	92	82
With eviQ Prescription	89	35	85	46	99	103	100	84
GTV D100% >100% Presc. Dose	41	29	44	41	37	93	35	79
GTV D100% >95% Presc. Dose	52	29	54	41	42	93	35	79
GTV D0.1cc ≤140% Presc. Dose	97	29	100	41	100	93	100	79
PTV D90% > 100% Presc. Dose	38	31	33	45	34	96	30	82
PTV D80% > 100% Presc. Dose	74	31	69	45	80	96	85	82
GTV D2% > PTV D2%	93	29	98	41	99	93	100	79
SC PRV Dmax below threshold	75	24	73	44	76	79	68	69
SC PRV D0.035cc below threshold	71	24	77	44	92	79	90	69
Oesophagus D0.035cc below threshold	100	16	95	38	79	48	88	40
Satisfying all dosimetric eviQ recommendations	0	35	20	46	23	103	14	84
Satisfy all non-dosimetric eviQ recommendations	0	35	2	46	23	103	19	84
Satisfy all eviQ recommendations	0	35	0	46	3	103	4	84
Number of patient plans with 1 fraction	0		1		22		21	
Number of patient plans with 2 fractions	13		19		79		63	
Number of patient plans with 3 fractions	7		6		2		0	
Number of patient plans with 4 fractions	0		0		0		0	
Number of patient plans with 5 fractions	14		20		0		0	

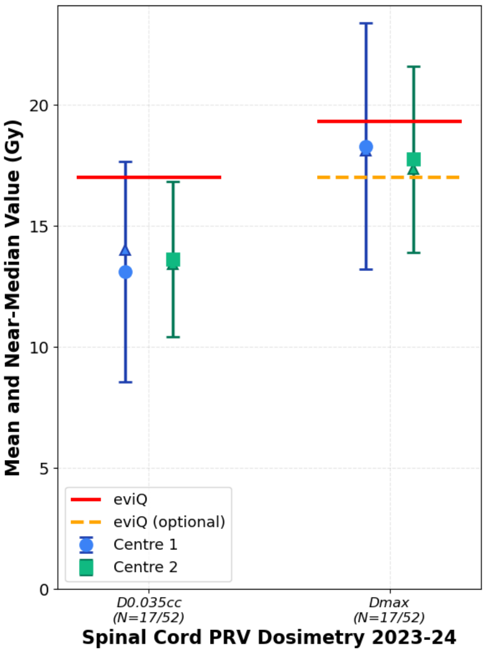

Figure 28: Spinal Cord PRV dosimetric results for two fraction plans, with the eviQ recommended tolerances for two fraction treatments shown.

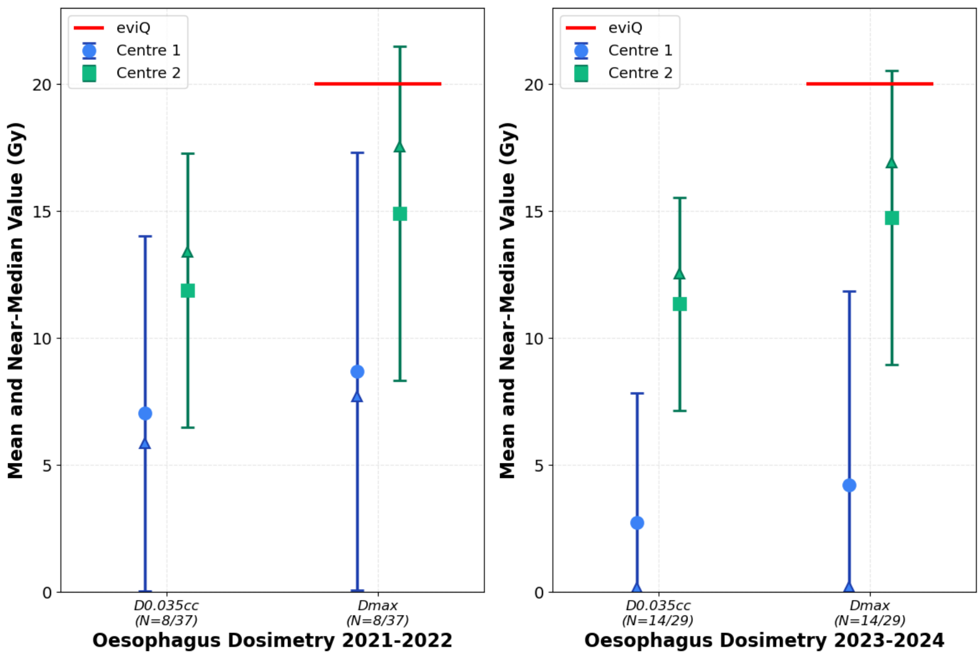

Figure 29: The 2021-2022 and 2023-2024 oesophagus dosimetric results for two fraction plans, with the eviQ recommended tolerances for two fraction treatments shown.

The target and spinal cord PRV graphs show similar results for both centres. The average and near-median oesophagus $D_{0.035cc}$ and D_{max} doses were lower at Centre 1 for 2023-2024 compared to 2021-2022. This is likely due to the introduction of AI contouring at Centre 1 in June 2023, with the oesophagus contoured for all patients when present in the planning images, even if distant from the PTV. The oesophageal doses were also found to be higher, at Centre 2 compared to Centre 1, across both time periods. This difference may be due to differing numbers of patients with targets close to the oesophagus. Data on the location of the targets could not be extracted to determine if this was indeed the cause.

Potentially more important as part of this audit is the number of plans where the eviQ recommended doses were not achieved, as show in Table 14. Centre 2 had 13% more plans exceeding the eviQ oesophagus dose limits compared with Centre 1 across both time periods.

Centre 1 had more plans which exceeded the spinal cord PRV recommended limit. The Centre 1 planning protocol aligns with the eviQ recommendations for 1 and 2 fraction treatments but the Centre 1 protocol did not contain a planning aim for the spinal cord PRV dose for 3-5 fraction treatments. 81% of the plans at Centre 1 found to have deviated from the protocol for this metric were for 3-5 fraction treatments. A documented planning aim may have reduced the number of plans exceeding the eviQ recommendations. The treatment protocol at Centre 1 is currently being reviewed based on these results.

Considering the non-dosimetric metrics, the audit results show that neither centre is routinely achieving the recommended 2-week simulation to treatment timeline recommended by eviQ. A review of the data at Centre 1 showed this was, at least partially, due to MRI availability. Considering instead the time from the latter of the MRI or CT to treatment, the near median for 2023-2024 dropped to 15 days, 3 days lower than calculated just from the CT date. At Centre 2, the planning timeline is accelerated only for a subset of spine SABR patients based on clinical evidence. As this is not part of the eviQ protocol, this was not considered in this study. However, further investigation into the data is planned at Centre 2 to determine if this is the cause of the longer average simulation to treatment times.

The auditing of the contours for each patient was performed manually, but with the process significantly expedited through the production of Portable Network Graphic (PNG) image files which displayed the contours and CT image outside of the treatment planning system. An initial review was performed by a medical physicist at each centre with a final review performed by a radiation oncologist at Centre 1. The contouring at Centre 1 was only found to be complying with the protocol in 44% of cases, compared to 96% at Centre 2 (2023-2024). The main reasons for the contouring being rated as non-compliant at Centre 1 were that the CTV or GTV had not been contoured or that the CTV was created as a geometric expansion of the GTV cropped to the extent of the bone, rather than including the parts of the vertebra specified in the recommendations.

The CTV to PTV margins were less likely to satisfy the eviQ protocol at Centre 1, with 46% of plans having a margin greater than 3 mm in the 2023-2024 time period. Plans at Centre 2 also failed to satisfy this requirement with 12% of CTV to PTV margins smaller than 2 mm and 6% of CTV to PTV margins larger than 3 mm for (2023-2024). It is worth noting that a single margin value is reported for each contour set, calculated as the difference in the bounding boxes of the CTV and PTV contours. This simple calculation cannot describe a complex, non-uniform expansion as might result from manual adjustment of the PTV. Such changes are not allowed for in the eviQ protocol and may account for some of the margins found to be non-compliant.

The prescription data is shown in Table 16. The largest standard deviation in the average prescription dose was for the 5 fraction plans. Similarly, the majority of plans not meeting the eviQ recommendations were also the 5 fraction plans. The 5 fraction plans which did not satisfy the eviQ protocol were all prescribed a dose less than 30Gy. Comparing the two centres, Centre 2 uses fewer fractions for SABR spine patients compared to Centre 1.

Table 16: The mean, standard deviation (SD) and near median dose (Med) values in Gray prescribed at both Centres for 1, 2, 3 and 5 fractions.

	Centre 1						Centre 2					
	2021-2022			2023-2024			2021-2022			2023-2024		
Fr	Mean	SD	Med	Mean	SD	Med	Mean	SD	Med	Mean	SD	Med
1							19.5	1.7	20.0	20	0.0	20.0
2	23.7	1.1	24.0	24.0	0.0	24.0	24.0	0.0	24.0	24.1	0.5	24.0
3	27.4	1.9	27.0	27.0	3.0	27.0						
5	30.0	2.7	30.0	28.8	3.5	30.0						

Both centres used 6 and/or 10MV beams for treatment, as required by the protocol. However, it is notable that 90% in 2021-2022 and 92% 2023-2024 of SABR spine plans at Centre 2 were treated with 10MV alone, compared to 3% in 2021-2022 and 13% in 2023-2024 at Centre 1. Both centres have good access to both energies and 10FFF is used by default at Centre 2. At Centre 1, 10FFF was not available in conjunction with stereoscopic kilovoltage imaging until February 2024, explaining their preference of 6FFF before this time. The data does not indicate that Centre 1 has switched to using 10FFF after this date. The continued preference for 6FFF could be attributed to habit or plan quality. Data from more centres in the future may show a preference not visible in the current data.

Comparing the data from 2023-2024 with the earlier two-year period at Centre 1, the use of FFF for SABR spine plans increased 66% and 6MV-alone plans decreased by 45%. This can also be attributed changes in treatment equipment at Centre 1 in 2024. Data from Centre 2 show little change in the beam energies used with all plans using FFF beams in both time periods.

At Centre 1, the use of T1/T2 MRI imaging increased 21% and the use of CBCT increased 14%, to 100% between the two time periods. The MRI data are not currently available for Centre 2 and no change was observed in the number of treatments which used CBCT.

The changes with time noted at Centre 1 reflect the increased availability of or access to technological improvements and do not appear to indicate any change in practice due to the release of the eviQ protocol in November 2022. No large changes in practice were observed at Centre 2. Potentially, the treatment protocols at both centres referred to the evidence synthesized into the eviQ protocol, and therefore no change in practice was required.

9.5 DISCUSSION

This work has demonstrated that automated auditing of radiation therapy treatments against published standards is possible. In this instance, the ACDN Distributed Learning Network provided the digital infrastructure, however the processes used were based on freely available software and could be replicated by organisations or centres wishing to complete their own clinical audits of radiation therapy treatment records.

Audit Framework

The audit framework created in this work has successfully been used to audit SABR spine patients from two hospitals. All data were extracted digitally and automatically analysed, with the exception of the contours, which were visually reviewed using specifically created image files. However, it was not possible for this study to assess the following items reference by the eviQ protocol:

- the suitability of the patient for spine SABR
- the diagnostic information availability
- the immobilisation used
- the dose conformity (D2cm <50%)
- the alignment of treatment verification images
- the treatment verification imaging protocols
- the recommendations to 'consider'.

While the eviQ spine SABR protocol is evidence-based, it is difficult to determine which of the recommendations in the protocol are likely to affect patient outcomes, and therefore importance of these missing items relative to the audited items, or to each other.

One method to assess these items in the future would be to review the local clinical protocols and patient pathways as part of the audit. While the purpose of this audit was to assess individual spine SABR treatments, a review of the local protocols could identify reasons for non-compliance with the eviQ protocol and provide further details. For example, CBCT imaging was used for 100% of patients at Centre 1 in 2023-2024 but, at this stage, the timing and action thresholds of this imaging could not be assessed. An assessment of the relevant protocols and/or discussions with treatment staff may provide more detailed information.

Some data could not be extracted at Centre 2 using the methods shown in Table 14, potentially alternate methods may have resolved this. Table 14 outlines potential alternate extraction methods that could be used for future audits and for the expansion of this audit into other centres. In general, the listed future extraction methods focus on extraction from the DICOM files and SQL queries of the OIS. The use of such methods should ensure more consistent processes across hospitals, simplifying and standardising data extraction.

Limitations and Challenges

Some limitations and challenges were found in performing this audit which should be accounted for in future work. This study includes four years of patient data. At Centre 1, the planning system used for spine SABR changed during this time. Data from the MRI for planning could not be extracted from the earlier planning system, and, as such, these patients were excluded from the analysis for MRI related recommendations.

The assessment of the doses received by the organs-at-risk in this study was limited to the spinal cord PRV and oesophagus. The eviQ protocol contains dose constraints for 16 other OARs. These were not assessed in this study as the number of patients with a significant dose to each OAR was likely to be too low to produce meaningful conclusions. Future studies looking at the treatment of other sites are likely to have larger patient numbers, and therefore more OARs could be considered. Additionally, future studies could evaluate the dose to all OARs for internal review, with only summarised data for certain OARs shared between centres for comparison.

From a technical perspective, 5 of the identified patients at each centre could not be converted into Neuroimaging Informatics Technology Initiative format (NIfTI) and JavaScript Object Notation (json) files for analysis by PyDicer, due to unusual structure naming. Future versions of PyDicer could be adjusted to accommodate structure names containing characters which cannot be used in computer file names.

A challenge for this study was the identification of eligible patients (those meeting the inclusion criteria). The eviQ consensus protocol is indicated for patient with oliometastic disease and spinal metastases from a solid primary tumour. However, not all patients meeting these criteria will be treated stereotactically. Stereotactic or SABR treatments have been defined as a high dose, hypo-fractionated treatment that is image guided (195-197). In a modern radiation therapy centre, many non-stereotactic spine treatments would be hypo-fractionated and image-guided, and the term "high dose" may be interpreted differently at different centres. Some publications have specified that stereotactic radiation therapy should spare organs at risk, such as the spinal cord, or have steep dose gradients (17, 198). These criteria may help to refine our definition but is still vague and difficult to assess without reviewing individual plans. Finally, the definition of what constitutes a stereotactic treatment may change over time and the retrospective assessment of plans may be biased to exclude plans which were considered stereotactic at the time.

In this study, Centre 1 selected plans based on their referral for a stereotactic physics check, refined based on the location of the target. Centre 2 identified plans based on the treatment site and treatment technique reported to the Victorian Radiotherapy Minimum Data Set (194). The differences in practice between centres necessitated flexibility in the methodology used. It is, however, important to note that these differences may contribute to differences between the data from centres.

Another challenge was the identification of the relevant PTV and OARs for analysis. Patients being treated for spinal metastases may also have other targets treated concurrently. As a result, structure sets containing the spine target volumes will often contain other target volumes, as well. Some patients may have boost targets within the lower dose PTV. For patients having multiple spinal metastases treated, the spinal cord PRV dose may be the dose limiting OAR structure for one plan but the cauda equina more relevant for another target. The correct structures for analysis were identified using a variety of methods including the target name, the median and maximum dose received and by visual review.

Inconsistent naming of structures has been identified as a challenge in previous publications (199-202). This was also found to be an issue in this work. The naming of the oesophagus was found to be consistent and predictable. However, the naming of the spinal cord structure PRV was not. Improved processes could increase consistency in future data but cannot easily correct existing data.

Previous studies using the ACDN network have taken a subset of patients for analysis. This work is different, aiming to assess all patients in the cohort to avoid bias and ensure all relevant patient data are reviewed. It was therefore important to minimise the data which could not be extracted or assessed.

As some of the assessment was based on the presence or absence of a particular item in the treatment record, it was important to ensure data was not marked as missing incorrectly. For example, if a spinal cord PRV was not identified by the audit process, it may not exist or it may not have been identified based on the naming as the spinal cord PRV. To avoid such errors, any missing data was manually verified against the OIS or TPS. This was achievable for this data set. For audits of larger data sets, it may be necessary to spot check rather than verify the data in each plan.

Automated Auditing

This work represents, to this author's knowledge, the first independent, automated clinical audit of this type and breadth conducted of real-world patient records in radiation oncology. It provides a new template for the review of patient treatments, which is less laborious and allows for more treatments to be audited compared to previous methods.

The importance of routine and frequent checks and reviews to ensure the quality of radiation therapy treatment has been established (38) with compliance with quality indicators associated with increased survival (203). Such audits aim to increase the quality and safety of radiation therapy through external review (13, 185). Internationally, several networks have been established to perform such clinical audits, but this is not common nor are the audits simple to perform (13, 185, 186).

In Belgium, national audits are conducted by on-site auditors every 5-6 years, with the gathering of accurate and comprehensive data found to be complex and challenging (185). The IAEA conducts quality audits globally, auditing 77 centres in ten years (13) based on voluntary requests, and covering countries with varying financial resources. A recent study reviewed the clinical audits available in Europe (186) finding that systematic audit pathways were underdeveloped and that data collection was inconsistent and burdensome, suggesting that this could be improved by an enhanced digital, automated infrastructure.

Looking at treatment practices more broadly, digital data are being used to review treatment practices, with audits of Victorian databases being used to assess the patterns of care for pancreas cancer (204), including the use of radiation therapy. However, these audits do not include detailed review of dose prescription, dose distribution, treatment verification imaging or contouring which have been shown to be valuable measure of treatment quality related to patient outcomes. In-depth reviews of digital data for patients enrolled in clinical trials have been reported (205-207) however these reviews target specific parameters related to features that may impact on the trial conclusions, with data representing only patients eligible for the study. The auditing processes discussed in this chapter aim to target entire population groups so that centres may self-assess their performance against those of other centres or consensus guidelines.

Recently Liu et al (208) reported on a knowledge-based anomaly detection algorithm designed to prioritize plans for clinical audit. This implementation reduced the overall auditing time and preferentially identified plans with the greatest potential for improvement. The work presented here goes beyond this, reviewing all plans in the selected cohort against a published standard using an automated process, that could be used across multiple radiation therapy centres. This type of audit, covering all patients, should be better able to separate systematic from aberrant planning errors, focussing quality improvement on the most prevalent issues.

The differences between this audit and a traditional audit are demonstrated by comparing this work to the well-documented audit process of the IROCA project (38, 183, 209), Table 17.

This comparison shows the large time savings this new approach can bring to clinical audits. In addition, the ability to audit all, or nearly all, patients ensures a more complete review of practice. These two methods are, however, not mutually exclusive. An automated audit could be used to ensure a large proportion of patients are reviewed while also highlighting patients which should be investigated further, in a similar way to the algorithm based method described earlier (208).

Table 17: Comparison of the IROCA in-person audit (38). This audit and possible future audits utilising digital data extraction and analysis.

	IROCA in-person audit	This automated audit	Future automated audits
Technological requirements	None	ACDN SQL and DICOM infrastructure	Ability to query OIS, DICOM extraction technique, Python code
Centres involved	6	Currently 2	Large numbers possible
Patients audited per centre	40 (maximum)	80 (Centre 1), 105 (Centre 2)	Large numbers possible
Training required	Two days (full team)	Initially several days but decreasing (1-2 people)	Potentially 2 hr or less
Time to perform audit	At least 2 weeks (full team)	2-4 hrs (plan number and hardware dependent)	Estimated 2 hr to 3 days
Patient outcomes reviewed	Yes	Not currently	Through OIS query or external databases

An example of a combined automated and manual audit has been performed by the U.S. Veterans Health Administration (VA) (210). DICOM files were assessed against dosimetric quality metrics using custom software, while assessors extracted data from medical records, in a process which took one week to assess 50 cases. However, as the VA have recently developed new data extraction and storage systems for their quality surveyance program (211), further automation of these quality processes is now highly feasible.

In the audit presented here, all data were assessed automatically with the exception of the contours. The contour review process was simplified and expedited in this work but still required manual review. In the future, this may not be necessary. Chlap et al (212) have recently shown that protocol-violating contours can be detected automatically using artificial intelligence (AI) in a trial setting. A similar process could potentially be expanded to clinical audits as well with the potential for AI to be used in other aspects of the as well.

The use of MRI for spine SABR patients was not assessed at Centre 2. Additional customised data extraction would have been required to assess metrics relating to these data. Resources were not available to complete this work. Despite this, the patient treatments were able to be assessed against the other metrics, and the audit results can be updated in the future to include this when the resources become available.

A review of eight representative radiation therapy treatment protocols on the eviQ website showed that the methods used in this work could be adapted to audit most of the requirements of these protocols. Metrics not assessed in this work are considered in Table 18. Additional resources would be required to create and perform automated audits for additional sites but less than would be required to perform such audits manually. Potentially the most challenging and most important data required would be complex target and OAR contours. In this work an image file was produced to simplify the process of reviewing contours. However, studies looking at head and neck cancer may require additional information allowing larger and complex contours based on multi-modality imaging to be reviewed (213).

Table 18: Metrics or Requirements to extend this work to cover other eviQ protocols, and the potential availability of this data.

Example Treatment Site	Metric or Requirement	Availability
Head and Neck, Liver SABR	Fractions treated per time or gap between fractions	Scheduling information available with SQL query
Head and Neck, Breast	Complex target contouring	Further visualisation images could be produced. Multimodality images may be required for Head and Neck.
Rectum, Lung	Organs-at-risk contouring	Automated processes could assess length/extent in addition to contour review images
Brain	Additional dose metrics (conformity, gradient indices)	Can be calculated from DICOM data
Liver SABR	Motion management (4DCT or breath-hold use)	4DCT use can be accessed using the methodology used to assess MRI at Centre 1. The use of breath-hold should be recorded and available, but the location may differ between centres.

Table 17 also shows that this audit did not include a review of patient outcomes. The eviQ protocol does not include recommendations for baseline clinical data reporting or expected clinical outcomes for comparison but such data could be used for intercomparisons between centres and to investigate correlations between treatment and outcomes. Future work is planned to use the registry database connections incorporated into the ACDN network to extract outcomes data for such comparisons.

Unlike traditional auditing methods, augmentation or adjustment of the quality indicators used in an automated audit would be reasonably simple. This would allow the audit to be re-run on the same patient records if new recommendations or new trial results show additional or different quality indicators should be used. The audit method could also be re-applied to more recent patient data to look for improvements or changes in protocol compliance.

9.6 CONCLUSION

Using the ACDN network infrastructure, a framework for performing automated clinical audits was established. This framework was used to audit up to 23 metrics for all SABR spine patients treated at two radiation oncology centres in the selected time frame. To this author's knowledge, results from an automated clinical audit of this type have not previously been published. This work succeeded in auditing all patients referred for a specific treatment, not just those enrolled in a trial or randomly selected. This type of audit will both complement and enhance existing clinical audits, allowing more patients to be reviewed with less staff resources. Expansion and refinement will further increase the utility of this framework.

9.7 POSTAMBLE

This chapter aimed to address Research Question 7 by establishing a framework for an audit of spine SABR patients across multiple centres.

Research Question 6:

Can the ACDN research framework be used to simplify the auditing of patient treatments against published standards, such as eviQ?

Key Findings from this Chapter:

- The ACDN digital framework can and has now been used to conduct an automated audit of patient treatments against published standards.
- The audit provided valuable information about current and past practice to the centres involved, potentially leading to changes in practice and improved quality.
- The potential exists to expand on the data extracted and analysed to make future audits more comprehensive. Outcomes data could be included in this and future audits.

Summary:

The treatment of Spine SABR patients between 2012-2024 was automatically audited using digitally extracted data. This provides a framework for future audits, using readily available infrastructure and software solutions.

CHAPTER 10

Discussion, Future Work and Conclusions

10.1 SUMMARY

The work in this thesis aimed to identify barriers to the safe, high-quality and timely implementation of new technologies and techniques into New South Wales (NSW) radiation oncology centres and implement targeted projects to address these barriers.

Previous studies have shown that improvements in the technology and techniques used in radiation therapy can increase tumour control (214) and patient survival (215, 216). It follows that further technological advances in the future may lead to additional survival benefits. To ensure these potential benefits are realised, such advances need to be implemented into clinical practice while maintaining high levels of quality and safety. It is therefore essential that new technologies and the techniques they enable are available in a timely manner, in a high quality and safe way, across NSW, ensuring that all patients benefit from these improvements.

Data show that the incidence of cancer in Australia is rising and that cancer mortality rates are decreasing (217); together these trends have led to an increased number of cancer survivors (217). With more people surviving and living longer after treatment, reducing long-term treatment toxicities is becoming more important, in order to preserve patients' quality of life. Historically, new techniques enabled by new technologies have led to reduced toxicity (215, 218) improving the quality of life for survivors of cancer. Future technological improvements, implemented safely into practice, are essential to further minimise long-term toxicities for NSW radiation therapy patients.

As the number of people with cancer increases, the number of patients requiring radiation therapy also increases. This increased demand will require the purchase of additional radiation therapy equipment and an increase in the workforce, but radiation therapy services will also need to become more efficient to treat this higher number of patients with the limited resources available. Advances in technology and treatment techniques have the potential to safely treat more patients in less time and with less resources and may provide the efficiency gains required to meet the additional demand. However, risk management strategies need to be in place to ensure that patient safety is not compromised at the expense of rapid access to new techniques and technologies.

To summarise, advanced technologies and techniques have the potential to increase patient survival and tumour control, decrease side effects and provide the necessary increase in the capacity of the NSW radiation therapy services to treat the increasing number of patients. It is therefore essential that technological improvements are implemented in a timely manner across NSW, while maintaining safety and quality, to ensure equity and the best outcomes for our patients.

The initial chapters of this thesis assessed the quality and timeliness of these implementations and identified a number of issues and barriers. The implementation of the stereotactic ablative body radiotherapy (SABR) technique was found to be delayed at some centres, particularly in regional areas. While the implementation of SABR was generally in line with recommendations, areas for improvement were identified. The latter part of the thesis describes the targeted interventions created to address the identified issues and to improve the speed and quality of technological implementations.

In contrast to some other states in Australia, NSW has a large number of small radiation oncology centres (typically 2-3 linacs/centre). While formal connections between centres do exist, many centres operate independently leading to a situation where each centre will separately, and potentially concurrently, implement new techniques and technologies, independently climbing similar learning curves. Several projects to increase cross-centre collaboration were investigated in this thesis.

Knowledge-based planning is a technological innovation designed to increase efficiency and consistency in treatment planning. A collaborative, multidisciplinary, NSW-wide group was formed to help with the implementation of knowledge-based planning using the Varian treatment planning system. A research project was designed within this group to determine how best to work collaboratively on this implementation, potentially sharing knowledge-based models. This project showed that collaboration between centres was beneficial, increasing the knowledge of those involved and potentially expediting the implementation process, but can also be limited by differences in practice between centres and administrative barriers.

A second project, a collaboration between the ACPSEM and the University of Sydney, lead to an online workshop addressing the community need for practical knowledge on motion management for radiation therapy. This workshop allowed collaboration between centres, sharing practical experiences and, potentially, increasing the speed and quality of motion management at the attendee's centres.

The investigations into the implementation of SABR in NSW determined that formal risk assessment processes were not routinely carried out in the centres surveyed. The AAPM published the report of Task Group 100 (172) in 2016 which was largely based on the Failure Modes and Effects Analysis (FMEA). Since then, alternate modes have been proposed but none have become commonly used in NSW. To address this, a training program was introduced focused on prospective risk assessment. This program succeeded in providing training to most radiation therapy centres in NSW and increased the use of formal risk assessments.

To further increase collaboration and assist with the timely implementation of new technologies and techniques, a collaborative online platform was developed to facilitate knowledge-sharing between radiation therapy centres. This platform has the potential to expand, allowing further knowledge-sharing and for multidisciplinary collaboration with the agility required to remain relevant in the fast-changing area of radiation oncology.

Finally, a pilot study for automated auditing of patient treatments was completed. This pilot study demonstrated a new way to assess the quality of patient treatments in a quick and adaptable way, focussing on the ability to perform self-assessment against published standards. This automated method of conducting clinical audits can be extended to new treatment techniques quickly, providing up-to-date feedback on quality during the early stages of implementation.

This chapter summarises the results of the work presented in this thesis, synthesises the findings, discusses recent relevant publications and presents future work which will follow this thesis.

10.2 SYNTHESIS OF FINDINGS

Equity in healthcare requires that everyone has access to the highest level of healthcare. Unfortunately, the implementation of SABR treatments into NSW radiation therapy centres was delayed compared to some other countries. In 2019, the CHISEL phase III trial provided clinical evidence of superior local control in stage 1 inoperable non-small cell lung cancer using a SABR technique compared with standard radiotherapy. SABR for lung cases was not available until 2021 in some areas of NSW (Chapter 3). As a result, some patients will have travelled long distances to receive this new treatment technique or instead receive a longer course of standard radiation therapy at their closest radiation therapy centre.

Following the work presented in Chapter 3, Burton et al. surveyed Australasian centres about their respiratory motion management practices (96) to inform the creation of a new dosimetric audit. While this survey did not provide information on the timing of implementation of motion management techniques, differences were observed between the practices of regional and metropolitan centres.

Studies looking at the timelines of implementation of new techniques and planned future directions of practice, similar to those seen in Chapter 3, are rarely published but are vitally important. They allow the assessment of equity and availability of up-to-date treatments, and for the planning of future training and collaborative projects. The collection and publication of these types of data from across the country could benefit health care professionals and highlight inequities in the current system. Unfortunately, government-run nation-wide surveys are unlikely to occur as health care is provided by state governments in Australia. It will therefore be important for researchers to identify new practices and perform ad-hoc surveys, informed by previous works (Chapter 3).

Following on from the practice survey in Chapter 3, the work in Chapter 4 investigated the quality and safety of the implementation of the SABR technique in NSW radiation therapy centres. The implementation was found to comply with RANZCR recommendations (17) in most areas, but with improvement required in the areas of auditing, risk assessment, reporting and the review of clinical outcomes. During this investigation, staff interviewed described how a lack of coordination between centres resulted in the same work being replicated at each centre. Radiation therapy professionals felt they had a lack of support from other centres in the implementation of new techniques and technologies, and struggled with knowledge transfer and gaining practical experience.

Since the publication of the work in Chapter 4, no similar audit-style evaluations have been published in Australia. Shaw et al (219) reported the introduction of comprehensive dosimetric audits for SABR treatments in Australasia. Pilgrim et al (204) looked at the treatment of pancreas cancer within Victoria using government databases. This study was, in some ways, similar to that described in Chapter 9 of this thesis, but looking at a higher level and only considering whether radiation therapy was or was not used in treatment. A long-term solution to the lack of comprehensive auditing, particularly when implementing new techniques and technologies, needs to be found. The work presented in Chapter 9 seeks to address this and is discussed later in this chapter.

The lack of coordination and cooperation across centres highlighted by those interviewed for the study in Chapter 4 led to the collaborative, knowledge-sharing projects in Chapter 5 and Chapter 6. Chapter 5 described the results of a collaborative project between three radiation therapy centres to share knowledge-based treatment planning models aiming to reduce the implementation work required for individual centres and ensure better treatment plans were available to patients more quickly. This collaborative work provided internal benchmarking for the centres involved and mentoring for one centre with limited experience in building knowledge-based treatment planning models. The study found, however, the ability to use shared models was limited by the different treatment aims of each radiation therapy centre. More broadly, this work shows that differences in practice may make the sharing of resources between centres difficult, as these resources may not align with the needs of the centre. Successful sharing may require a preliminary stage to first align practice, with resources designed to allow for differences between centres and changes in practice, similar to the methods used by the Victorian Rapidplan consortium (220). Sharing may also be more successful between centres with similar equipment or in specialized areas where patient numbers may be low and the ability to build a generalisable model limited.

A more qualitative sharing approach was presented in Chapter 6. In this chapter, Australasian centres shared their experiences and expertise through a workshop on motion management. The workshop was successful due to the relevance of the topic at that time and had the potential to improve the quality of radiation therapy delivery, while the online format allowed equal access to all centres. Previously, similar workshops have been held looking at cranial stereotactic radiotherapy (221) and quality management (222) in Australia. As new technological advances become available, it will be important to continue these workshops aiming to make the implementation of new techniques and technologies faster and easier for late adopters and promoting safety and quality in practice for all. This will require proactive horizon scanning and knowledge of the current implementation projects across the region. It is also important to devise ways to ensure these learning opportunities can be available in the future so that centres can apply these resources when they are ready to implement these new techniques.

Chapter 7 outlines another collaborative project instigated by the work in Chapter 4. The results of Chapter 4 show that prospective risk assessments were rarely performed when implementing SABR techniques. In Chapter 7, knowledge and expertise regarding prospective risk assessments were shared though an innovative, peer-to-peer training program. The training was successful in providing practical skills and tools to radiation therapy professionals throughout NSW, but was most relevant to those who could immediately apply the learning. This work shows that focused knowledge-sharing is effective and can help reduce the knowledge differences between centres. While this style of training requires enthusiastic advocates, it has been shown to be well suited to addressing specific deficits in knowledge and should become one of the standard methods used for addressing knowledge gaps within the workforce.

The COPPER initiative (Chapter 8) uses a different method again to facilitate collaborative learning and knowledge sharing. It was designed to reduce the replication of work across centres, and provide a method to support centres with limited staff resources. The online platform allows the long-term storage and distribution of resources, ensuring resources are available when required. The radiation therapy centre profiles on the platform provide information on the treatment equipment and ancillary equipment including the brand and model, and the techniques in use. This collated, detailed level of information is not available anywhere else within Australia. By providing this information about the equipment and techniques available at radiation therapy centres, it allows centres to form informal networks with others using similar equipment or facing similar challenges, ensuring knowledge-sharing is both relevant and timely. The concept of more formal and coordinated state-wide implementation projects has yet to be explored. Using the same proactive methods described in this thesis, state-wide implementation projects could lead to the safer, quicker and more efficient implementation of new techniques and technologies. Such projects would need to be well managed to avoid potentially delaying some centres who have been early adopters of change in the past. Support structures such as a generalised workshop framework could allow early adopters to more easily share their experiences. It is, however, naïve to assume that inter-centre cooperation would be simple, after decades functioning independently under separate Local Health District (LHD) administration entities. This thesis demonstrated the value of working towards better cooperation in the long-term, while supporting centres to deliver excellent radiation therapy treatment now.

The penultimate chapter in this thesis (Chapter 9) describes a project designed to address the lack of available auditing when introducing a new technique, an issue identified in Chapter 4. This work uses existing research infrastructure to assess current practice against quality standards in a timely, efficient and adaptable manner. The pilot study presented in Chapter 9 is, to this author's knowledge, the first automated clinical audit of non-trial radiation therapy treatments where patient data does not need to leave the radiation therapy centre, and will act as a template for future automated audits. Unlike traditional clinical audits, automated audits allow all relevant patient treatments to be audited, potentially highlighting systemic issues as well as cases which may require further investigation. The increased efficiency of automated audits will allow more audits to be performed and more inter-centre comparison, identifying a greater number of issues and differences in practice than is possible with traditional clinical audits.

However, as the first audit of this type, the work required to extract and analyse these audit data was significant. The differences in infrastructure between the two centres involved and a lack of standardisation required customisation of the data extraction and analysis at each centre. At this stage, outcomes data have not been extracted with the audit data. The use of the ACDN (18) for this project may allow patient outcomes to be correlated with the quality metrics assessed in the audits in the future, identifying factors which particularly affect patient outcomes.

Automated auditing is particularly suited to the rapidly evolving field of radiation therapy. As technology drives changes in treatment, automated audits can provide real time feedback during the early stages of implementation. The adaptability and speed of automated auditing will be particularly beneficial for reviewing existing practice against new evidence or recommendations. The implementation of partial or fully automated audits represents a step-forward in both the quality and safety of radiation therapy.

10.3 FUTURE WORK

The automated audit results in Chapter 9 form part of a continuing project. Based on the experience gained in auditing the first two centres, the auditing method will be refined and expanded to include additional radiation therapy centres, allowing more patient treatments to be audited and providing further information on differences in practice between centres. Further, the connection of the ACDN to state and national registries will allow outcomes data to be added to the auditing records. Future work will look at correlations between patient outcomes and compliance with specific metrics. More broadly, the framework from this pilot study will be used by other researchers to audit additional treatments against quality standards.

The COPPER initiative will also continue. This work will require ongoing effort to change attitudes to sharing and collaboration but should lead to better cooperation between radiation therapy centres, increased sharing of resources and assistance for centres at risk of falling behind technologically.

More generally, following on from this work, it will be important to continue to assess how new techniques and technologies are implemented, looking for areas that require improvement and proactively addressing this. Utilisation of technological resources, such as the ACDN, will allow faster feedback about performance with less strain on human resources. Additionally, the establishment of templates for collaborative projects such as workshops and training programs will simplify the creation of similar initiatives as new techniques and technologies become available. Identification of 'leading centres' may lead to further focused training projects and opportunities for the sharing of experience.

The idea of pre-planning and collaborative implementation should be explored for future state-wide advances. By prospectively working collaboratively, it may be possible to overcome the traditional separation of radiation therapy centres and establish synergistic relationships.

The new techniques and technologies which could benefit from a prospective or planned approach can be categorised by how widespread these technologies are likely to be. Improvements in simulation with the further introduction of MRI and imminent introduction of photon counting CTs are likely to be widespread, eventually becoming standard practice in perhaps all radiation therapy centres. Similarly, software advances including AI-based planning and improved offline and online adaptive treatments are likely to become common place. It is these types of innovations which could benefit most from a coordinated approach, or from collaborative sharing, such as workshops and COPPER. This is in contrast to new technologically-advanced treatment techniques like proton and charged particle therapy, boron neutron capture therapy and FLASH, where the high cost, smaller number of benefiting patients and experimental nature of the technology may limit their implementation to only a few specialised centres. For these techniques, prospective risk assessment and frequent automated quality audits will be very important to ensure high quality treatments. That isn't to say that collaboration does not have a role for these more specialised techniques, but more that the role may need to be adjusted, as the level and use of knowledge required by radiation therapy workers across the state will vary.

10.4 LIMITATIONS

A major limitation of this study is that it was conducted in a specific time, and therefore focused on the technology and techniques relevant during that period. It was not possible to explore projects aimed at long-term change or to corroborate the findings. By continuing the projects outlined in the section above and implementing new projects as technological changes arise, a broader view of the roles of collaborative quality projects could be achieved.

A limitation of this work is that it was written from the perspective of a clinical medical physicist. Whilst several projects incorporated multi-disciplinary participation, future work should aim to balance the perspective across all radiation oncology professions.

10.5 OVERALL CONCLUSION

The work described in this thesis has demonstrated that it is possible to determine barriers to the high quality and timely implementation of new techniques and technology, and successfully implement strategies to address these barriers, improving the quality of radiation therapy available to patients throughout NSW.

Future projects aimed at improving the implementation of new techniques and technology should be targeted on known problem areas and incoming technological changes, but also account for current differences between radiation therapy centres. Automated auditing will allow faster auditing of more patient treatments. It can also be used during new technology implementation to provide a fast feedback process and to correlate outcomes with treatment parameters. Future work should look at how to prospectively address new developments in a collaborative and multi-disciplinary way.

REFERENCES

1. World Health Organization. Cancer: WHO; 2024 Accessed:12/12/2024. Available from: https://www.who.int/news-room/fact-sheets/detail/cancer.

2. Cancer Australia. Cancer in Australia Statistics: Cancer Australia; 2024 Accessed:12/12/2024. Available from: https://www.canceraustralia.gov.au/impacted-cancer/what-cancer/cancer-australia-statistics.

3. Cancer Institute NSW. Cancer Statistics NSW 2024 Accessed:12/12/2024. Available from: https://www.cancer.nsw.gov.au/research-and-data/cancer-data-and-statistics/data-available-now/cancer-statistics-nsw/cancer-incidence-mortality-survival.

4. Australian Institute of Health and Welfare. Cancer data in Australia: AIHW; 2024 Accessed:12/12/2024. Available from: https://www.aihw.gov.au/reports/cancer/cancer-data-in-australia/contents/overview.

5. Cheng M, Jolly S, Quarshie WO, Kapadia N, Vigneau FD, Kong FS. Modern Radiation Further Improves Survival in Non-Small Cell Lung Cancer: An Analysis of 288,670 Patients. J Cancer. 2019;10(1):168-77.10.7150/jca.26600

6. Baumann M, Krause M, Overgaard J, Debus J, Bentzen SM, Daartz J, et al. Radiation oncology in the era of precision medicine. Nat Rev Cancer. 2016;16(4):234-49.10.1038/nrc.2016.18

7. Barton MB, Jacob S, Shafiq J, Wong K, Thompson SR, Hanna TP, et al. Estimating the demand for radiotherapy from the evidence: a review of changes from 2003 to 2012. Radiother Oncol. 2014;112(1):140-4.10.1016/j.radonc.2014.03.024

8. Jaffray DA, Knaul F, Baumann M, Gospodarowicz M. Harnessing progress in radiotherapy for global cancer control. Nat Cancer. 2023;4(9):1228-38.10.1038/s43018-023-00619-7

9. Fiorino C, Guckemberger M, Schwarz M, van der Heide UA, Heijmen B. Technology-driven research for radiotherapy innovation. Mol Oncol. 2020;14(7):1500-13.10.1002/1878-0261.12659

10. Pacelli R, Caroprese M, Palma G, Oliviero C, Clemente S, Cella L, et al. Technological evolution of radiation treatment: Implications for clinical applications. Semin Oncol. 2019;46(3):193-201.10.1053/j.seminoncol.2019.07.004

11. Chetty IJ, Martel MK, Jaffray DA, Benedict SH, Hahn SM, Berbeco R, et al. Technology for Innovation in Radiation Oncology. Int J Radiat Oncol Biol Phys. 2015;93(3):485-92.10.1016/j.ijrobp.2015.07.007

12. World Health Organization. Radiotherapy risk profile: technical manual. Geneva, Switzerland: World Health Organization. 2008

13. Izewska J, Coffey M, Scalliet P, Zubizarreta E, Santos T, Vouldis I, et al. Improving the quality of radiation oncology: 10years' experience of QUATRO audits in the IAEA Europe Region. Radiother Oncol. 2018;126(2):183-90.10.1016/j.radonc.2017.09.011

14. Sundaresan P, King MT, Stockler MR, Costa DS, Milross CG. Barriers to radiotherapy utilisation in New South Wales Australia: Health professionals' perceptions of impacting factors. J Med Imaging Radiat Oncol. 2015;59(4):535-41.10.1111/1754-9485.12334

15. Batista V, Gober M, Moura F, Webster A, Oellers M, Ramtohul M, et al. Surface guided radiation therapy: An international survey on current clinical practice. Tech Innov Patient Support Radiat Oncol. 2022;22:1-8.10.1016/j.tipsro.2022.03.003

16. AlDuhaiby EZ, Breen S, Bissonnette JP, Sharpe M, Mayhew L, Tyldesley S, et al. A national survey of the availability of intensity-modulated radiation therapy and stereotactic radiosurgery in Canada. Radiat Oncol. 2012;7:18.10.1186/1748-717X-7-18

17. RANCZR. Guidelines for Safe Practice of Stereotactic Body (Ablative) Radiation Therapy. Sydney: Faculty of Radiation Oncology, The Royal Australian and New Zealand College of Radiologists; 2015.

18. Field M, Vinod S, Aherne N, Carolan M, Dekker A, Delaney G, et al. Implementation of the Australian Computer-Assisted Theragnostics (AusCAT) network for radiation oncology data extraction, reporting and distributed learning. J Med Imaging Radiat Oncol. 2021;65(5):627-36.10.1111/1754-9485.13287

19. UNSW. Australian Cancer Data Network NSW: UNSW; 2023 updated 8/5/2023 Accessed:17/12/2025. Available from: https://australian-cancer-data.network/.

20. EviQ. Spinal bone metastases palliative EBRT stereotactic St Leonards, NSW, Australia: Cancer Institute NSW; 2022 Accessed:30/4/2025; ID: 4098 v.1:[Available from: https://www.eviq.org.au/radiation-oncology/palliative/4098-spinal-bone-metastases-palliative-ebrt-stereo.

21. Donabedian A. Evaluating the quality of medical care. Milbank Mem Fund Q. 1966;44(3):Suppl:166-206

22. Institute of Medicine (US) Committee on Quality of Health Care in America. Crossing the Quality Chasm: A New Health System for the 21st Century. Washington (DC): National Academy Press; 2001.

23. Albert JM, Das P. Quality assessment in oncology. Int J Radiat Oncol Biol Phys. 2012;83(3):773-81.10.1016/j.ijrobp.2011.12.079

24. Cionini L, Gardani G, Gabriele P, Magri S, Morosini PL, Rosi A, et al. Quality indicators in radiotherapy. Radiother Oncol. 2007;82(2):191-200.10.1016/j.radonc.2006.12.009

25. IAEA. Comprehensive Audits of Radiotherapy Practices A Tool for Quality Improvement: International Atomic Energy Agency; 2007.

26. Radiation Oncology Alliance. Radiation Oncology Practice Standards Part A: Fundementals: The Royal Australian and New Zealand College of Radiologists; 2022.

27. Vaandering A, Jansen N, Weltens C, Moretti L, Stellamans K, Vanhoutte F, et al. Radiotherapy-specific quality indicators at national level: How to make it happen. Radiother Oncol. 2023;178:109433.10.1016/j.radonc.2022.11.022

28. Canadian Partnership for Quality Radiotherapy. Quality assurance guidelines for Canadian radiation treatment programs. 2015

29. Chiew KL, Sundaresan P, Jalaludin B, Vinod SK. A narrative synthesis of the quality of cancer care and development of an integrated conceptual framework. Eur J Cancer Care (Engl). 2018;27(6):e12881.10.1111/ecc.12881

30. Donaldson H, Cao J, French J, Gillan C, Milosevic M, Lam C, et al. Quality standards in radiation medicine. Pract Radiat Oncol. 2014;4(4):208-14.10.1016/j.prro.2013.09.004

31. Wright JL, Terezakis SA, Ford E. Safety First: Developing and Deploying a System to Promote Safety and Quality in Your Clinic. Pract Radiat Oncol. 2021;11(2):92-100.10.1016/j.prro.2020.05.002

32. The Tripartite Committee. Radiation oncology practice standards. RANZCR, Sydney. 2011

33. Radiation Oncology Alliance. Radiation Oncology Practice Standards Part A: Fundamentals: The Royal Australian and New Zealand College of Radiologists; 2017.

34. Salma N, Vysakh R, Ranjith C, Anjana P, Gupta T, Laskar S. Structural Quality Indicators in Radiation Oncology: Insights and Implications. Clinical Oncology. 2025;38:103624

35. Manjali JJ, Gupta T, Vinod S, Agarwal JP. Bridging Gaps in Cancer Care With Quality Indicators in Radiotherapy. Clinical Oncology. 2025;41

36. Harden SV, Chiew KL, Millar J, Vinod SK. Quality indicators for radiation oncology. J Med Imaging Radiat Oncol. 2022;66(2):249-57.10.1111/1754-9485.13373

37. Buckley JG, Wilkinson D, Malaroda A, Metcalfe P. Investigation of the radiation dose from cone-beam CT for image-guided radiotherapy: A comparison of methodologies. J Appl Clin Med Phys. 2018;19(1):174-83.10.1002/acm2.12239

38. Torras MG, Fundowicz M, Aliste L, Asensio E, Boladeras AM, Borras JM, et al. Improving radiation oncology through clinical audits: Introducing the IROCA project. Rep Pract Oncol Radiother. 2017;22(5):408-14.10.1016/j.rpor.2017.07.004

39. Weber DC, Poortmans PM, Hurkmans CW, Aird E, Gulyban A, Fairchild A. Quality assurance for prospective EORTC radiation oncology trials: the challenges of advanced technology in a multicenter international setting. Radiother Oncol. 2011;100(1):150-6.10.1016/j.radonc.2011.05.073

40. Ibbott GS, Haworth A, Followill DS. Quality assurance for clinical trials. Front Oncol. 2013;3:311.10.3389/fonc.2013.00311

41. Clark CH, Hurkmans CW, Kry SF, Global Quality Assurance of Radiation Therapy Clinical Trials Harmonisation G. The role of dosimetry audit in lung SBRT multi-centre clinical trials. Phys Med. 2017;44:171-6.10.1016/j.ejmp.2017.04.003

42. Nakamura M, Zhou D, Minemura T, Kito S, Okamoto H, Tohyama N, et al. A virtual audit system for intensity-modulated radiation therapy credentialing in Japan Clinical Oncology Group clinical trials: A pilot study. J Appl Clin Med Phys. 2023;24(6):e14040.10.1002/acm2.14040

43. ACDS. Australian Clinical Dosimetry Service: ARPANSA; Accessed:5/12/2023. Available from: https://www.arpansa.gov.au/our-services/testing-and-calibration/calibration/australian-clinical-dosimetry-service.

44. AAPM. Safety Profile Assessment (SPA) Alexandria, VA: American Association of Physicists in Medicine; Accessed:16/9/2025.

45. Ritter T, Balter JM, Lee C, Roberts D, Roberson PL. Audit tool for external beam radiation therapy departments. Pract Radiat Oncol. 2012;2(4):e39-e44.10.1016/j.prro.2012.03.011

46. Atwell DB, Booth C, Vignarajah DD, Knesl M, Buddle N, Hoozer M, et al. Radiation Oncology Quality Assessment Tool: A proposal for a new audit tool in modern radiation oncology. J Med Imaging Radiat Oncol. 2019;63(5):691-7.10.1111/1754-9485.12928

47. Abratt RP, Rautenbach M, Govender Y, Oelofse I. A quality improvement programme in radiotherapy using workflow audits. S Afr Med J. 2021;111(2):106-9.10.7196/SAMJ.2021.v111i2.15310

48. Le Cornu E, Murray S, Brown E, Bernard A, Shih FJ, Ferrari-Anderson J, et al. Impact of technological and departmental changes on incident rates in radiation oncology over a seventeen-year period. J Med Radiat Sci. 2021;68(4):356-63.10.1002/jmrs.517

49. Giddings A, Nica L, French J, Davis C-A, Smoke M, Bolderston A. Patterns of practice in Canadian radiation treatment centres: results of a national survey. Journal of medical imaging and radiation sciences. 2018;49(1):23-30

50. Kallman P, Lind B, Eklof A, Brahme A. Shaping of arbitrary dose distributions by dynamic multileaf collimation. Phys Med Biol. 1988;33(11):1291-300.10.1088/0031-9155/33/11/007

51. Boyer AL, Ochran TG, Nyerick CE, Waldron TJ, Huntzinger CJ. Clinical dosimetry for implementation of a multileaf collimator. Med Phys. 1992;19(5):1255-61.10.1118/1.596757

52. Klein EE, Harms WB, Low DA, Willcut V, Purdy JA. Clinical implementation of a commercial multileaf collimator: dosimetry, networking, simulation, and quality assurance. Int J Radiat Oncol Biol Phys. 1995;33(5):1195-208.10.1016/0360-3016(95)00198-0

53. Das IJ, Desobry GE, McNeeley SW, Cheng EC, Schultheiss TE. Beam characteristics of a retrofitted double-focused multileaf collimator. Med Phys. 1998;25(9):1676-84.10.1118/1.598348

54. Klein EE, Tepper J, Sontag M, Franklin M, Ling C, Kubo D. Technology assessment of multileaf collimation: a North American users survey. Int J Radiat Oncol Biol Phys. 1999;44(3):705-10.10.1016/s0360-3016(99)00046-2

55. Cho B. Intensity-modulated radiation therapy: a review with a physics perspective. Radiat Oncol J. 2018;36(1):1-10.10.3857/roj.2018.00122

56. Frenzel T, Krüll A. The use of IMRT in Germany. Strahlentherapie und Onkologie. 2015;191(11):821-6

57. Cooper T, Williams MV. Implementation of intensity-modulated radiotherapy: lessons learned and implications for the future. Clin Oncol (R Coll Radiol). 2012;24(8):539-42.10.1016/j.clon.2012.06.004

58. Smith BD, Pan IW, Shih YC, Smith GL, Harris JR, Punglia R, et al. Adoption of intensity-modulated radiation therapy for breast cancer in the United States. J Natl Cancer Inst. 2011;103(10):798-809.10.1093/jnci/djr100

59. Jaffray DA. Image-guided radiotherapy: from current concept to future perspectives. Nat Rev Clin Oncol. 2012;9(12):688-99.10.1038/nrclinonc.2012.194

60. Dolezel M, Odrazka K, Zouhar M, Vaculikova M, Sefrova J, Jansa J, et al. Comparing morbidity and cancer control after 3D-conformal (70/74 Gy) and intensity modulated radiotherapy (78/82 Gy) for prostate cancer. Strahlentherapie und Onkologie. 2015;191(4):338-46

61. Bauman G, Rumble R, Chen J, Loblaw A, Warde P, Panel IIE. Intensity-modulated radiotherapy in the treatment of prostate cancer. Clinical Oncology. 2012;24(7):461-73

62. Trofymov A, Bschleipfer T, Aigner T, Grabenbauer GG. Intensity modulated radiation therapy in prostate cancer—Better survival with higher total dose? Strahlentherapie und Onkologie. 2025:1-9

63. Burman C, Chui C-S, Kutcher G, Leibel S, Zelefsky M, LoSasso T, et al. Planning, delivery, and quality assurance of intensity-modulated radiotherapy using dynamic multileaf collimator: a strategy for large-scale implementation for the treatment of carcinoma of the prostate. International journal of radiation oncology, biology, physics. 1997;39(4):863-73

64. Bak K, Dobrow MJ, Hodgson D, Whitton A. Factors affecting the implementation of complex and evolving technologies: multiple case study of intensity-modulated radiation therapy (IMRT) in Ontario, Canada. BMC health services research. 2011;11(1):178

65. Mayles W. Survey of the availability and use of advanced radiotherapy technology in the UK. Clinical Oncology. 2010;22(8):636-42

66. Bridge P, Dempsey S, Giles E, Maresse S, McCorkell G, Opie C, et al. Practice patterns of radiation therapy technology in Australia: results of a national audit. Journal of medical radiation sciences. 2015;62(4):253-60

67. Banjade D, Allan J, Thuraisingam K, Mishra A, Newham B, Tan SJ, et al. Implementation of advanced radiotherapy technology to improve clinical outcomes in rural NSW. Australian Journal of Rural Health. 2020;28(3):311-6

68. Shen X, Showalter TN, Mishra MV, Barth S, Rao V, Levin D, et al. Radiation oncology services in the modern era: Evolving patterns of usage and payments in the office setting for Medicare patients from 2000 to 2010. Journal of oncology practice. 2014;10(4):e201-e7

69. Shumway DA, Griffith KA, Pierce LJ, Feng M, Moran JM, Stenmark MH, et al. Wide variation in the diffusion of a new technology: Practice-based trends in intensity-modulated radiation therapy (IMRT) use in the state of Michigan, with implications for IMRT use nationally. Journal of oncology practice. 2015;11(3):e373-e9

70. Bak K, Dobrow MJ, Hodgson D, Whitton A. Factors affecting the implementation of complex and evolving technologies: multiple case study of intensity-modulated radiation therapy (IMRT) in Ontario, Canada. BMC Health Serv Res. 2011;11:178.10.1186/1472-6963-11-178

71. Lam W, Partowmah M, Lee D, Wharam M, Lam K. On-line measurement of field placement errors in external beam radiotherapy. The British Journal of Radiology. 1987;60(712):361-5

72. Lam K, Partowmah M, Lam W. An on-line electronic portal imaging system for external beam radiotherapy. The British Journal of Radiology. 1986;59(706):1007-13

73. Ezz A, Munro P, Porter A, Battista J, Jaffray D, Fenster A, et al. Daily monitoring and correction of radiation field placement using a video-based portal imaging system: a pilot study. International Journal of Radiation Oncology* Biology* Physics. 1992;22(1):159-65

74. Michalski JM, Wong JW, Gerber R, Yan D, Cheng A, Graham MV, et al. The use of on-line image verification to estimate the variation in radiation therapy dose delivery. International Journal of Radiation Oncology* Biology* Physics. 1993;27(3):707-16

75. Herman MG, Abrams RA, Mayer RR. Clinical use of on-line portal imaging for daily patient treatment verification. International Journal of Radiation Oncology* Biology* Physics. 1994;28(4):1017-23

76. Jaffray DA, Chawla K, Yu C, Wong JW. Dual-beam imaging for online verification of radiotherapy field placement. International journal of radiation oncology, biology, physics. 1995;33(5):1273-80

77. Jaffray DA, Drake DG, Moreau M, Martinez AA, Wong JW. A radiographic and tomographic imaging system integrated into a medical linear accelerator for localization of bone and soft-tissue targets. International Journal of Radiation Oncology* Biology* Physics. 1999;45(3):773-89

78. McBain CA, Henry AM, Sykes J, Amer A, Marchant T, Moore CM, et al. X-ray volumetric imaging in image-guided radiotherapy: the new standard in on-treatment imaging. International Journal of Radiation Oncology* Biology* Physics. 2006;64(2):625-34

79. Sorcini B, Tilikidis A. Clinical application of image-guided radiotherapy, IGRT (on the Varian OBI platform). Cancer/Radiothérapie. 2006;10(5):252-7

80. Simpson DR, Lawson JD, Nath SK, Rose BS, Mundt AJ, Mell LK. A survey of image-guided radiation therapy use in the United States. Cancer. 2010;116(16):3953-60

81. Batumalai V, Holloway LC, Kumar S, Dundas K, Jameson MG, Vinod SK, et al. Survey of image-guided radiotherapy use in Australia. J Med Imaging Radiat Oncol. 2017;61(3):394-401.10.1111/1754-9485.12556

82. Padayachee J, Loh J, Tiong A, Lao L. National survey on image-guided radiotherapy practice in New Zealand. Journal of Medical Imaging and Radiation Oncology. 2018;62(2):262-9

83. Beaton L, Bandula S, Gaze MN, Sharma RA. How rapid advances in imaging are defining the future of precision radiation oncology. British journal of cancer. 2019;120(8):779-90

84. Batumalai V, Descallar J, Wong K, Gabriel G, Delaney GP, Shafiq J, et al. Trends in the use of short-course radiation therapy for rectal cancer in New South Wales, Australia. Journal of Medical Imaging and Radiation Oncology. 2022;66(3):436-41

85. Hua Ch, Vern-Gross TZ, Hess CB, Olch AJ, Alaei P, Sathiaseelan V, et al. Practice patterns and recommendations for pediatric image-guided radiotherapy: a Children's Oncology Group report. Pediatric blood & cancer. 2020;67(10):e28629

86. Nabavizadeh N, Elliott DA, Chen Y, Kusano AS, Mitin T, Thomas CR, Jr., et al. Image Guided Radiation Therapy (IGRT) Practice Patterns and IGRT's Impact on Workflow and Treatment Planning: Results From a National Survey of American Society for Radiation Oncology Members. Int J Radiat Oncol Biol Phys. 2016;94(4):850-7.10.1016/j.ijrobp.2015.09.035

87. Keall PJ, Mageras GS, Balter JM, Emery RS, Forster KM, Jiang SB, et al. The management of respiratory motion in radiation oncology report of AAPM Task Group 76. Med Phys. 2006;33(10):3874-900.10.1118/1.2349696

88. Ball HJ, Santanam L, Senan S, Tanyi JA, van Herk M, Keall PJ. Results from the AAPM Task Group 324 respiratory motion management in radiation oncology survey. J Appl Clin Med Phys. 2022;23(11):e13810.10.1002/acm2.13810

89. Pham D, Kron T, Styles C, Whitaker M, Bressel M, Foroudi F, et al. The use of dual vacuum stabilization device to reduce kidney motion for stereotactic radiotherapy planning. Technol Cancer Res Treat. 2015;14(2):149-57.10.7785/tcrt.2012.500410

90. Fontanarosa D, van der Meer S, Bamber J, Harris E, O'Shea T, Verhaegen F. Review of ultrasound image guidance in external beam radiotherapy: I. Treatment planning and inter-fraction motion management. Phys Med Biol. 2015;60(3):R77-114.10.1088/0031-9155/60/3/R77

91. Korreman SS. Image-guided radiotherapy and motion management in lung cancer. Br J Radiol. 2015;88(1051):20150100.10.1259/bjr.20150100

92. Kisivan K, Farkas A, Kovacs P, Glavak C, Lukacs G, Mahr K, et al. Pancreatic SABR using peritumoral fiducials, triggered imaging and breath-hold. Pathol Oncol Res. 2023;29:1611456.10.3389/pore.2023.1611456

93. Wu VWC, Ng APL, Cheung EKW. Intrafractional motion management in external beam radiotherapy. J Xray Sci Technol. 2019;27(6):1071-86.10.3233/XST-180472

94. Caillet V, Booth JT, Keall P. IGRT and motion management during lung SBRT delivery. Phys Med. 2017;44:113-22.10.1016/j.ejmp.2017.06.006

95. Brandner ED, Chetty IJ, Giaddui TG, Xiao Y, Huq MS. Motion management strategies and technical issues associated with stereotactic body radiotherapy of thoracic and upper abdominal tumors: A review from NRG oncology. Med Phys. 2017;44(6):2595-612.10.1002/mp.12227

96. Burton A, Beveridge S, Hardcastle N, Lye J, Sanagou M, Franich R. Adoption of respiratory motion management in radiation therapy. Phys Imaging Radiat Oncol. 2022;24:21-9.10.1016/j.phro.2022.09.003

97. Blomgren H, Lax I, Naslund I, Svanstrom R. Stereotactic high dose fraction radiation therapy of extracranial tumors using an accelerator. Clinical experience of the first thirty-one patients. Acta Oncol. 1995;34(6):861-70.10.3109/02841869509127197

98. Uematsu M, Shioda A, Tahara K, Fukui T, Yamamoto F, Tsumatori G, et al. Focal, high dose, and fractionated modified stereotactic radiation therapy for lung carcinoma patients: a preliminary experience. Cancer. 1998;82(6):1062-70

99. Blomgren H, Lax I, Näslund I, Svanström R. Stereotactic High Dose Fraction Radiation Therapy of Extracranial Tumors Using An Accelerator: Clinical experience of the first thirty-one patients. Acta Oncologica. 2009;34(6):861-70.10.3109/02841869509127197

100. Fakiris AJ, McGarry RC, Yiannoutsos CT, Papiez L, Williams M, Henderson MA, et al. Stereotactic body radiation therapy for early-stage non-small-cell lung carcinoma: four-year results of a prospective phase II study. Int J Radiat Oncol Biol Phys. 2009;75(3):677-82.10.1016/j.ijrobp.2008.11.042

101. Guckenberger M, Andratschke N, Dieckmann K, Hoogeman MS, Hoyer M, Hurkmans C, et al. ESTRO ACROP consensus guideline on implementation and practice of stereotactic body radiotherapy for peripherally located early stage non-small cell lung cancer. Radiother Oncol. 2017;124(1):11-7.10.1016/j.radonc.2017.05.012

102. Lindberg K, Grozman V, Karlsson K, Lindberg S, Lax I, Wersall P, et al. The HILUS-Trial-a Prospective Nordic Multicenter Phase 2 Study of Ultracentral Lung Tumors Treated With Stereotactic Body Radiotherapy. J Thorac Oncol. 2021;16(7):1200-10.10.1016/j.jtho.2021.03.019

103. Bahig H, Tonneau M, Blais N, Wong P, Filion E, Campeau MP, et al. Stereotactic Ablative Radiotherapy for oligo-progressive disease refractory to systemic therapy in Non-Small Cell Lung Cancer: A registry-based phase II randomized trial (SUPPRESS-NSCLC). Clin Transl Radiat Oncol. 2022;33:115-9.10.1016/j.ctro.2021.12.008

104. Ho CB, Tsai JT, Chen CY, Shiah HS, Chen HY, Ting LL, et al. Effectiveness of Stereotactic Ablative Radiotherapy for Systemic Therapy Respondents with Inoperable Pulmonary Oligometastases and Oligoprogression. Diagnostics (Basel). 2023;13(9).10.3390/diagnostics13091597

105. Allignet B, De Ruysscher D, Martel-Lafay I, Waissi W. Stereotactic body radiation therapy in unresectable stage III non-small cell lung cancer: A systematic review. Cancer Treat Rev. 2023;118:102573.10.1016/j.ctrv.2023.102573

106. Siva S, Sakyanun P, Mai T, Wong W, Lim A, Ludbrook J, et al. Long-Term Outcomes of TROG 13.01 SAFRON II Randomized Trial of Single- Versus Multifraction Stereotactic Ablative Body Radiotherapy for Pulmonary Oligometastases. J Clin Oncol. 2023;41(19):3493-8.10.1200/JCO.23.00150

107. Schefter TE, Kavanagh BD, Timmerman RD, Cardenes HR, Baron A, Gaspar LE. A phase I trial of stereotactic body radiation therapy (SBRT) for liver metastases. Int J Radiat Oncol Biol Phys. 2005;62(5):1371-8.10.1016/j.ijrobp.2005.01.002

108. Mendez Romero A, Wunderink W, Hussain SM, De Pooter JA, Heijmen BJ, Nowak PC, et al. Stereotactic body radiation therapy for primary and metastatic liver tumors: A single institution phase i-ii study. Acta Oncol. 2006;45(7):831-7.10.1080/02841860600897934

109. Kavanagh BD, Schefter TE, Cardenes HR, Stieber VW, Raben D, Timmerman RD, et al. Interim analysis of a prospective phase I/II trial of SBRT for liver metastases. Acta Oncol. 2006;45(7):848-55.10.1080/02841860600904870

110. Lee MT, Kim JJ, Dinniwell R, Brierley J, Lockwood G, Wong R, et al. Phase I study of individualized stereotactic body radiotherapy of liver metastases. J Clin Oncol. 2009;27(10):1585-91.10.1200/JCO.2008.20.0600

111. Rusthoven KE, Kavanagh BD, Cardenes H, Stieber VW, Burri SH, Feigenberg SJ, et al. Multi-institutional phase I/II trial of stereotactic body radiation therapy for liver metastases. J Clin Oncol. 2009;27(10):1572-8.10.1200/JCO.2008.19.6329

112. Cardenes HR, Price TR, Perkins SM, Maluccio M, Kwo P, Breen TE, et al. Phase I feasibility trial of stereotactic body radiation therapy for primary hepatocellular carcinoma. Clin Transl Oncol. 2010;12(3):218-25.10.1007/s12094-010-0492-x

113. Xi M, Yang Z, Hu L, Fu Y, Hu D, Zhou Z, et al. Radiofrequency Ablation Versus Stereotactic Body Radiotherapy for Recurrent Small Hepatocellular Carcinoma: A Randomized, Open-Label, Controlled Trial. J Clin Oncol. 2025;43(9):1073-82.10.1200/JCO-24-01532

114. Dawson LA, Winter KA, Knox JJ, Zhu AX, Krishnan S, Guha C, et al. Stereotactic Body Radiotherapy vs Sorafenib Alone in Hepatocellular Carcinoma: The NRG Oncology/RTOG 1112 Phase 3 Randomized Clinical Trial. JAMA Oncol. 2025;11(2):136-44.10.1001/jamaoncol.2024.5403

115. Maas JA, Dobelbower MC, Yang ES, Clark GM, Jacob R, Kim RY, et al. Prostate Stereotactic Body Radiation Therapy with a Focal Simultaneous Integrated Boost: Five Year Toxicity and Biochemical Recurrence Results from a Prospective Trial: Prostate SBRT with Focal SIB: 5 Year Results. Pract Radiat Oncol. 2023.10.1016/j.prro.2023.05.004

116. Houlihan OA, Redmond K, Fairmichael C, Lyons CA, McGarry CK, Mitchell D, et al. A Randomised Feasibility Trial of Stereotactic Prostate Radiotherapy with or without Elective Nodal Irradiation in High-Risk Localised Prostate Cancer (SPORT Trial). Int J Radiat Oncol Biol Phys. 2023.10.1016/j.ijrobp.2023.02.054

117. van Goor I, Daamen LA, Besselink MG, Bruynzeel AME, Busch OR, Cirkel GA, et al. A nationwide randomized controlled trial on additional treatment for isolated local pancreatic cancer recurrence using stereotactic body radiation therapy (ARCADE). Trials. 2022;23(1):913.10.1186/s13063-022-06829-1

118. Hannan R, McLaughlin MF, Pop LM, Pedrosa I, Kapur P, Garant A, et al. Phase 2 Trial of Stereotactic Ablative Radiotherapy for Patients with Primary Renal Cancer. Eur Urol. 2023.10.1016/j.eururo.2023.02.016

119. Dumago MP, Agas RAF, Jainar CJE, Yap ET, Co LBA, Ortin TTS. Stereotactic Body Radiation Therapy With or Without Transarterial Chemoembolization Versus Transarterial Chemoembolization Alone in Early-Stage Hepatocellular Carcinoma: A Systematic Review and Meta-Analysis. J Gastrointest Cancer. 2023.10.1007/s12029-023-00940-5

120. Zarkar A, Henderson D, Carver A, Heyes G, Harrop V, Tutill S, et al. First UK patient cohort treated with stereotactic ablative radiotherapy for primary kidney cancer. BJUI Compass. 2023;4(4):464-72.10.1002/bco2.199

121. Ippolito E, Silipigni S, Pantano F, Matteucci P, Carrafiello S, Marrocco M, et al. BOMB trial: First results of stereotactic radiotherapy to primary breast tumor in metastatic breast cancer patients. Front Oncol. 2023;13:1062355.10.3389/fonc.2023.1062355

122. Krug D, Zaman A, Eidinger L, Grehn M, Boda-Heggemann J, Rudic B, et al. Radiosurgery for ventricular tachycardia (RAVENTA): interim analysis of a multicenter multiplatform feasibility trial. Strahlenther Onkol. 2023;199(7):621-30.10.1007/s00066-023-02091-9

123. Viani GA, Gouveia AG, Pavoni JF, Louie AV, Detsky J, Spratt DE, et al. A Meta-analysis of the Efficacy and Safety of Stereotactic Arrhythmia Radioablation (STAR) in Patients with Refractory Ventricular Tachycardia. Clin Oncol (R Coll Radiol). 2023.10.1016/j.clon.2023.04.004

124. Lund CR, Cao JQ, Liu M, Olson R, Halperin R, Schellenberg D. The distribution and patterns of practice of stereotactic ablative body radiotherapy in Canada. Journal of medical imaging and radiation sciences. 2014;45(1):8-15

125. Distefano G, Baker A, Scott AJ, Webster GJ, Group USCQA. Survey of stereotactic ablative body radiotherapy in the UK by the QA group on behalf of the UK SABR Consortium. Br J Radiol. 2014;87(1037):20130681.10.1259/bjr.20130681

126. Distefano G, Garikipati S, Grimes H, Hatton M. Current status of stereotactic ablative body radiotherapy in the UK: six years of progress. BJR Open. 2019;1(20190022):1-12.doi.org/10.1259/bjro.20190022

127. Alfaifi S, Louie AV, Siva S, Guckenberger M, Videtic GM, Higgins KA, et al. International Patterns of Practice for SABR for Early-Stage Non-Small Cell Lung Cancer: Are We All in Sync? International Journal of Radiation Oncology* Biology* Physics. 2025

128. Taplin K, Hannan R, Lo SS, Morgan SC, Ali M, Sigurdson S, et al. Stereotactic ablative radiotherapy for primary kidney cancer–An international patterns of practice survey. Clinical and Translational Radiation Oncology. 2025;50:100891

129. Fogliata A, Reggiori G, Stravato A, Lobefalo F, Franzese C, Franceschini D, et al. RapidPlan head and neck model: the objectives and possible clinical benefit. Radiat Oncol. 2017;12(1):73.10.1186/s13014-017-0808-x

130. Tol JP, Delaney AR, Dahele M, Slotman BJ, Verbakel WF. Evaluation of a knowledge-based planning solution for head and neck cancer. Int J Radiat Oncol Biol Phys. 2015;91(3):612-20.10.1016/j.ijrobp.2014.11.014

131. Hussein M, South CP, Barry MA, Adams EJ, Jordan TJ, Stewart AJ, et al. Clinical validation and benchmarking of knowledge-based IMRT and VMAT treatment planning in pelvic anatomy. Radiother Oncol. 2016;120(3):473-9.10.1016/j.radonc.2016.06.022

132. Chang ATY, Hung AWM, Cheung FWK, Lee MCH, Chan OSH, Philips H, et al. Comparison of Planning Quality and Efficiency Between Conventional and Knowledge-based Algorithms in Nasopharyngeal Cancer Patients Using Intensity Modulated Radiation Therapy. Int J Radiat Oncol Biol Phys. 2016;95(3):981-90.10.1016/j.ijrobp.2016.02.017

133. Radiation Oncology Tripartite Committee. Planning for the Best: Tripartite National Strategic Plan for Radiation Oncology 2012-2022. Sydney, Australia: Radiation Oncology Tripartite Committee; 2012.

134. Williams M, Cooper T, Mackay R, Staffurth J, Routsis D, Burnet N. The implementation of intensity-modulated radiotherapy in the UK. Clinical Oncology. 2010;22(8):623-8

135. Engels B, Soete G, Verellen D, Storme G. Conformal arc radiotherapy for prostate cancer: increased biochemical failure in patients with distended rectum on the planning computed tomogram despite image guidance by implanted markers. Int J Radiat Oncol Biol Phys. 2009;74(2):388-91.10.1016/j.ijrobp.2008.08.007

136. Rath F. Tools for developing a quality management program: proactive tools (process mapping, value stream mapping, fault tree analysis, and failure mode and effects analysis). Int J Radiat Oncol Biol Phys. 2008;71(1 Suppl):S187-90.10.1016/j.ijrobp.2007.07.2385

137. Zheng Y, Johnson R, Larson G. Minimizing treatment planning errors in proton therapy using failure mode and effects analysis. Med Phys. 2016;43(6):2904-10.10.1118/1.4948686

138. Teixeira FC, de Almeida CE, Saiful Huq M. Failure mode and effects analysis based risk profile assessment for stereotactic radiosurgery programs at three cancer centers in Brazil. Med Phys. 2016;43(1):171.10.1118/1.4938065

139. Noel CE, Santanam L, Parikh PJ, Mutic S. Process-based quality management for clinical implementation of adaptive radiotherapy. Med Phys. 2014;41(8):081717.10.1118/1.4890589

140. Hindmarsh J, Crowe S, Walsh J, Kairn T, Dieterich S, Booth J, et al. A prospective hazard analysis of real-time adaptive helical tomotherapy. J Appl Clin Med Phys. 2026;27(2):e70478.10.1002/acm2.70478

141. Schneider EC, Sarnak DO, Squires D, Shah A, Doty MM. Mirror, Mirror 2017: International Comparison Reflects Flaws and Opportunities for Better US Health Care (2017). The Commonwealth Fund; 2017

142. Blumenthal D, Gumas E, Shah A. Mirror, mirror 2024: a portrait of the failing US health system. 2024

143. Armstrong BK, Gillespie JA, Leeder SR, Rubin GL, Russell LM. Challenges in health and health care for Australia. Medical Journal of Australia. 2007;187(9):485-9

144. Australian Institute of Health and Welfare. Health system overview: Australian Institute of Health and Welfare; 2024 updated 8/4/2025 Accessed:16/9/2025. Available from: https://www.aihw.gov.au/reports/australias-health/health-system-overview.

145. NSW Health. Local health districts and specialty networks: NSW Government; 2024 updated 29/8/2024 Accessed:16/9/2025. Available from: https://www.health.nsw.gov.au/lhd/pages/default.aspx.

146. Cancer Institute NSW. Radiotherapy Treatment Services to NSW Residents: 2017 Annual Report. Sydney: Cancer Institute NSW; 2018 12/2018.

147. Cancer Institute NSW. Reporting for Better Cancer Outcomes: Radiation therapy. Sydney: Cancer Institute NSW; 2023.

148. Department of Health Disability and Ageing. Radiation Oncology Health Program Grants Scheme 2025 updated 26/5/2025 Accessed:16/9/2025.

149. NSW EPA. Population and the environment 2024: NSW EPA,; 2025. Available from: https://www.soe.epa.nsw.gov.au/all-themes/drivers/population-and-the-environment-2024.

150. The Royal Australian and New Zealand College of Radiologists. Establishing and Sustaining Regional and Rural Radiation Therapy Centres. The Royal Australian and New Zealand College of Radiologists,; 2020 11/5/2020.

151. Gabriel G, Barton M, Delaney GP. The effect of travel distance on radiotherapy utilization in NSW and ACT. Radiother Oncol. 2015;117(2):386-9.10.1016/j.radonc.2015.07.031

152. Yap ML, O'Connell DL, Goldsbury D, Weber M, Barton M. Factors Associated With Radiotherapy Utilisation In New South Wales, Australia: Results From The 45 and Up Study. Clin Oncol (R Coll Radiol). 2020;32(5):282-91.10.1016/j.clon.2020.01.007

153. Henry MJ, Jones P, Morrissy K, Matheson LM, Pitson G, Healy P, et al. Radiotherapy in the Barwon South Western Region: a rural perspective. J Med Imaging Radiat Oncol. 2014;58(5):612-7.10.1111/1754-9485.12208

154. Merie R, Gabriel G, Shafiq J, Vinod S, Barton M, Delaney GP. Radiotherapy underutilisation and its impact on local control and survival in New South Wales, Australia. Radiother Oncol. 2019;141:41-7.10.1016/j.radonc.2019.09.012

155. Butler SM. Changes to radiotherapy utilisation in Western NSW after the opening of a local service. J Med Radiat Sci. 2017;64(4):251-8.10.1002/jmrs.204

156. Harrow S, Palma DA, Olson R, Gaede S, Louie AV, Haasbeek C, et al. Stereotactic Radiation for the Comprehensive Treatment of Oligometastases (SABR-COMET): Extended Long-Term Outcomes. Int J Radiat Oncol Biol Phys. 2022;114(4):611-6.10.1016/j.ijrobp.2022.05.004

157. Palma DA, Olson R, Harrow S, Gaede S, Louie AV, Haasbeek C, et al. Stereotactic Ablative Radiotherapy for the Comprehensive Treatment of Oligometastatic Cancers: Long-Term Results of the SABR-COMET Phase II Randomized Trial. J Clin Oncol. 2020;38(25):2830-8.10.1200/JCO.20.00818

158. Claridge Mackonis ER, Hardcastle N, Haworth A. Stereotactic ablative body radiation therapy (SABR) in NSW. Phys Eng Sci Med. 2020;43(2):641-50.10.1007/s13246-020-00866-3

159. Foote M, Bailey M, Smith L, Siva S, Hegi-Johnson F, Seeley A, et al. Guidelines for safe practice of stereotactic body (ablative) radiation therapy. J Med Imaging Radiat Oncol. 2015;59(5):646-53.10.1111/1754-9485.12336

160. Claridge Mackonis ER, Hardcastle N, Haworth A. A survey of compliance with stereotactic ablative body radiotherapy quality recommendations. J Med Imaging Radiat Oncol. 2023.10.1111/1754-9485.13526

161. Hu J, Liu B, Xie W, Zhu J, Yu X, Gu H, et al. Quantitative Comparison of Knowledge-Based and Manual Intensity Modulated Radiation Therapy Planning for Nasopharyngeal Carcinoma. Front Oncol. 2020;10:551763.10.3389/fonc.2020.551763

162. Yu S, Xu H, Sinclair A, Zhang X, Langner U, Mak K. Dosimetric and planning efficiency comparison for lung SBRT: CyberKnife vs VMAT vs knowledge-based VMAT. Med Dosim. 2020;45(4):346-51.10.1016/j.meddos.2020.04.004

163. Scaggion A, Fusella M, Roggio A, Bacco S, Pivato N, Rossato MA, et al. Reducing inter- and intra-planner variability in radiotherapy plan output with a commercial knowledge-based planning solution. Phys Med. 2018;53:86-93.10.1016/j.ejmp.2018.08.016

164. Claridge Mackonis E, Sykes J, Hardcastle N, Espinoza A, Brown A, Perez G, et al. A comparison of in-house and shared RapidPlan models for prostate radiation therapy planning. Phys Eng Sci Med. 2022;45(4):1029-41.10.1007/s13246-022-01151-1

165. Claridge Mackonis E, Stensmyr R, Poldy R, White P, Moutrie Z, Gorjiara T, et al. Improving motion management in radiation therapy: findings from a workshop and survey in Australia and New Zealand. Phys Eng Sci Med. 2024.10.1007/s13246-024-01405-0

166. Kohn LT, Corrigan JM, Donaldson MS. In: Kohn LT, Corrigan JM, Donaldson MS, editors. To Err is Human: Building a Safer Health System. Washington (DC)2000.

167. Malicki J, Bly R, Bulot M, Godet JL, Jahnen A, Krengli M, et al. Patient safety in external beam radiotherapy, results of the ACCIRAD project: Current status of proactive risk assessment, reactive analysis of events, and reporting and learning systems in Europe. Radiother Oncol. 2017;123(1):29-36.10.1016/j.radonc.2017.02.016

168. Dunscombe P. Recommendations for safer radiotherapy: what's the message? Front Oncol. 2012;2:129.10.3389/fonc.2012.00129

169. Pardo Masferrer J, Del Cerro Penalver E, Contreras Martinez J, Ferrer Albiach C, Patient S, Quality Working Group of the Spanish Society of Radiation O. Patient safety in radiation oncology in Spain: a need to change. Clin Transl Oncol. 2020;22(5):751-8.10.1007/s12094-019-02184-x

170. European Commission, Directorate-General for Energy. General guidelines on risk management in external beam radiotherapy: Publications Office; 2015.

171. Vilaragut JJ, Dumenigo C, Delgado JM, Morales J, McDonnell JD, Ferro R, et al. Prevention of accidental exposure in radiotherapy: the risk matrix approach. Health Phys. 2013;104(2):139-50.10.1097/HP.0b013e3182680379

172. Huq MS, Fraass BA, Dunscombe PB, Gibbons JP, Jr., Ibbott GS, Mundt AJ, et al. The report of Task Group 100 of the AAPM: Application of risk analysis methods to radiation therapy quality management. Med Phys. 2016;43(7):4209.10.1118/1.4947547

173. Claridge Mackonis E, Ralston A, Yuen J, Hardcastle N, Haworth A. Increasing the use of prospective risk assessment through training. Phys Med. 2025;140:105213.10.1016/j.ejmp.2025.105213

174. Tabakov S, Stoeva M. Collaborative networking and support for medical physics development in low and middle income (LMI) countries. Health Technol (Berl). 2021;11(5):963-9.10.1007/s12553-021-00591-1

175. International Atomic Energy Agency. E-Learning Courses Radiotherapy Vienna: IAEA; 2023 Accessed:14/3/2024. Available from: https://www.iaea.org/resources/hhc/medical-physics/radiotherapy/e-learning.

176. Glicksman R, Ang M, Murray E, Simniceanu C, Lockhart E, Gilbert J, et al. Improving Quality of Radiation Therapy Care Across Ontario using a Community-of-Practice Approach. Pract Radiat Oncol. 2019;9(2):e242-e8.10.1016/j.prro.2018.10.017

177. Jacobs M, Martinussen H, Swart R, Gubbels A, Dirkx M, de Boer H, et al. A taskforce for national improvement of innovation implementation in radiotherapy. Radiother Oncol. 2024;192:110105.10.1016/j.radonc.2024.110105

178. Hiti CJ, Chang J, Gwal K, Escobedo E, Rea M, Bindra J. The New Normal: Coronavirus Pandemic Response Utilizing Microsoft SharePoint. Journal of Digital Imaging. 2021;34(2):257-62.10.1007/s10278-021-00419-4

179. Ohri N, Shen X, Dicker AP, Doyle LA, Harrison AS, Showalter TN. Radiotherapy protocol deviations and clinical outcomes: a meta-analysis of cooperative group clinical trials. J Natl Cancer Inst. 2013;105(6):387-93.10.1093/jnci/djt001

180. Jomy J, Sharma R, Lu R, Chen D, Ataalla P, Kaushal S, et al. Clinical impact of radiotherapy quality assurance results in contemporary cancer trials: a systematic review and meta-analysis. Radiother Oncol. 2025;207:110875.10.1016/j.radonc.2025.110875

181. Zhong H, Men K, Wang J, van Soest J, Rosenthal D, Dekker A, et al. The Impact of Clinical Trial Quality Assurance on Outcome in Head and Neck Radiotherapy Treatment. Front Oncol. 2019;9:792.10.3389/fonc.2019.00792

182. Peters LJ, O'Sullivan B, Giralt J, Fitzgerald TJ, Trotti A, Bernier J, et al. Critical impact of radiotherapy protocol compliance and quality in the treatment of advanced head and neck cancer: results from TROG 02.02. J Clin Oncol. 2010;28(18):2996-3001.10.1200/JCO.2009.27.4498

183. Fundowicz M, Aguiar A, de Castro CL, Torras MG, Deantonio L, Konstanty E, et al. Multicentre clinical radiotherapy audit in rectal cancer: results of the IROCA project. Radiat Oncol. 2020;15(1):208.10.1186/s13014-020-01648-7

184. Huang X, Field M, Vinod S, Ball H, Batumalai V, Keall P, et al. Radiotherapy protocol compliance in routine clinical practice for patients with stages I-III non-small-cell lung cancer. J Med Imaging Radiat Oncol. 2024.10.1111/1754-9485.13727

185. Vaandering A, Cucchiaro S. BQUATRO audits in radiotherapy: Crossperspectives between auditors and audited departments. Cancer Radiother. 2025;29(5-6):104679.10.1016/j.canrad.2025.104679

186. Brusadin G, Brady AP, Hierath M, Howlett DC. The QuADRANT project: Enhancing quality and safety in radiological procedures through clinical audit. Cancer Radiother. 2025;29(5-6):104689.10.1016/j.canrad.2025.104689

187. Chen X, LeCompte MC, Gui C, Huang E, Khan MA, Hu C, et al. Deviation from consensus contouring guidelines predicts inferior local control after spine stereotactic body radiotherapy. Radiother Oncol. 2022;173:215-22.10.1016/j.radonc.2022.05.035

188. eviQ. Welcome to eviQ St Leonards NSW: Cancer Institute NSW; 2025 Accessed:30/12/2025. Available from: https://www.eviq.org.au/.

189. NEMA. DICOMweb: NEMA; Accessed:26/12/2025. Available from: https://www.dicomstandard.org/using/dicomweb.

190. Chlap P, Al Mouiee D, Finnegan RN, Cui J, Chin V, Deshpande S, et al. PyDicer: An open-source python library for conversion and analysis of radiotherapy DICOM data. SoftwareX. 2025;29:102010

191. Cox BW, Spratt DE, Lovelock M, Bilsky MH, Lis E, Ryu S, et al. International Spine Radiosurgery Consortium consensus guidelines for target volume definition in spinal stereotactic radiosurgery. 2012;83(5):e597-e605

192. Dunne EM, Sahgal A, Lo SS, Bergman A, Kosztyla R, Dea N, et al. International consensus recommendations for target volume delineation specific to sacral metastases and spinal stereotactic body radiation therapy (SBRT). Radiother Oncol. 2020;145:21-9.10.1016/j.radonc.2019.11.026

193. Pieper S, Haouchine, N., Hackney, D.B., Wells, W.M. Sanhinova, M., Balboni, T., Spektor, A., Huynh, M., Tanguturi, S., Kim, E., Guenette, J.P., Kozono, D.E., Czajkowski, B., Caplan, S., Doyle, P., Kang, H., Alkalay, R.N. . Spine metastatic bone cancer: pre and post radiotherapy CT (Spine-Mets-CT-SEG) [Dataset] (Version 1). The Cancer Imaging Archive. 2024.https://doi.org/10.7937/kh36-ds04

194. Department of Health. Data about radiotherapy services: The Victorian Government; 2024 Accessed:9/12/2025. Available from: https://www.health.vic.gov.au/cancer-treatment/radiotherapy-services/data-about-radiotherapy-services.

195. Folkert MR, Bilsky MH, Tom AK, Oh JH, Alektiar KM, Laufer I, et al. Outcomes and toxicity for hypofractionated and single-fraction image-guided stereotactic radiosurgery for sarcomas metastasizing to the spine. Int J Radiat Oncol Biol Phys. 2014;88(5):1085-91.10.1016/j.ijrobp.2013.12.042

196. Das IJ, Dawes SL, Dominello MM, Kavanagh B, Miyamoto CT, Pawlicki T, et al. Quality and Safety Considerations in Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy: An ASTRO Safety White Paper Update. Pract Radiat Oncol. 2022;12(4):e253-e68.10.1016/j.prro.2022.03.001

197. Osborn VW, Lee A, Yamada Y. Stereotactic Body Radiation Therapy for Spinal Malignancies. Technol Cancer Res Treat. 2018;17:1533033818802304.10.1177/1533033818802304

198. Ahmed KA, Stauder MC, Miller RC, Bauer HJ, Rose PS, Olivier KR, et al. Stereotactic body radiation therapy in spinal metastases. Int J Radiat Oncol Biol Phys. 2012;82(5):e803-9.10.1016/j.ijrobp.2011.11.036

199. Mayo CS, Moran JM, Bosch W, Xiao Y, McNutt T, Popple R, et al. American Association of Physicists in Medicine Task Group 263: Standardizing Nomenclatures in Radiation Oncology. Int J Radiat Oncol Biol Phys. 2018;100(4):1057-66.10.1016/j.ijrobp.2017.12.013

200. Richardson SL, Bosch WR, Mayo CS, McNutt TR, Moran JM, Popple RA, et al. Order From Chaos: The Benefits of Standardized Nomenclature in Radiation Oncology. Pract Radiat Oncol. 2024;14(6):582-9.10.1016/j.prro.2024.04.002

201. Sleeman Iv WC, Nalluri J, Syed K, Ghosh P, Krawczyk B, Hagan M, et al. A Machine Learning method for relabeling arbitrary DICOM structure sets to TG-263 defined labels. J Biomed Inform. 2020;109:103527.10.1016/j.jbi.2020.103527

202. Syed K, Iv WS, Ivey K, Hagan M, Palta J, Kapoor R, et al. Integrated Natural Language Processing and Machine Learning Models for Standardizing Radiotherapy Structure Names. Healthcare (Basel). 2020;8(2).10.3390/healthcare8020120

203. Cheng SH, Wang CJ, Lin JL, Horng CF, Lu MC, Asch SM, et al. Adherence to quality indicators and survival in patients with breast cancer. Med Care. 2009;47(2):217-25.10.1097/MLR.0b013e3181893c4a

204. Pilgrim CHC, Finn N, Stuart E, Philip J, Steel S, Croagh D, et al. Changing patterns of care for pancreas cancer in Victoria: the 2022 Pancreas Tumour Summit. ANZ J Surg. 2023;93(11):2638-47.10.1111/ans.18522

205. Kearvell R, Haworth A, Ebert MA, Murray J, Hooton B, Richardson S, et al. Quality improvements in prostate radiotherapy: outcomes and impact of comprehensive quality assurance during the TROG 03.04 'RADAR' trial. J Med Imaging Radiat Oncol. 2013;57(2):247-57.10.1111/1754-9485.12025

206. Purdy JA. Quality assurance issues in conducting multi-institutional advanced technology clinical trials. Int J Radiat Oncol Biol Phys. 2008;71(1 Suppl):S66-70.10.1016/j.ijrobp.2007.07.2393

207. Palta JR, Frouhar VA, Dempsey JF. Web-based submission, archive, and review of radiotherapy data for clinical quality assurance: a new paradigm. Int J Radiat Oncol Biol Phys. 2003;57(5):1427-36.10.1016/s0360-3016(03)01624-9

208. Liu S, Chapman KL, Berry SL, Bertini J, Ma R, Fu Y, et al. Implementation of a knowledge-based decision support system for treatment plan auditing through automation. Med Phys. 2023;50(11):6978-89.10.1002/mp.16472

209. Fundowicz M, Macia M, Marin S, Bogusz-Czerniewicz M, Konstanty E, Modolel I, et al. Preoperative radiotherapy for rectal cancer: a comparative study of quality control adherence at two cancer hospitals in Spain and Poland. Radiol Oncol. 2014;48(2):210-8.10.2478/raon-2014-0008

210. Caruthers D, Brame S, Palta J, Hagan M, Wilson E, Cowan C, et al. Development and implementation of quality measures for the survey based performance assessment of radiation therapy in the VA. International Journal of Radiation Oncology, Biology, Physics. 2017;99(2):E391-E2

211. Katsoulakis E, Madison CJ, Kapoor R, Melson RA, Gao A, Bian J, et al. Leveraging Radiotherapy Data for Precision Oncology: Veterans Affairs Granular Radiotherapy Information Database. JCO Clin Cancer Inform. 2025;9:e2400219.10.1200/CCI-24-00219

212. Chlap P, Min H, Martin J, Sidhom M, Chan LX, Whitehead A, et al. Implementation of an automated contour quality assurance tool within the TROG 18.01 NINJA trial. Radiother Oncol. 2026;214:111269.10.1016/j.radonc.2025.111269

213. Corry J, Moore A, Kenny L, Wratten C, Fua T, Lin C, et al. Radiotherapy quality assurance in the TROG 12.01 randomised trial and its impact on loco-regional failure. Front Oncol. 2023;13:1333098.10.3389/fonc.2023.1333098

214. Zelefsky MJ, Kollmeier M, Cox B, Fidaleo A, Sperling D, Pei X, et al. Improved clinical outcomes with high-dose image guided radiotherapy compared with non-IGRT for the treatment of clinically localized prostate cancer. Int J Radiat Oncol Biol Phys. 2012;84(1):125-9.10.1016/j.ijrobp.2011.11.047

215. Wang S, Tang W, Luo H, Peng H, Jin F, He H, et al. The Impact of Image Guided Radiation Therapy (IGRT) on Efficacy and Toxicity of Prostate Cancer: A Systematic Review and Meta-Analysis. International Journal of Radiation Oncology, Biology, Physics. 2022;114(3):e562-e3.10.1016/j.ijrobp.2022.07.2206

216. Xu D, Li G, Li H, Jia F. Comparison of IMRT versus 3D-CRT in the treatment of esophagus cancer: A systematic review and meta-analysis. Medicine (Baltimore). 2017;96(31):e7685.10.1097/MD.0000000000007685

217. AIHW. Cancer data in Australia Australia: Australian Governement; 2025 updated 7/10/2025 Accessed:9/1/2026. Available from: https://www.aihw.gov.au/reports/cancer/cancer-data-in-australia/contents/overview.

218. Gupta T, Kannan S, Ghosh-Laskar S, Agarwal JP. Systematic review and meta-analyses of intensity-modulated radiation therapy versus conventional two-dimensional and/or or three-dimensional radiotherapy in curative-intent management of head and neck squamous cell carcinoma. PLoS One. 2018;13(7):e0200137.10.1371/journal.pone.0200137

219. Shaw M, Alves A, Lye J, Lehmann J, Kadeer F, Beveridge S, et al. Comprehensive end-to-end dosimetry audit for stereotactic body radiotherapy in spine, lung, and soft tissue. J Appl Clin Med Phys. 2025;26(7):e70133.10.1002/acm2.70133

220. Panettieri V, Ball D, Chapman A, Cristofaro N, Gawthrop J, Griffin P, et al. Development of a multicentre automated model to reduce planning variability in radiotherapy of prostate cancer. Physics and Imaging in Radiation Oncology. 2019;11:34-40.10.1016/j.phro.2019.07.005

221. Pudsey L, Haworth A, White P, Moutrie Z, Jonker B, Foote M, et al. Current status of intra-cranial stereotactic radiotherapy and stereotactic radiosurgery in Australia and New Zealand: key considerations from a workshop and surveys. Phys Eng Sci Med. 2022;45(1):251-9.10.1007/s13246-022-01108-4

222. Simpson-Page E, Coogan P, Kron T, Lowther N, Murray R, Noble C, et al. Webinar and survey on quality management principles within the Australian and New Zealand ACPSEM Workforce. Phys Eng Sci Med. 2022;45(3):679-85.10.1007/s13246-022-01160-0