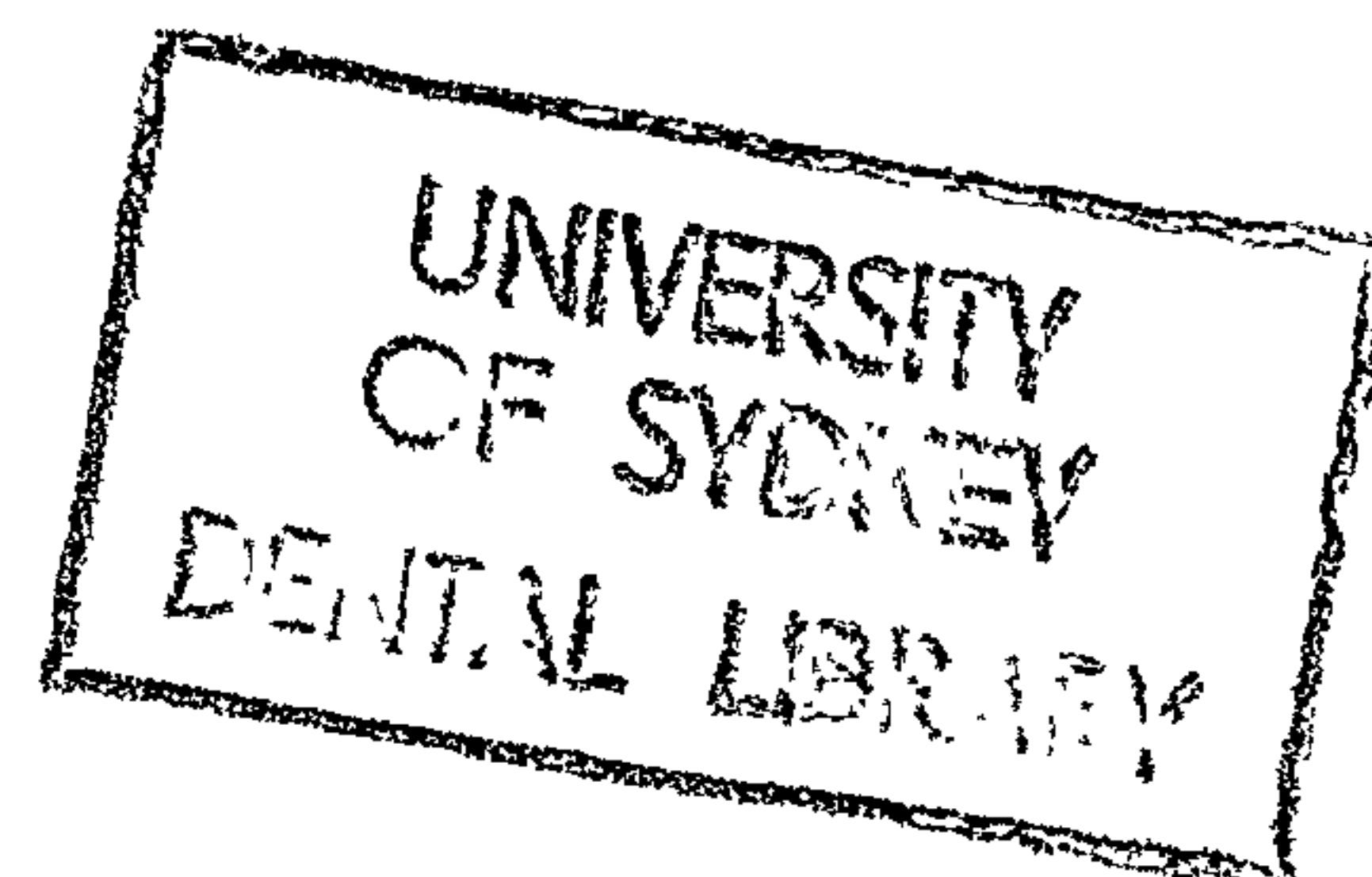




APPLIED RESEARCH IN
ENDODONTIC MORPHOLOGY

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26th March, 1976.

This thesis has been developed from original research conducted solely by the author during the period 17.5.1972 to 20.12.1975. In accordance with articles 30 to 33 (inclusive) of Chapter XV of the By-laws of the University of Sydney it is submitted in support of candidature for the degree of Doctor of Dental Science.

ACKNOWLEDGMENTS

For a privately practising dentist to conceive of an idea and develop it through the necessary experimental procedures into a workable project it is a difficult task. Not only is he required to learn new disciplines, but he must establish himself in a suitable location in which the work may be performed.

Should he also seek guidance from those more experienced than he and moreover, receive this along with a measure of moral support when things go awry, he is indeed fortunate. In this respect, my indebtedness to certain members of the Department of Anatomy within the University of Sydney is profound.

From the early encouragement given me by Professors N.W.G. McIntosh (forever known as Black Mac), M.J. Blunt and Barry Barker through to the ready availability of technical advice provided by Messrs. Barry Lockett, Ken Parsons and Peter Mills I gradually gathered momentum and eventually completed a task which at times appeared to be impossible.

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the task of preparing these but their constructive criticism and technical assistance were of inestimable value during the experimental phase regarding the radiographic study.

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INTRODUCTION

Throughout the centuries man has shown a desire to preserve his dentition. Despite on the one hand the influences of tribal rituals upon early tooth loss in primitive man and on the other the effects of dental caries and more recently the increase in traumatic injuries in civilised communities, the trend towards preservation continues.

Teeth which were once doomed because of excessive loss of coronal tooth substance may now be restored due to advances in both materials technology and operative dentistry techniques particularly throughout the last two decades. Likewise those with endodontic involvement may in the majority of cases now be restored to biological compatibility with the supporting tissues. This has been achieved due to the scientific and technological advances which have taken place in the science of endodontology in a like period.

The role played by the endodontist in conservative dental therapy has increased markedly in recent years. The majority of large population centres in the western world contain practitioners who have attained specialist skills in the science and who thus provide a specialist service to their colleagues. Throughout the same period, the interest shown by the dental profession at

large is demonstrated by the growth of societies and study clubs devoted to the exclusive study of endodontology. Parallel with this, dental schools throughout the world have included the study of endodontics within their curriculae both at the undergraduate and at the graduate level and learned societies and dental associations continue to make provision for courses of lectures in endodontics at dental meetings and congresses.

Endodontic practice has survived the apparent haphazard approach to canal preparation and obturation which preceded the development and use of the dental x-ray machine. It has also survived the period when the bogey of focal sepsis caused the premature loss of countless teeth. The period of antiseptis which followed, when intra-canal medication was used ad-nauseum in an endeavour to "sterilize" the root canal (more often than not perpetuating periapical discomfort and inhibiting a successful conclusion to treatment) was a long and tedious chapter in the history of modern endodontic practice. Clinicians may now take heart that the fashion has changed to one whereby a recognition of the simplicity of the first rule of surgery i.e. "the removal of the cause" has assumed importance. This (canal preparation) together with the provision of conditions which allow the surrounding

tissues to heal (canal obturation) virtually sums up the attitude adopted in endodontic practice today.

The achievement of endodontic success is now more of a reality than a questionable exercise. This is largely due to the advent of the dental x-ray machine, the early and continued studies of the internal anatomy of teeth, the technological advances made in instruments and materials used in endodontics and the studies related to these. Recognition of these advances must not detract from the massive amount of information which has been derived from all other areas of endodontic research. They merely provide a foundation upon which the ever increasing pyramid of endodontic knowledge is built.

Increases in the accumulation of knowledge in various areas of study have in the past been responsible for shifts in emphasis towards those areas in clinical practice. It is quite reasonable for the dentist to be impressed to such a degree that his clinical practice may be modified accordingly. This it may be assumed accounts for the various trends which have occurred in endodontics throughout the years. Fashions have changed from the poorly controlled conservation of the pre-focal sepsis era to the radical tooth loss period of the focal sepsis era and back again to a more enlightened form of

conservatism in this post-focal sepsis era. In this latter period techniques have varied according to the type of intra-canal medication used, the level of obturation (underextension, so-called flush, or over-extension) and the technique of obturation (single cone, sectional, diffusion, lateral or vertical condensation, sealer type) to name but a few.

It would appear, the techniques employed to achieve a satisfactory result are largely dependent upon the whim of the particular operator. It is evident that successful endodontic therapy may be provided by the use of any of the above methods of sealing a root canal depending upon the degree of knowledge and skill possessed by the clinician and the potential for repair demonstrated by the host.

Present day endodontists however seem to be less conscious of the need for intra-canal medication to prepare the host tissues for receiving a root filling than they were in past decades and their common intent appears to be to seal the internal anatomical structures of the endodontically involved tooth from the surrounding tissues.

With the current trend in endodontic practice leaning towards the effective sealing of all canal orifices to prevent the dissemination of material in either direction the present study was undertaken. In

doing so it was recognised that three important areas of endodontic practice were involved. These were :

1. A study of the internal anatomy of the teeth,
2. Root canal preparation,
3. Root canal obturation.

Initially, a method of studying the internal anatomy of a series of extracted human teeth by radiographic means using a contrast medium infused into the previously cleared canal systems had to be developed. In doing so it was paramount that the same specimens could be used for further study by allowing for the uninhibited use of endodontic instruments in their canals. Thus the root canals could be entered and prepared as in the clinical situation and their newly developed canal forms studied by the same technique as previously used. This allowed for a comparison of results of canal forms prior to and following canal preparation.

The method of canal preparation used was one which lent itself to a particular technique of canal obturation (lateral condensation) for the following reasons:

- a) It is the technique exclusively employed by the author in clinical practice and therefore was the one in which competence was most likely.

- b) It provided a ready comparison with clinical treatments conducted by the author in his practice.
- c) By flaring the canals according to the technique used it was hoped that sufficient radiopaque contrast medium would be present within each prepared canal to adequately demonstrate the levels at which canal preparation terminated in those canals successfully entered. It was further hoped that those not entered would show clearly from the former.

The technique utilised was successful and the appropriate information was able to be recorded, this appears in the list of appendices A to F inclusive.

The entire study has been divided into four papers which appear in sequence throughout the text of this thesis. It is intended that these papers be presented to a journal for publication, hence their present form. The data which appears in appendices A to F has been condensed and summarised and where applicable it has been included in the appropriate paper.

The study of endodontics is a continuing one and already since the completion of this work certain papers have been published which should rightfully be included in the discussion. In a moment of sheer madness this was attempted. Since then and following the publication of further material which could have

received like treatment, sanity has prevailed and the present work has been concluded. The prospect of never publishing because of the need for continued review has been resisted and the possibility of the inclusion of such information in later studies has restored balance to the situation.

ENDODONTIC MORPHOLOGY IAn Alternative Method of Study

In cases of pulp pathology, successful endodontic therapy depends upon the removal of the cause, the transfer of the site of inflammation to a level at which the body defence processes are competent and the effective sealing of the canal at that level. The same (with few exceptions) may also be said for cases of periapical pathology, the level so mentioned varying from patient to patient and in the same patient from root to root. The level of seal at which success may be best predicted appears to be within the canal and approximately 0.5 - 2.0mm from the external surface of the root^(1,2,3).

To be competent to perform the above the operator should possess a knowledge of the morphological characteristics of the internal anatomy of teeth^(4,5,6,7,8). At the time of treatment, this knowledge should provide for the operator an effective complement to the information obtained from the use of the various diagnostic aids at his disposal.

Despite the variations in internal anatomy which occur from tooth to tooth there are certain morphological features which are common to all and more specifically to different groups of teeth. Previous studies have provided this information^(9,10,11) much being of a statistical nature, together with the basic patterns which pertain to the various denominations of teeth.

In vitro studies have utilised processes such as radiography with and without⁽¹²⁾ the insertion of endodontic instruments^(13,14) or radiopaque contrast media⁽¹⁵⁾, canal

staining^(8,16), sectioning of teeth^(15,17), the injection of rubber⁽⁹⁾, silicone⁽¹⁵⁾ and pigmented resins^(7,15). In some instances the internal anatomy may lack detailed exposure for analysis and in others the very process either destroys the specimen or at best precludes the unimpeded entry of endodontic instruments for later study.

So far there has been little attempt to correlate the internal anatomy of an untreated tooth with that of the same tooth following canal preparation and root filling. This may however be undertaken, provided a suitable medium is used for demonstrating endodontic morphology, such a material being readily eliminated from the canal system without damage to the internal anatomy of the specimen. Hasselgren and Tronstad⁽¹⁸⁾ have recently reported the use of transparent (demineralised) teeth as a teaching aid. These specimens however, whilst useful as such, provide considerable visual assistance to the student beyond that which prevails in vivo.

The present study was commenced to attempt to develop a technique which would demonstrate the internal anatomy of an untreated tooth in such a way as to allow for canal preparation to be performed in the same specimen without it being influenced by the earlier process. This study employs the use of a radiopaque contrast medium introduced under vacuum into the root canal systems of extracted human teeth. The material is water soluble and may be washed from the interiors of the teeth so that they may be instrumented and subsequently subjected to the same process for radiographic analysis. Radiographs taken

at various angles during each process allow a comparison to be made between the uninstrumented and instrumented canal systems.

Method and Materials

One hundred and sixty four extracted human teeth of various types were selected at random and opened with a number six round bur through the cemento-enamel junction on the mesial or distal surfaces, with penetration into the pulp chambers. They were immersed in a fresh solution of papain and incubated at 37°C for seven days⁽¹⁹⁾. At the completion of this period this performance was repeated with a fresh solution of papain to ensure complete clearance of the contents of the pulp canal systems.

Each specimen was then flushed out with water by the use of hand pressure, the nozzle of a large hypodermic syringe being fitted to the bur hole at the neck of the tooth. Reverse flushing was carried out by immersing each specimen in water and applying a vacuum to the opening at the neck, utilising a venturi sucker attached to a (mains pressure) water tap. A further application of the hypodermic syringe was effected to ensure patency of the apical openings in each case. This was determined by the presence of a fine jet or jets of water emerging from the apical end of each root. It was noted in many cases apical ramifications produced a spectacular jet effect as a pattern of fine jets, and lateral canals also showed in this way (Figs 1 and 2). All specimens which did not exhibit patency at the apical end were discarded from the experiment as

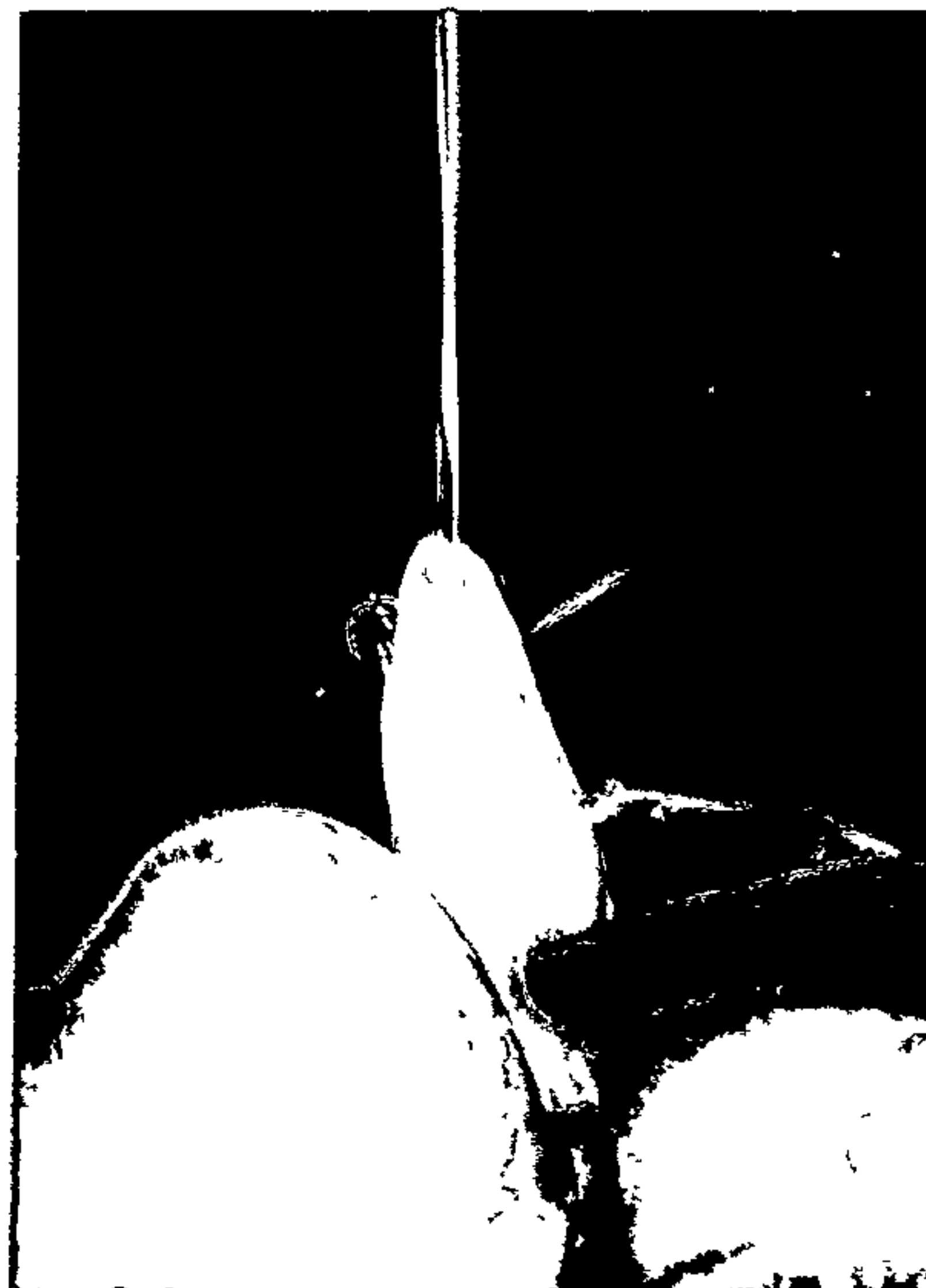
Fig. 1



The root canal system of a mandibular first molar being flushed with water following pulp removal with papain. The jet effect at the root apices demonstrates apical patency.

Fig. 2

Apical patency is seen in a maxillary central incisor following canal clearance. Fine water jets arising from two lateral canals at the commencement of the apical third of the root may be clearly seen.



it was believed at the time that apical stenosis may preclude complete perfusion of the contrast medium. This was proven to be open to doubt, as shown in a later experiment⁽²⁰⁾, where stenosed apical canals were able to be filled with contrast solution by the vacuum method.

Each specimen was dried by aspiration, immersed in a 70% solution of sodium iothalamate^{*} and placed under vacuum (29 ins. of mercury) with the cervical opening exposed to the view of the operator. Vacuum was allowed to proceed until all bubbles ceased to leave the canal system via the cervical opening. The vacuum was released to atmospheric pressure with the specimen still immersed and increased again to the former level and held for two minutes following the exit of the last bubble from the cervical opening. The specimen was then carefully removed from the solution and the surface made devoid of contrast by aspiration with the venturi sucker, irrigated with water under light pressure from a hand syringe and dried again by aspiration. Care was taken to ensure the meniscus of contrast solution remained undisturbed within the cervical opening throughout this process.

Radiographs were taken from the proximal, oblique and buccal surfaces with the contrast medium in situ, by placing each tooth onto an x-ray film^{**} and where necessary fixing the position of the tooth with soft wax. A further radiograph exposed from the buccal surface was taken for every tooth following the washing of the contrast from the tooth by water,

* Conray 420, May and Baker Ltd Dagenham, England

** Kodak Periapical Ultra-Speed Dental X-ray Film, Eastman Kodak Company, Rochester, N.Y., U.S.A. 14650

using the hand syringe and the venturi sucker to force or draw water through the canal system. This radiograph was able to show clearance of the contrast medium in each case.

All radiographs were taken using a standard technique employing a "Phillips Oralix" machine^{*} allowing four inches distance from cone tip to specimen, the exposure time being 7/20 sec. for the larger root ends and 6/20 sec. for the finer root ends. All films were developed according to the recommendations of the manufacturer at 20°C for 4½ minutes, fixed for 10 minutes, washed for 20 minutes and dried.

Each specimen was filed according to an identifying number as were the appropriate radiographs and these were retained for further study.

Results

A series of four radiographs was obtained for each specimen utilised during the experiment. Three radiographs showed the internal anatomy of the tooth as defined by the radiopaque contrast medium employed, one being from the proximal, one from the buccal and the third an oblique view. The fourth film (radiographed from the buccal) showed the pulp chamber and canal system cleared of the water soluble contrast (Figs 3, 4 and 5).

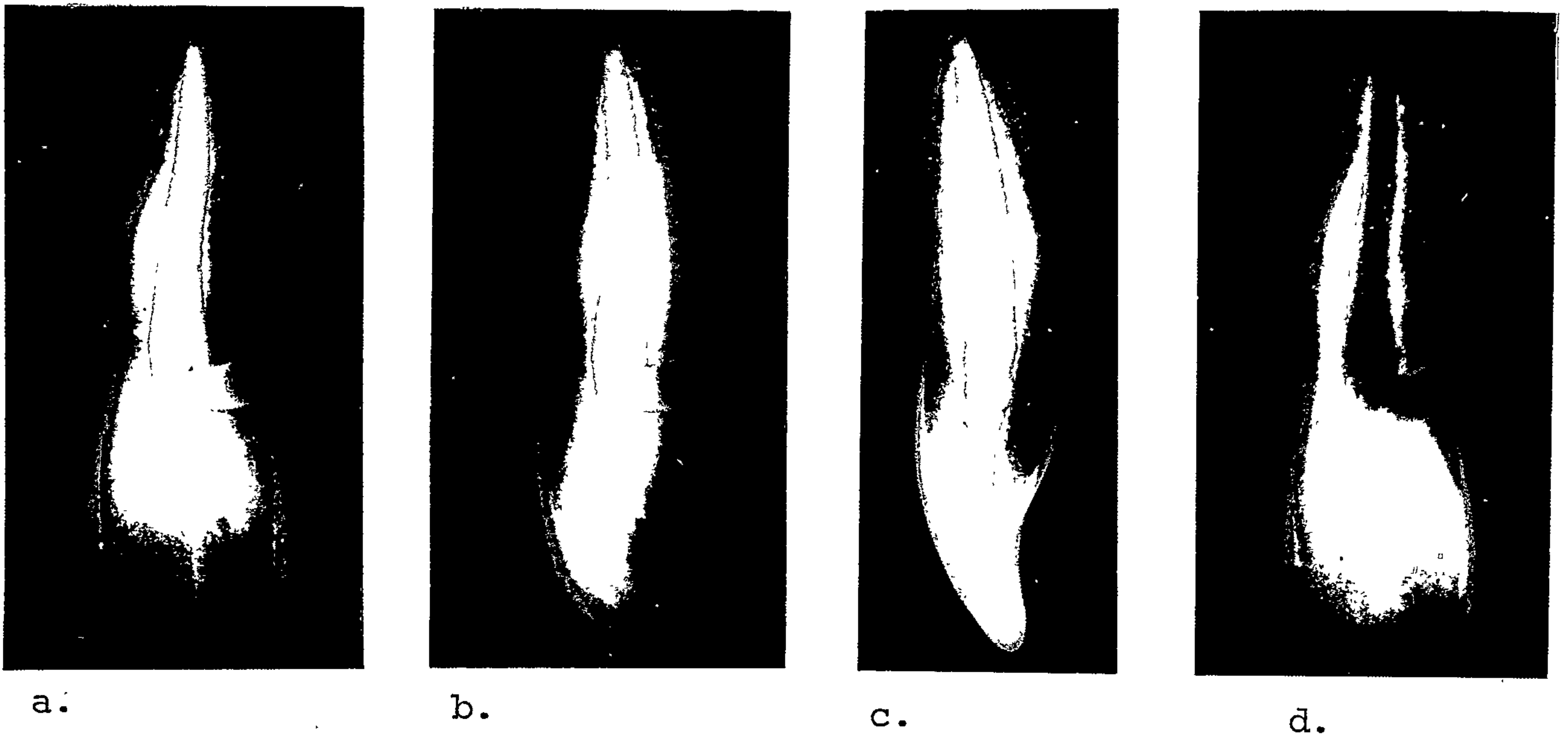
Discussion

The use of a radiopaque contrast medium which may be introduced into the root canals of extracted teeth has been used to demonstrate internal anatomy by Barker et al⁽¹⁵⁾. In this technique, the set mass of red lead-impregnated elastomer precludes the easy elimination of the contrast from the canal

^{*} 55 Kv, 7Ma.

Fig. 3

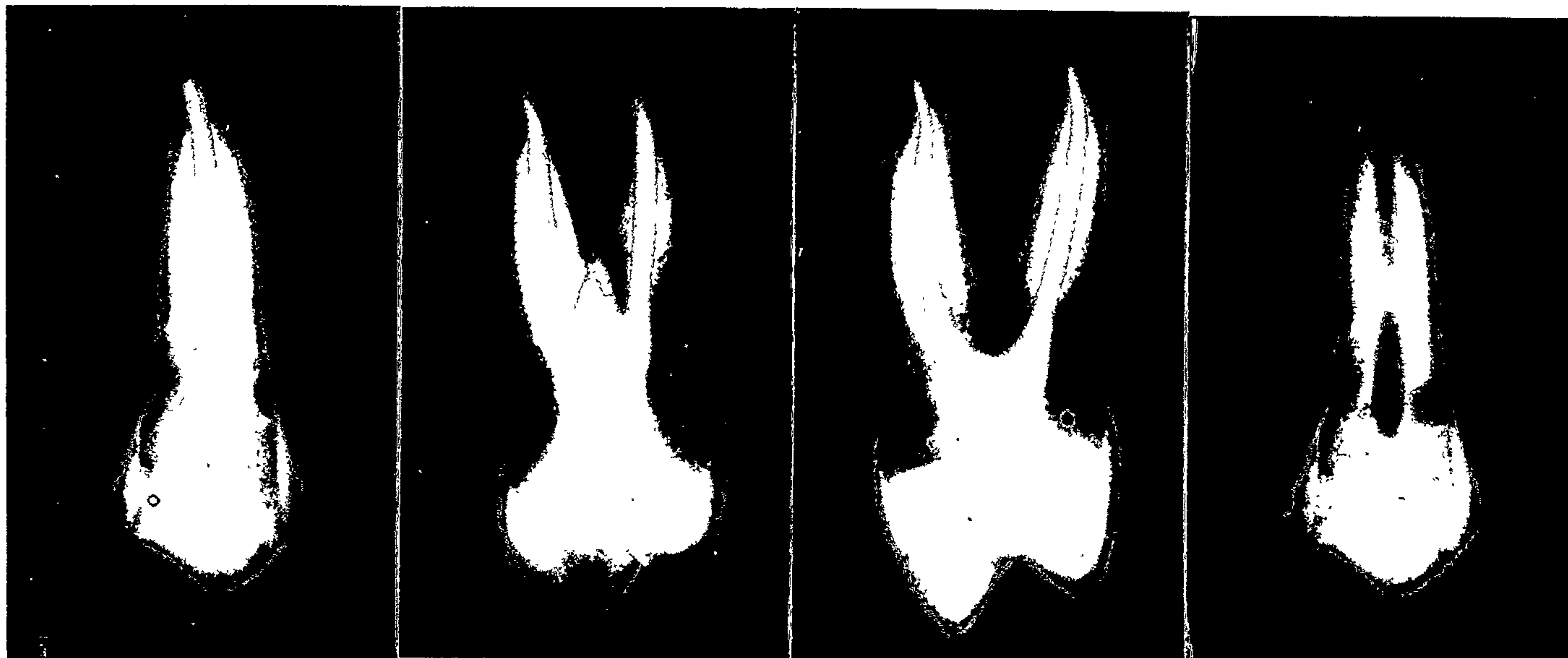
Maxillary Central Incisor



- a. Labio-lingual view of a contrast infused specimen. Note the size and shape of the pulp horns, the variation in canal width throughout and the meniscus formed by the contrast medium at the cervical opening.
- b. Three-quarter view showing the canal assuming a more regular shape as the tooth is rotated.
- c. Proximal view. Note the lack of variation in canal width compared with that seen in 3a.
- d. Labio-lingual view following clearance of the contrast medium shows the canal system completely free of radiopaque material.

Fig.4

Maxillary First Premolar



a.

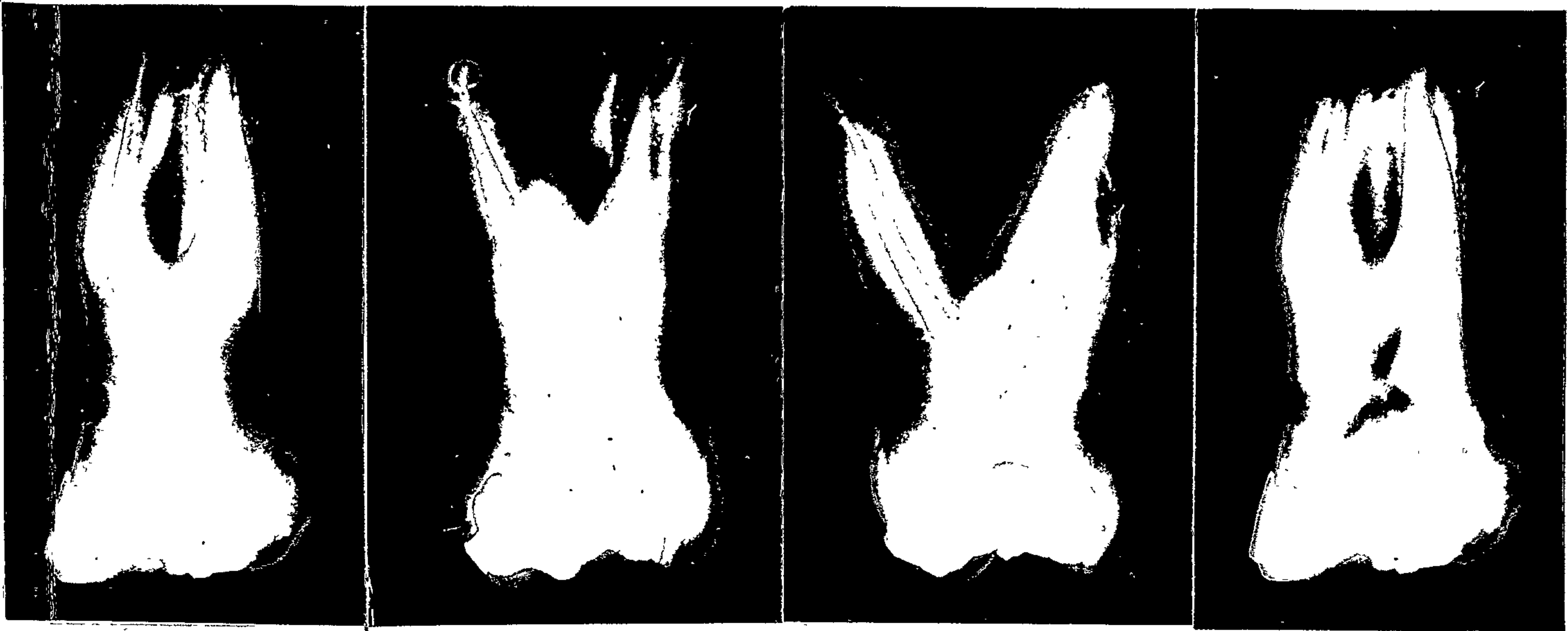
b.

c.

d.

- a. Bucco-lingual view of a contrast infused specimen. Two canals which are superimposed appear as one although apical "branching" is evident.
- b. Three-quarter view shows two roots and two canals. The small bubbles which appear in the contrast medium are due to inadequate vacuum control during the infusion process.
- c. Proximal view shows the outline of the pulp chamber and root canals follows that of the external surface of the tooth.
- d. Bucco-lingual view of the specimen cleared of contrast medium.

Maxillary First Molar



a.

b.

c.

d.

- a. Bucco-lingual view reveals three canals. Apical variations may be seen in the mesio-buccal and palatal canals.
- b. Three-quarter view clearly shows a lateral branch in the apical third of the palatal root and delta formation at the apex of the mesio-buccal root. The broad mesio-buccal root is also seen to contain two canals which join in the apical third. The circular form seen at the apex of the palatal root is an artifact caused by leakage of the contrast medium from the canal.
- c. Proximal view shows superimposition of the buccal roots.
- d. Bucco-lingual view following clearance of contrast medium.

system. Indeed the internal anatomy of the tooth may be altered from the original if endodontic instruments and/or chemical agents were employed to effect its removal. The use of a suitable water soluble contrast allows for its total elimination from the tooth without damage to the internal structures.

Lowman et al⁽²¹⁾ has used a radiopaque dye (Hypaque 90% with 2% methylene blue) to demonstrate canal morphology with particular reference to the presence of accessory canals. The technique employed by Lowman is different in detail, being more complex than the one hereby described although both are similar in principle. It is important to note, each technique was developed independently and apparently with different purposes in view. The purpose of the development of the technique described here is to provide a basis for comparison between the original morphology of the canal systems of teeth and that prevailing following the implementation of canal preparation with endodontic instruments.

The procedures undertaken by clinicians may be assessed by radiographic interpretation combined with the presence or absence of clinical features and symptomatology⁽²²⁾. This of course only relates to those cases where the patient returns upon recall by the endodontist. The attendance of patients for follow-up examination is generally poor⁽²³⁾ and this combined with the questionable nature of radiographic assessment⁽²⁴⁾ points up the need for the development of further techniques to evaluate the technical procedures utilised in endodontic therapy. The process so illustrated provides the facility for the individual assessment of technique by clinicians as well as

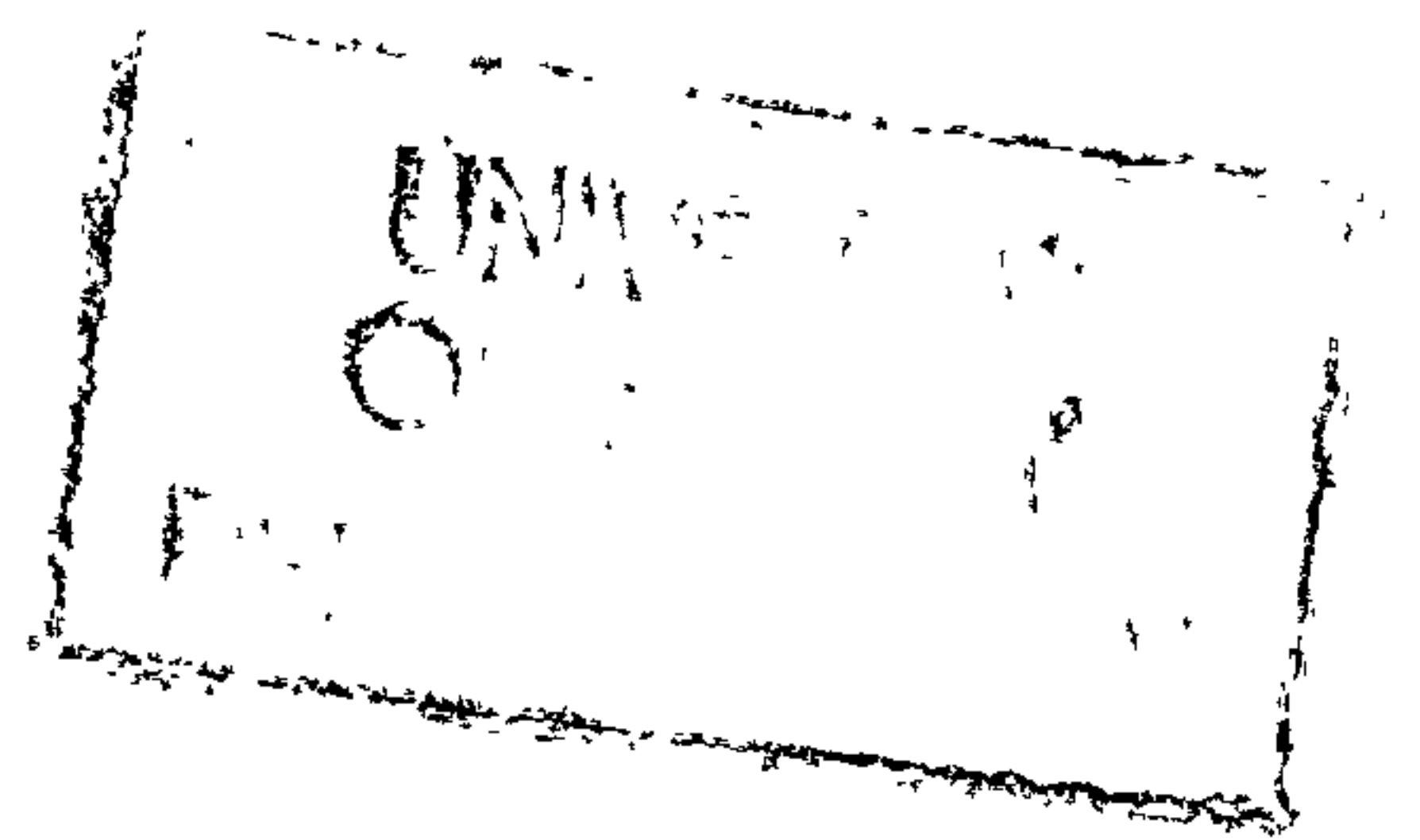
being one which may be easily incorporated into teaching programmes. The same method may be utilised on a larger scale for the mounting of research programmes to assess on a statistical basis the potential for clinical success.

Summary

A number of techniques have been reported whereby canal systems may be demonstrated in vitro. An additional technique has been developed which allows for the study of the internal anatomy of teeth prior to and following instrumentation on the same specimens. The use of a water soluble contrast medium infused into root canal systems provides for easy removal of the contrast without alteration to the internal anatomy.

The pulps were eliminated from one hundred and sixty four extracted human teeth by enzyme action, the pulp chambers and root canal systems were filled under vacuum with a water soluble radiopaque contrast medium and each tooth was radiographed from three angles with the contrast medium in situ. The contrast medium was cleared and a further radiograph taken.

The potential for this procedure in the evaluation and assessment of the technique of canal preparation has been projected.



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ENDODONTIC MORPHOLOGY IIA Radiographic Analysis

Since Hess⁽¹⁾ wrote his treatise on the anatomy of root canals early this century, the importance of a knowledge of the internal anatomy of teeth in the practice of endodontics has gone without challenge. Despite the apparent shortcomings⁽²⁾ of the technique used in demonstrating the canal systems in that monumental work, there were relatively few alternative methods of study developed until comparatively recent times. Research in endodontics has now produced a number of techniques for the demonstration of endodontic morphology⁽³⁻¹¹⁾ however with one exception⁽¹¹⁾ the more accurate of these preclude the use of the tooth from further endodontic study.

A technique utilising a radiopaque contrast medium within extracted teeth which have had their pulps cleared by enzyme action has been previously outlined⁽¹²⁾. This paper draws attention to the information which has been gained from the accumulation of data obtained by using this technique on a number of extracted human teeth.

Method and Materials

As previously outlined⁽¹²⁾ one hundred and sixty four extracted human teeth of various denominations were opened at the cemento-enamel junction, subjected to enzyme action to remove the internal soft tissues⁽¹³⁾ and tested by water injection and by aspiration to ensure the pulp spaces were cleared and the apical foramina were patent. The teeth were then infused under

vacuum with a 70% solution of sodium iothalamate* and radiographed from the proximal, buccal and an oblique angle with the contrast medium in situ. The canal systems were cleared by the injection and aspiration of water through the teeth and a further radiograph was taken from the buccal aspect in each case. The films were processed in strict accordance with the instructions of the manufacturer and filed ready for further study.

Each radiograph was examined under ten magnifications over a ground glass screen backed by an artificial light source. Information was recorded (Table I) according to the number and distribution of teeth, the number and distribution of canals, the presence of apical ramifications, the presence of lateral (radicular) canals and the presence of accessory canals emanating from the pulp chamber (furcation canals).

The criterion for establishing the presence or absence of canal aberrations was such that the characteristic must show in at least two radiographs supported by their proximity to other features in the morphologic "character" of the tooth. The specimens under study were representative of the entire range of human teeth, the smallest group comprising three teeth (mandibular first and third molars) and the largest group comprising twenty four teeth (maxillary second premolars).

* Conray 420, May and Baker Ltd. Dagenham, England.

TABLE I Analysis and Distribution of Canals

A. Maxillary Teeth

Tooth	No. of Specimens	No. of Canals					Lateral Canals		Apical Ramifications	Furcation Canals
		1	2	3	4	5	1	2		
1	14	14	-	-	-	-	4	2	-	-
2	6	6	-	-	-	-	2	-	1	-
3	6	6	-	-	-	-	-	-	1	-
4	12	1	10	1	-	-	4	-	1	-
5	24	9	15	-	-	-	1	-	8	-
6	9	-	-	1	7	1	-	-	7	-
7	12	-	2	6	4	-	-	-	7	-
8	12	2	3	7	-	-	1	-	5	-

B. Mandibular Teeth

Tooth	No. of Specimens	No. of Canals					Lateral Canals		Apical Ramifications	Furcation Canals
		1	2	3	4	5	1	2		
1	6	2	3	1	-	-	-	-	-	-
2	7	3	3	1	-	-	-	-	1	-
3	9	8	1	-	-	-	1	-	4	-
4	16	11	4	1	-	-	-	-	6	-
5	12	11	1	-	-	-	-	-	6	-
6	3	-	-	2	1	-	-	-	5	-
7	13	-	1	10	2	-	-	-	2	-
8	3	-	1	2	-	-	-	1	1	-

Results

Maxillary Incisors and Canines:

It is significant to note, in each of the twenty six specimens only one main canal was evident and both pulp chamber and canal morphology related directly to the descriptions given by previous authors^(1,14,15). The incidence of lateral canals was rather higher than expected in the case of central incisors, four specimens of fourteen showing evidence of this and in two of these there were two lateral canals present in the one root (Fig.1). There were two cases where lateral canals were evident in six lateral incisor roots, there being none present in the canines studied.

Apical ramifications were rather rare and only two roots (one lateral incisor and one canine) of the twenty six examined demonstrated this feature.

Maxillary Premolars:

These teeth comprised the largest group investigated. Again the basic anatomical features recorded in previous studies were noted and this was particularly evident when considering the number and distribution of canals. First premolars nearly always exhibited two canals and two roots (one buccal and one palatal) although two teeth were atypical, one containing one canal (dumbell shaped in section) and one root and the other three canals (two buccal and one palatal) and two roots (Fig.2). Second premolars were found to contain two canals rather than one in the ratio of 5:3, although all possessed single roots. Of those with two canals eight pairs joined before reaching the root apex and seven pairs progressed to separate exits. The

Fig. 1



a.



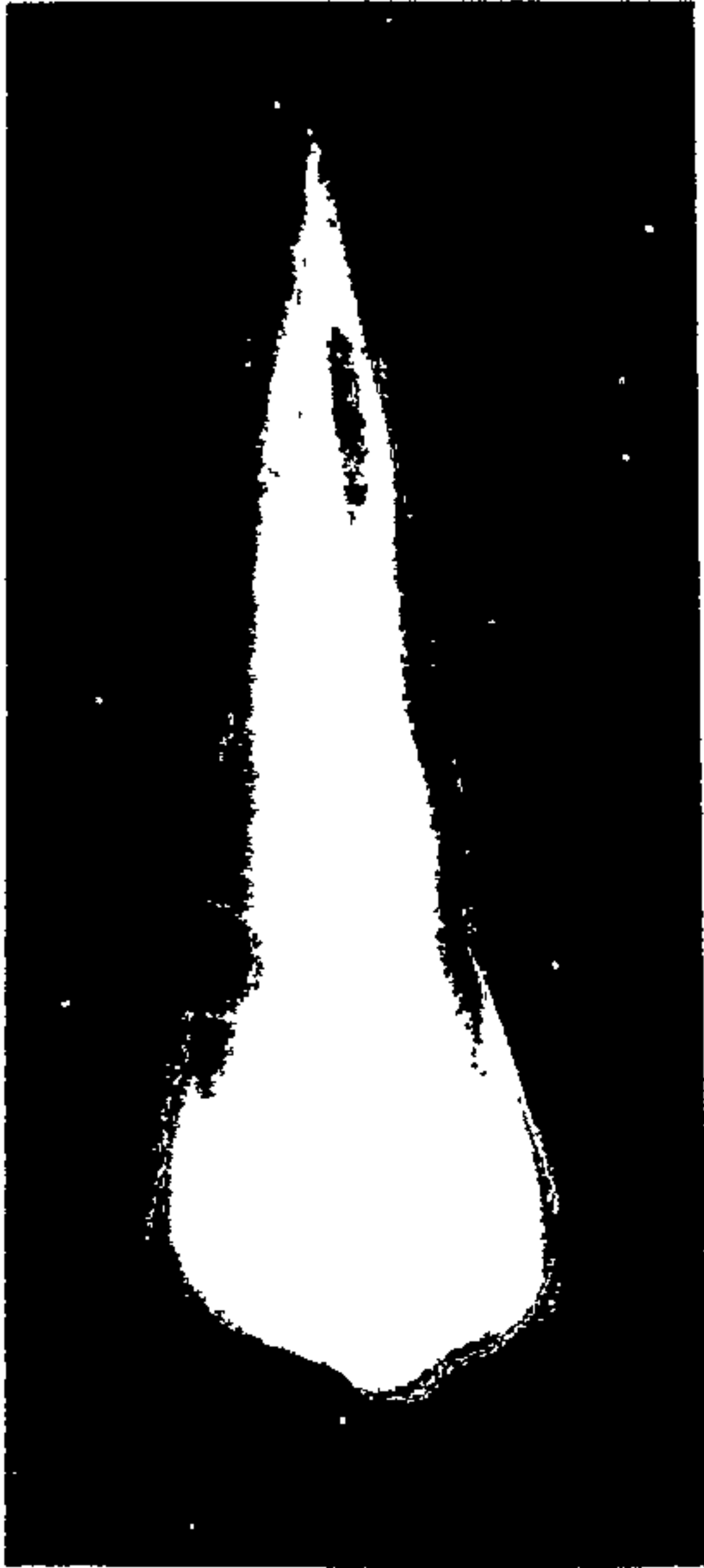
b.



c.

Maxillary central incisor radiographed from three different angles showing fine lateral canals at the beginning and end of the middle third of the root.

Fig. 2



a.



b.



c.

Maxillary first premolar. The buccal root contains two separate canals which join apically.

presence of lateral canals was less than in the case of the maxillary incisors (only five of thirty six teeth studied) whereas that of apical ramifications was greater, there being nine cases in the thirty six teeth studied.

There were no furcation canals observed.

Maxillary Molars :

These comprised the second largest group reviewed and there were two features which were outstanding when these specimens were examined.

Of nine first molars, seven presented with four canals (two in the mesio-buccal root and two others), one (Fig.3) presented with five canals (two in the mesio-buccal root, two in the disto-buccal root and one other) and only one tooth showed (the desired and more often than not accepted by clinicians) three canals, distributed as mesio-buccal, disto-buccal and palatal. In all cases of mesio-buccal roots showing two canals there was a confluence to one, prior to the canals reaching the end of the root. In the one case which contained five canals, the "extra" disto-buccal canal possessed its own apical foramen.

Second and third molars varied in the number and distribution of canals, from two to four (second molars) and one to three (third molars). Of the four second molars which contained four canals (i.e. two mesio-buccal canals) only one showed two separate canals throughout the entire root length, the remaining three roots contained two canals which joined prior to the root end being reached.

Of all maxillary molars examined (thirty three teeth)

Fig. 3



a.



b.



c.

Maxillary first molar with a complex canal system. The three-quarter (b) and proximal (c) views show there to be two separate canals in both the mesio-buccal and disto-buccal roots.

only one tooth (a third molar) contained a lateral canal whereas nineteen canals demonstrated apical ramifications (Table IA). The latter were fairly evenly distributed from tooth to tooth although the mesio-buccal roots of first molars were most commonly affected in this manner, there being five of the nine mesio-buccal roots showing this feature (Table IIA).

There were no furcation canals present.

Mandibular Incisors and Canines:

Here the number of canals present did not reflect the number of roots except in the case of canines. In approximately half of the incisors studied there was more than one canal. Six of the thirteen incisors contained two canals and two of the thirteen contained three canals (Fig.4). All except one canine of the nine studied possessed one canal, the exception containing two canals and in that case two separate roots. Six of the eight incisors with multiple canals showed a confluence of these prior to the canals reaching the apical ends of the roots.

One lateral canal was seen in this group (the two rooted canine) and five canal systems showed apical ramifications, four of which were in canines (four of the nine studied).

Mandibular Premolars:

This was also a large group compared with those others in this study and all possessed one root. In the majority of cases (twenty two of twenty eight in the group) there was only one canal present, this being more evident in second premolars (eleven cases in twelve) than in first premolars (eleven cases in sixteen). Of those containing multiple canals, five specimens contained two canals and one contained three canals (Fig.5), all

TABLE II Distribution of Apical Ramifications

A. Maxillary Molars

Tooth	Canal				
	Buccal	Mesio-buccal	Mesio-lingual	Disto-buccal	Palatal
6	-	5	-	-	2
7	1	3	-	3	-
8	2	1	-	-	2

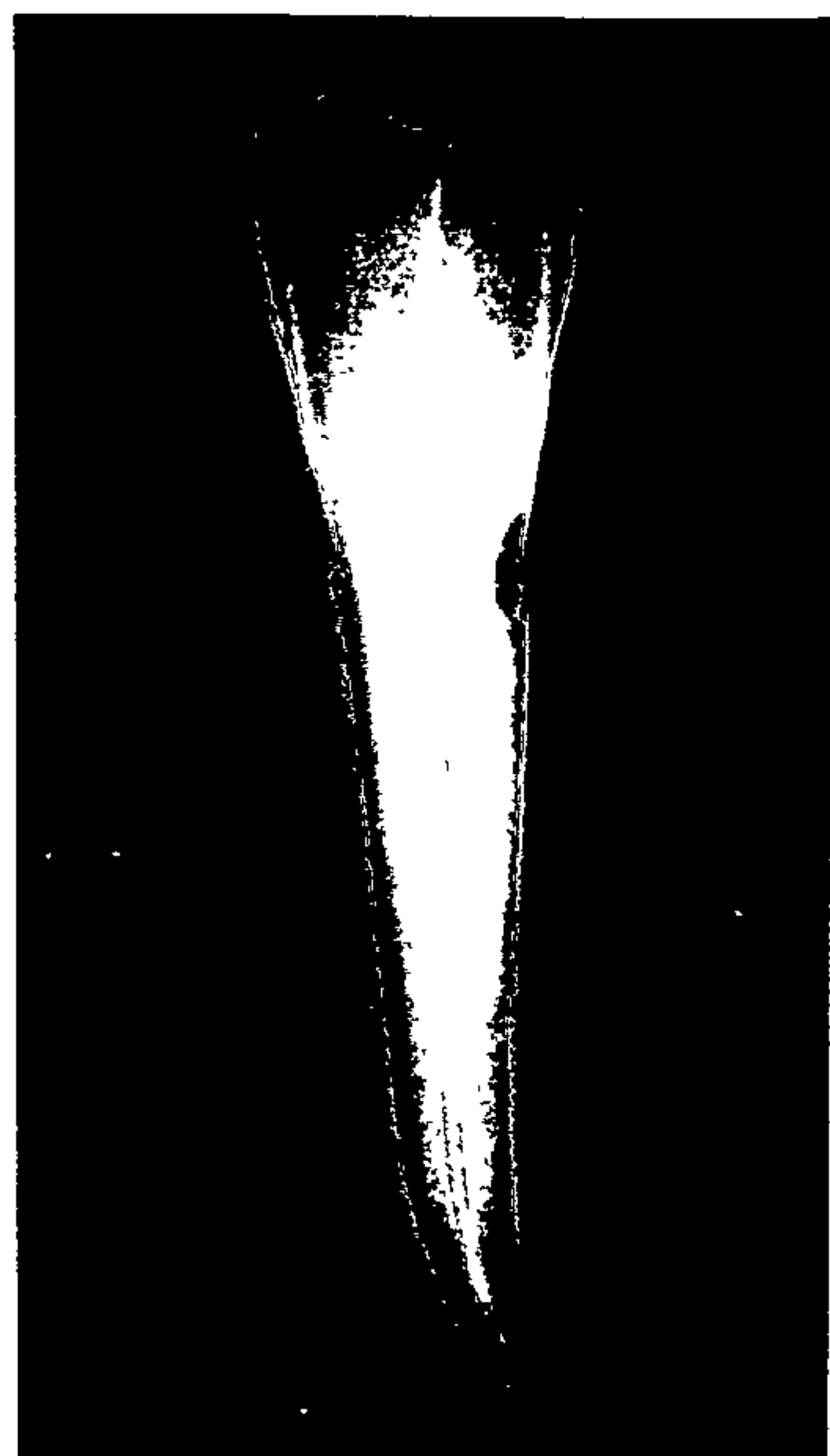
N.B. Apical ramifications present in 19 of 103 canals studied (18.4%)

B. Mandibular Molars

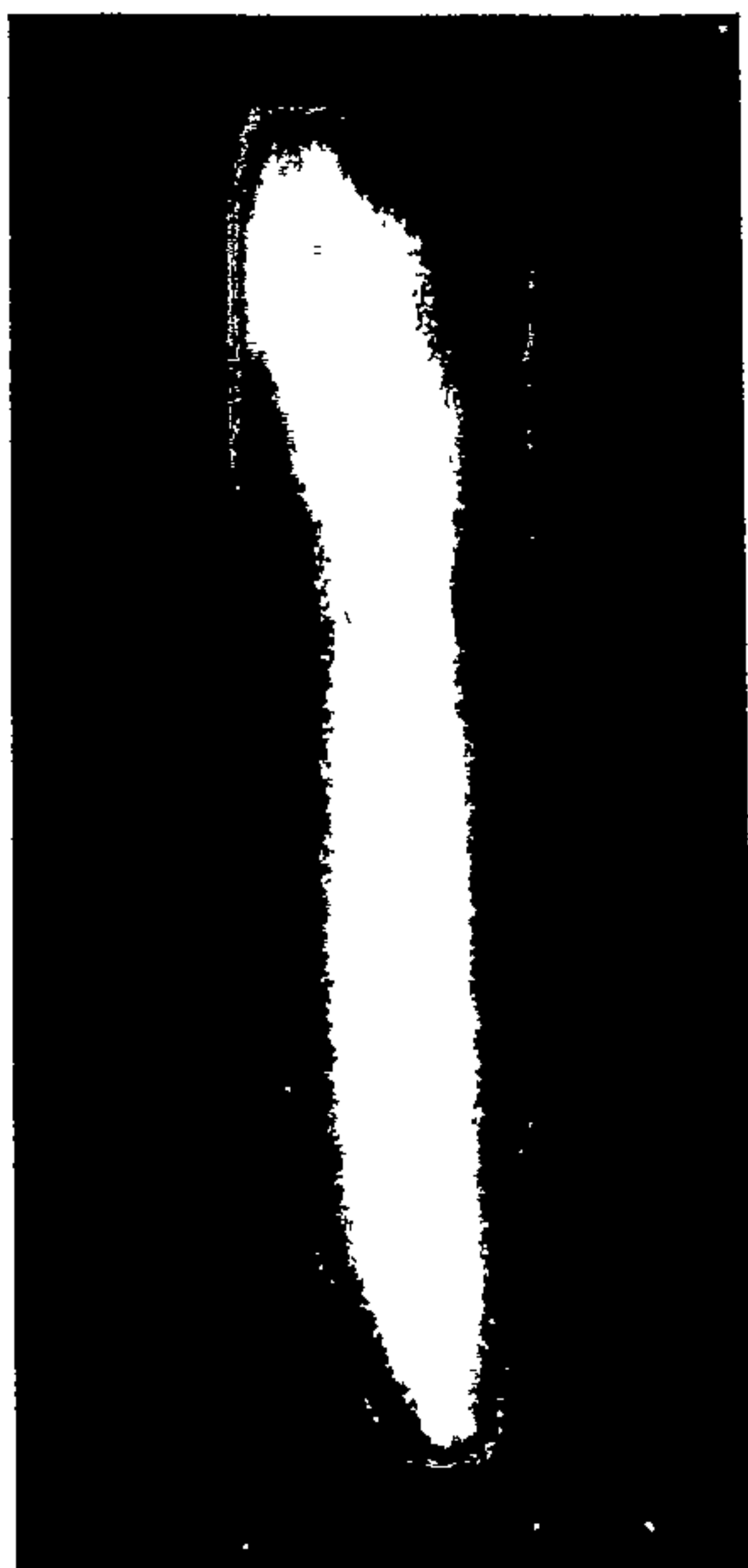
Tooth	Canal					
	Mesio-buccal	Mesio-lingual	Mesial	Disto-buccal	Disto-lingual	Distal
6	-	-	3	-	-	2
7	-	1	1	-	-	-
8	-	-	1	-	-	-

N.B. Apical ramifications present in 8 of 58 canals studied (13.8%)

Fig. 4



a.



b.



c.

Mandibular central incisor containing three canals, two of which join apically. Note that the labio-lingual view (a) gives no indication of the complexity of the canal system.

Fig. 5



a.



b.



c.

Mandibular first premolar. From a simple coronal canal form the system increases in complexity in an apical direction, terminating in a pronounced delta formation.

of which proceeded to separate exits at the root ends.

There were no lateral canals present and twelve specimens showed apical ramifications, with second premolars having a slight predominance in this respect. Apical ramifications were present in six first premolars of sixteen studied and in six second premolars of twelve studied.

Mandibular Molars:

This group more closely resembled the expected norm^(16,17) (i.e. two roots and three canals - mesio-buccal, mesio-lingual and distal) than the maxillary molars. Of nineteen teeth under examination, fourteen conformed to this specification (Fig.6) whilst three showed two separate distal canals (all of which joined apically) and two (a second and a third molar) contained only two canals (one mesial and one distal).

Lateral canals were notable by their absence, only two showed in the nineteen specimens examined. There were fewer canals which demonstrated apical ramifications than in those of the maxillary molars, these occurring most frequently in first molars.

There were no furcation canals present.

Discussion

As previously noted⁽¹²⁾ the reason for developing the technique of infusion has been to provide a means to study the internal anatomy of extracted teeth without causing damage to the internal walls so that the same specimens may be subjected to endodontic instrumentation, thus allowing a comparison study to be made at the completion of the latter.

Fig. 6



a.



b.



c.

Mandibular first molar which conforms to the two root/three canal concept, the two mesial canals joining before reaching the root apex. Note the apical accessory canal which exits onto the mesial surface of the distal root.

This has been carried out and the results from such a study will be reported in due course. Notwithstanding the small number of specimens available for study in some groups of teeth, there are certain facts which have emerged which may be of interest to the endodontist and which could assist in the practice of endodontics.

It was found that an analysis of the radiographs produced in this experiment was difficult in the case of multi-rooted teeth due to the superimposition of tooth substance caused by the number of roots. A more careful approach to angulation of the tooth to the central ray would have made accurate radiographic assessment a far easier goal to accomplish than that which prevailed. Much care in checking and double-checking against known anatomical features was necessary to correctly assess the detail so recorded.

It is widely recognised the number of canals generally conforms with the number of roots with notable exceptions being the maxillary premolars, the maxillary first and second molars, the mandibular incisors and canines and the mandibular first and second molars⁽¹⁾. This was seen to be the case in this study however the mesio-buccal roots of maxillary first and second molars presented with a large proportion of "fourth canals". These in all cases were located in the mesio-buccal root. There was one case (which must be regarded as atypical) where a "fifth" canal was present and this was one of the two found in the disto-buccal root of a maxillary first molar.

The presence of a "fourth" canal in the mesio-buccal root

of maxillary first molars has been well documented^(1,18). Barker et al⁽¹⁹⁾ have drawn attention to the mesio-buccal roots of maxillary molars which are "compressed mesio-distally, broad at the cervix and heavily grooved longitudinally on (the) distal aspect". They further state "a single canal in this root is the exception, apart from very young specimens, and when present apical division may be encountered". Pineda⁽³⁾ showed in a survey of two hundred and forty five such roots that 40.8% had one canal and one foramen whilst the remainder showed multiple canal systems. This study although small in comparison with Pineda's indicated a much higher incidence of two canals in the mesio-buccal root than was the case in the larger survey although all demonstrated a confluence before reaching the apical foramen. The results obtained here may if nothing else point up the need for constant awareness of the potential for the presence of multiple canal systems in this root. It may be argued, the number under study being so small is not representative of the conditions which prevail with a larger sample. It does, however, have a distinct bearing upon the practice of endodontics as a "run" of eight out of nine teeth showing complex canal systems in the mesio-buccal root may occur just as readily in the clinical as in the laboratory situation. In this respect the endodontist must be ever watchful that all canal entry points are located and where possible, penetrated to facilitate adequate debridement, shaping and obturation, there being no guarantee that apical confluence would always prevail.

The presence and complexity of accessory canals has been well exposed^(1,20,21,22) although there is a paucity of

information available as to their frequency. In this study evidence of lateral canals was mainly confined to the maxillary teeth, only three being present in the sixty nine mandibular teeth which were examined. The highest incidence was found in maxillary incisors (ten present in twenty teeth) with the only other group of note being the maxillary premolars (five present in thirty six teeth). In considering the significance of lateral branches it is important for the clinician who undertakes endodontic treatment to ensure in all cases the complete obliteration of the root canal to the full extent of the depth to which instruments penetrate within the canal. Unfilled portions of the main canal adjacent to lateral canals would predispose to failure⁽²³⁾ particularly when necrotic tissue is present in the lateral canal. In this respect, the employment of root resection and retrograde filling⁽²⁴⁾ must be considered an inferior method of endodontic treatment when compared with the condensation techniques of orthgrade obturation.

Apical ramifications were present in all groups of teeth studied except maxillary and mandibular central incisors. Variations from the results of Hess's study⁽¹⁾ may well result from the small sample of each tooth under review. It is significant, however, that apical ramifications were evident in fifty five canals of three hundred and eighteen in this study (17.3%). In endodontic treatment the case for canal preparation to terminate short of the root apex has been put by various authors^(25, 26, 27) and many reasons for this have been propounded. It is recognised, the limitation of endodontic procedures to a level approximating that of the dentino-cemental junction not

only reduces post treatment apical trauma but enhances the potential for periapical repair^(28,29). Parallel with this the clinician should remember that root length and canal length are not synonymous due to the variation in position of the apical foramen in relation to the radiographic apex⁽⁴⁾ and this was an obvious feature observed in this study.

As early as 1930, Grove⁽³⁰⁾ drew attention to the presence of an apical constriction and recommended terminating canal preparation and root filling at this level. Further, with the knowledge that apical ramifications are often present, Davis⁽³¹⁾ suggested "partial vital pulpectomy" claiming continued vitality in the residual pulp tissue in over 90% of cases. From the results of the present study it may be assumed, in about one case in six it would be difficult to instrument through the apical end of the root to the periodontal membrane due to the lack of a single pathway. To attempt to create such a pathway would mean stripping the apical end of the root by penetrating through tooth substance which should be retained. It must be contended that the termination of the canal preparation and root filling should be close to the proposed 1.0 - 1.5mm from the radiographic apex⁽²⁵⁾ or as near thereto as instruments are able to penetrate without the use of undue force.

A Note on Furcation Canals :

The established endodontic texts give scant mention to these anatomic phenomena although it has been widely accepted

that radiolucencies in the furcation region may be related to their presence. When repair follows conservative endodontic treatment in such cases, it is not known whether the lesion had arisen from the coronal pulp space or by extension from the apical region. The results of two of the latest studies serve to demonstrate the relationship between pulp and periodontal pathosis. Langeland et al⁽³²⁾ showed pathological changes occur in pulp tissue following the cumulative effects of periodontal disease but specified "total (pulp) disintegration apparently occurs only when all main apical foramina are involved by bacterial plaque". Sinai and Soltanoff⁽³³⁾ using experimental rats were able to produce changes in the pulp through induced periodontal disease and vice-versa and they conclude "Inflammatory changes in the periodontal ligament and pulpal necrosis apparently produce changes across the barrier of the intact tooth surface by undetermined mechanisms".

Three recent investigations have been carried out to determine the frequency of occurrence of furcation canals in extracted human posterior teeth. Vertucci and Williams⁽³⁴⁾ in a study of 100 mandibular first molars found 23% demonstrating an accessory canal arising from the pulp chamber. Burch and Hulen⁽³⁵⁾ in a study involving 95 maxillary and 100 mandibular first and second molars were able to show 76% as containing accessory foramina in the furca. Lowman et al⁽¹¹⁾ using a technique similar in principle to the one described in this paper found 55% of maxillary and 63% of mandibular first and second molars to possess accessory canals in the coronal and middle thirds of the root surface. They did not differentiate between those which arose from the root canals rather than those

arising from the pulp chamber. They specify the results were obtained from teeth which had been subjected to root planing and they postulate occluded canals are made patent by this procedure.

Of the 52 maxillary and mandibular molars examined by the process used in this study there were no furcation canals arising from the pulp chamber shown by radiographic means. One specimen (a maxillary second molar) contained a fine canal which originated from a point just within the entrance to the palatal canal and this was filled with contrast medium.

The results obtained in this study differ so greatly from those mentioned above that further investigation should be undertaken to clarify this issue. In the present study there were two methods of demonstrating accessory canals which became evident. One was the "jet effect" caused by water infusion under pressure⁽¹²⁾ and the other was by the examination of radiographs after the canal systems were permeated by radiographic contrast medium. It was always a simple matter to demonstrate radicular and apical accessory canals by either of the above means and yet this was not so regarding those arising from the pulp chamber.

Until further evidence has been accumulated it must be assumed accessory canals are known to arise from the pulp chamber and may present problems if not treated. The technique of sealing the floor of the pulp chamber by the use of alloy⁽³⁴⁾, condensation of warm gutta percha⁽³⁶⁾ or preferably zinc oxide and eugenol cement⁽³⁷⁾ as advocated by Vertucci and Williams may thus be advised as a routine procedure.

Summary

Radiographs of one hundred and sixty four extracted human teeth were examined under magnification following the infusion of their empty canal systems by a radiopaque contrast medium under vacuum.

An analysis of the results was made from the statistics recorded and some conclusions have been drawn from these. The form and number of canals generally conformed with that of the roots which housed them, with some exceptions. The presence of two canals in the mesio-buccal roots of maxillary first molars and the incidence of lateral, accessory and furcation canals has been noted. A discussion upon the role of the endodontist in the treatment of teeth with such anatomical features has been undertaken.

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ENDODONTIC MORPHOLOGY IIICanal Preparation

The aim in canal preparation is to remove the contents of the root canal system to a predetermined level and in so doing, shape the canals to allow for the sterilization and ultimate obliteration of the system with root filling material. The achievement of this aim has traditionally been effected by the use of broaches, reamers and files within the root canals following the establishment of an adequate access cavity through the crown of the tooth. Radiographic assessment pre-operatively, throughout the course of treatment and post operatively has been a useful guide for the operator in the judgment of his performance.

In the practice of endodontics, radiographs exposed from the buccal are often inconclusive in establishing a true picture of the three dimensional geography of the canal systems of teeth. The problems caused by the lack of definition of fine canals combined with the variable density of bone, the overlapping of adjacent structures and angulation difficulties necessitate a fine balance between awareness of anatomical variations and attention to radiographic detail by the clinician. Recognising the difficulties inherent in the study of radiographs in vivo⁽¹⁾ it was decided that a comparison study be undertaken to ascertain the potential for entering and adequately preparing a number of canal systems in extracted teeth.

The technique of demonstrating the internal anatomy of one hundred and sixty four extracted human teeth by the use of

a water soluble radiopaque contrast medium* has been previously reported⁽²⁾. The same specimens were later opened coronally and the canals prepared with endodontic instruments. Records were kept for statistical assessment and for later comparison with "pre- and post-treatment" radiographs following infusion of each specimen with the same radiopaque contrast medium.

Method and Materials

All teeth were opened coronally with a plane-cut 70L tapered fissure bur in an airturbine handpiece, the final shaping of the access cavity being carried out with a number 6 round bur and tapered diamond points ("Horico" 20a, 20a1) in a low speed handpiece. The coronal outlines were cut after the designs of Ingle⁽³⁾ with slight modifications according to the dictates of the tooth in question (Figs 1, 2, 3 and 4). The coronal openings were made in such a way as to leave the floors of the pulp chambers undisturbed as a guide to determining the various canal entry points, the roof being completely removed in each case to facilitate vision.

The specimens were not mounted so the operator had the benefit of the external anatomical features of the roots being an aid to determining the number and shape of the root canals. To balance this it was decided not to study the pre-operative radiographs nor to use radiographic assistance during canal preparation. The pre-operative radiographs had

* Conray 420, May and Baker Ltd., Dagenham, England

Fig. 1



Maxillary Central Incisor :

Outline form of the access cavity follows the coronal outline, being triangular in shape with the cingulum being included within one well rounded apex. The cavity should be extended to include the pulp horns and to provide adequate access for instruments to be used in an unstrained form.

Fig. 2

Mandibular First Premolar :

Outline form is ovoid, following that of the occlusal surface of the tooth. It includes both pulp horns and provides as near as is possible straight line access for instruments. The dark centre in the occlusal opening is the apical portion of the canal.



Fig. 3



Maxillary First Molar:

Occlusal access cavity is basically triangular with the apices corresponding to the canal entry points. The mesial side should be additionally opened to provide for access to the mesio-palatal canal entry point. Any further opening which may be necessary should be directed towards the mesio-buccal to ensure adequate entry into the canal systems of that root. It is generally unnecessary to break through the transverse ridge on the occlusal surface of the tooth.

Mandibular First Molar:

The triangular outline form of the access cavity corresponds with the outline of the occlusal surface of the tooth, being somewhat mesially placed. Adequate vision of the canal entry points is required and should further expansion be necessary, this is best provided at the expense of the mesio-buccal cusp.

Fig. 4



been filed for later reference one year previous to the commencement of canal preparation and they were deliberately not seen again until all canals had been prepared. Length determination for each canal entered was established by working a number 10 K file as far apically as possible (when obstructed) or through the apical foramen and then withdrawing it flush with the apical opening. All lengths were recorded by applying a fine bead of unset zinc oxide and eugenol cement to the shaft of the instrument at a level adjacent to a coronal reference point, the latter being either the incisal edge or the highest cusp tip (Fig.5). The canals were prepared to a depth one millimetre short⁽⁴⁾ of the actual tooth length except where the instrument was precluded from reaching the apical opening. In the latter cases the canals were prepared to the maximum depth to which instruments would enter and this length was recorded.

Instrumentation

All canals were prepared by the use of standardised Cord and Kerr K and Cord Hedstrom (H) files in an attempt to create a form which would facilitate the sealing of each canal with laterally condensed gutta percha cones.

The technique was to establish wherever possible an apical seat and/or apical funnel, one millimetre short of the apical opening, into which a master cone may be firmly positioned. The canals were flared quite markedly toward the coronal leaving each apical funnel approximately two millimetres in depth. In the case of relatively wide and

Fig. 5



A maxillary first premolar with a K file inserted into the buccal canal. The method of marking the length on the instrument using a small bead of unset zinc oxide and eugenol paste is shown.

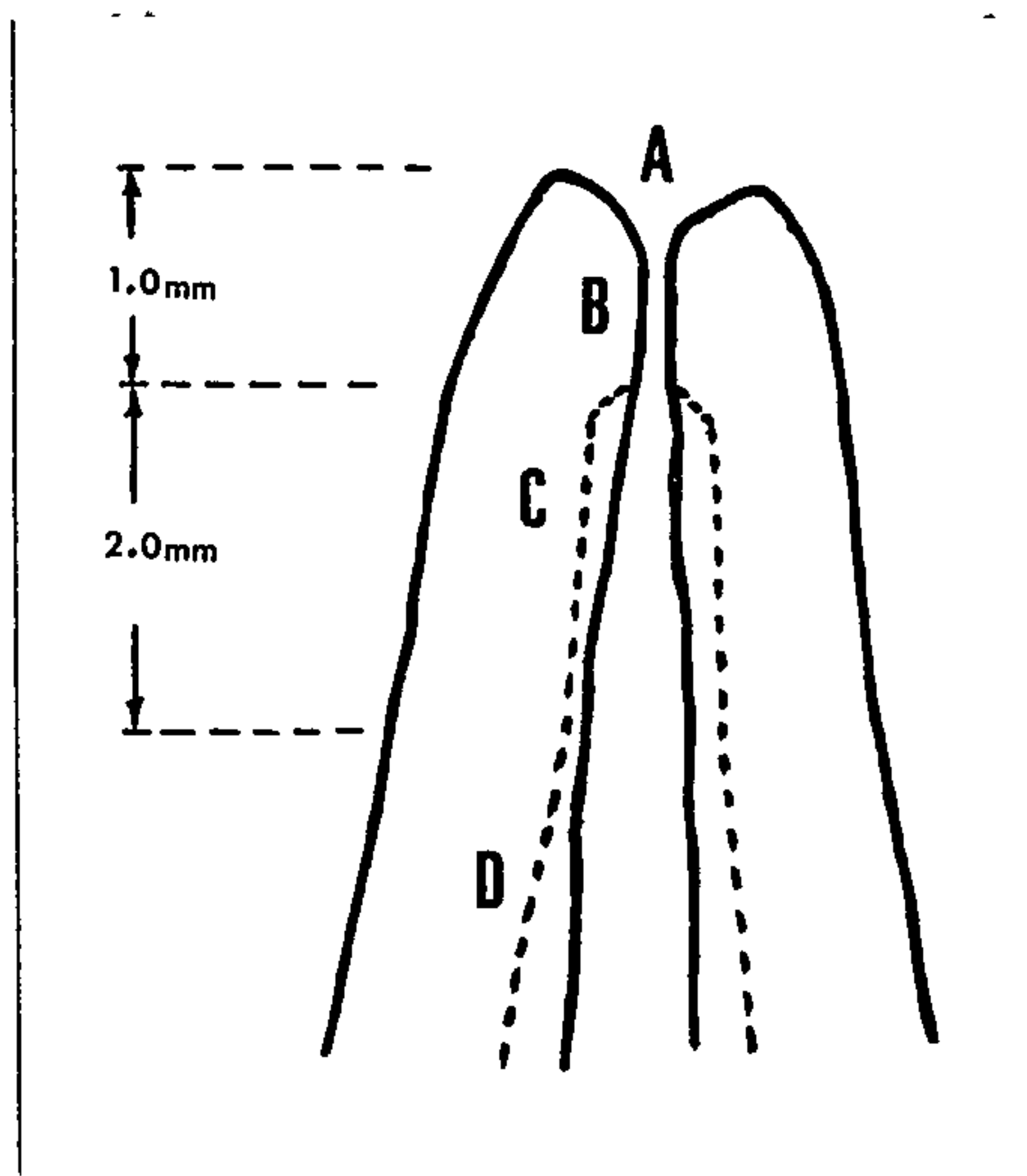
straight canals it was possible to form a shoulder or seat at the desired depth, apical to the funnel and against which a master cone may be fitted (Fig. 6a). Where curves exist the rotation of instruments is contra-indicated⁽⁵⁾ and large instruments are unable to negotiate these to the full depth of penetration. In such cases it was thus neither possible nor desirable to attempt to create an apical shoulder, and an apical funnel slightly larger than the size of the largest K file used was accepted. Flaring of the canal toward the coronal, approximately two millimetres short of maximum depth of penetration was then effected (Fig. 6b).

In each case, K files were used to open the canal to a size 25 or larger before H files were used to establish the flare. Only K files were allowed to proceed into the apical funnel, thus confining the dimensions of each funnel to a size slightly larger than that of the largest K file used⁽⁶⁾. All H files were marked 2.0mm short of the maximum canal depth (i.e. in most cases 3.0mm short of the apical opening) and in this manner an attempt was made to establish the apical shoulder/funnel and coronal flare so illustrated.

In all cases a combined flotation medium and chelating agent^{**} was used to facilitate canal entry and debridement. It was found that this material was inadequate as a chelate⁽⁷⁾ and where fine canals were present the use of E.D.T.A.⁽⁸⁾ as an unbuffered 5.5% solution was necessary to assist the entry into and the negotiation of the full length of such canals.

^{**} R.C. Prep., Premier Dental Products Co. Philadelphia, Pa.19107

Fig. 6



a.

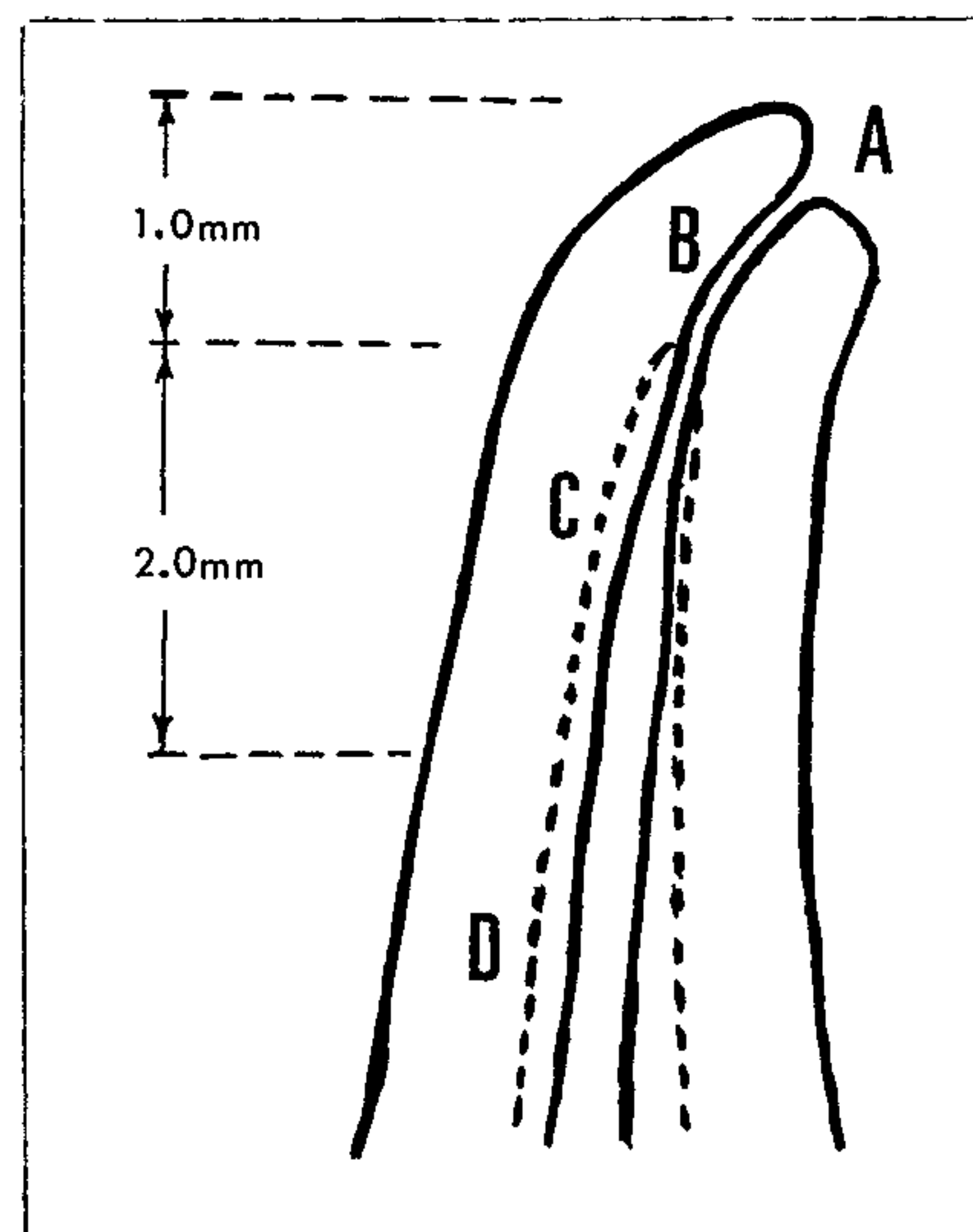
Apical shoulder formation when the canal is moderately large and straight.

- A. Apical opening.
- B. Untreated apical canal.
- C. Apical funnel, cut with a standardised K file into which a master cone may be fitted against the shoulder so formed. The master cone after being seated should resist displacement in a coronal direction.
- D. Canal body, which is flared coronally by H files to allow a space for the free and unimpeded placement of the master cone into position. The space is subsequently filled with subsidiary gutta percha cones thus stabilising the master cone.

Apical funnel formation when the canal is fine and curved.

- A. Apical opening.
- B. Untreated apical canal.
- C. Apical funnel, approximating the size of the largest K file used and into which a master cone may be fitted as in 6a.
- D. Canal body, which is flared coronally using H files to allow for uninhibited seating of the master cone to the end of the space marked C. The residual space is later filled with subsidiary gutta percha cones thus stabilising the master cone.

Fig. 6



b.

Upon completion of canal widening to an acceptable clinical standard, which for the purposes of this experiment was deemed to be two instrument sizes larger than that of the first which commenced to cut at the apical end, the canals were irrigated by means of a pipette with sodium hypochlorite (4.0%), hydrogen peroxide (3.0%), sodium hypochlorite (4.0%) and tap water in that order. In all cases an attempt was made to prepare the canal in the apical region to a size which would accept a 25K file or larger. As it was intended to prepare all canals to receive gutta percha master cones and subsequent obturation by lateral condensation, the above minimum apical dimension was considered to be desirable.

Observations

1. Chelates:

The action of R.C. Prep. was found to be inadequate in softening calcific obstructions found both at the points of entry and deep within fine root canals. This was overcome when 5.5% E.D.T.A. was used by flooding the pulp chamber and "working" the K file through a puddle of chelate. The risk of instrument failure was lessened whilst successful negotiation of each canal was progressed, in most cases, in less than one minute. The use of 5.5% E.D.T.A. was found to be of particular assistance when a fine canal entry point would only allow unassisted instrument penetration to a depth of one millimetre or less. In such instances the operator was able to see through the clear fluid and in a very short time progress the instrument into the canal. Where R.C. Prep. was used, not only did the initial penetration point become obscured by the opacity of the medium

but the success rate for entry was poor.

The usefulness of R.C. Prep. was much more evident when the canal had been negotiated to its full length. Whereas the canals were all made devoid of their contents prior to conducting this study⁽⁹⁾, in the clinical situation this would not be the case. The effervescent action of urea peroxide when in contact with organic matter is significant and the lubrication effect of this material is of assistance to the clinician in the freedom with which instruments may be used within root canals.

2. Apical Debris :

During instrumentation it was noted there was a tendency to force the canal contents towards the apex. Despite the canals being devoid of their natural contents, the flotation medium was seen to appear at the apical end of most roots during instrumentation. This was particularly evident where R.C. Prep. was used and more so when the size of the instrument approximated that of the canal. The expression of root canal contents through the apical foramen has been reported by Chapman⁽¹⁰⁾. Human incisors which had been sealed into the caps of bijou bottles containing nutrient broth were instrumented, allowing the passage of an indicator organism through the apical foramen in 94% of cases. The hydrostatic pressure developed by such a "piston in cylinder" effect surely produces an excess at the apex and one may question whether this is inadvertently routinely reproduced in the clinical situation. It may be postulated that early flaring of the canal walls

would lessen the potential for a positive apically directed hydrostatic pressure, by the establishment of an adequate coronal escape-way.

3. Instrument Failures :

In an investigation of the cutting efficiency of endodontic instruments, Oliet and Sorin⁽¹¹⁾ confirmed some of the accepted principles regarding their use in endodontic practice. Triangular cross-sectional instruments were found to cut more efficiently but had a greater failure rate than those of square section. They also state "instruments generally fail because of deformation or fracture of the blades".

In this study, the potential for instrument failure appeared to be greater when fine canals were being prepared rather than large ones. Most failures occurred when "difficult" canals were being negotiated, fine instruments being fractured although some instruments in the middle range (numbers 25-45) also failed.

Instrument failure was generally detected by cleaning the instrument from time to time during use and examining it under reflected light where unwinding of the blade could be easily determined. On other occasions the instrument was felt to "give" within the canal (a sensation well known to endodontists) and upon withdrawal it was found to be deficient in length. At times it was possible to by-pass the fractured remnant with another instrument of smaller size, generally using E.D.T.A. as an adjunct whilst at others it was not possible to do so.

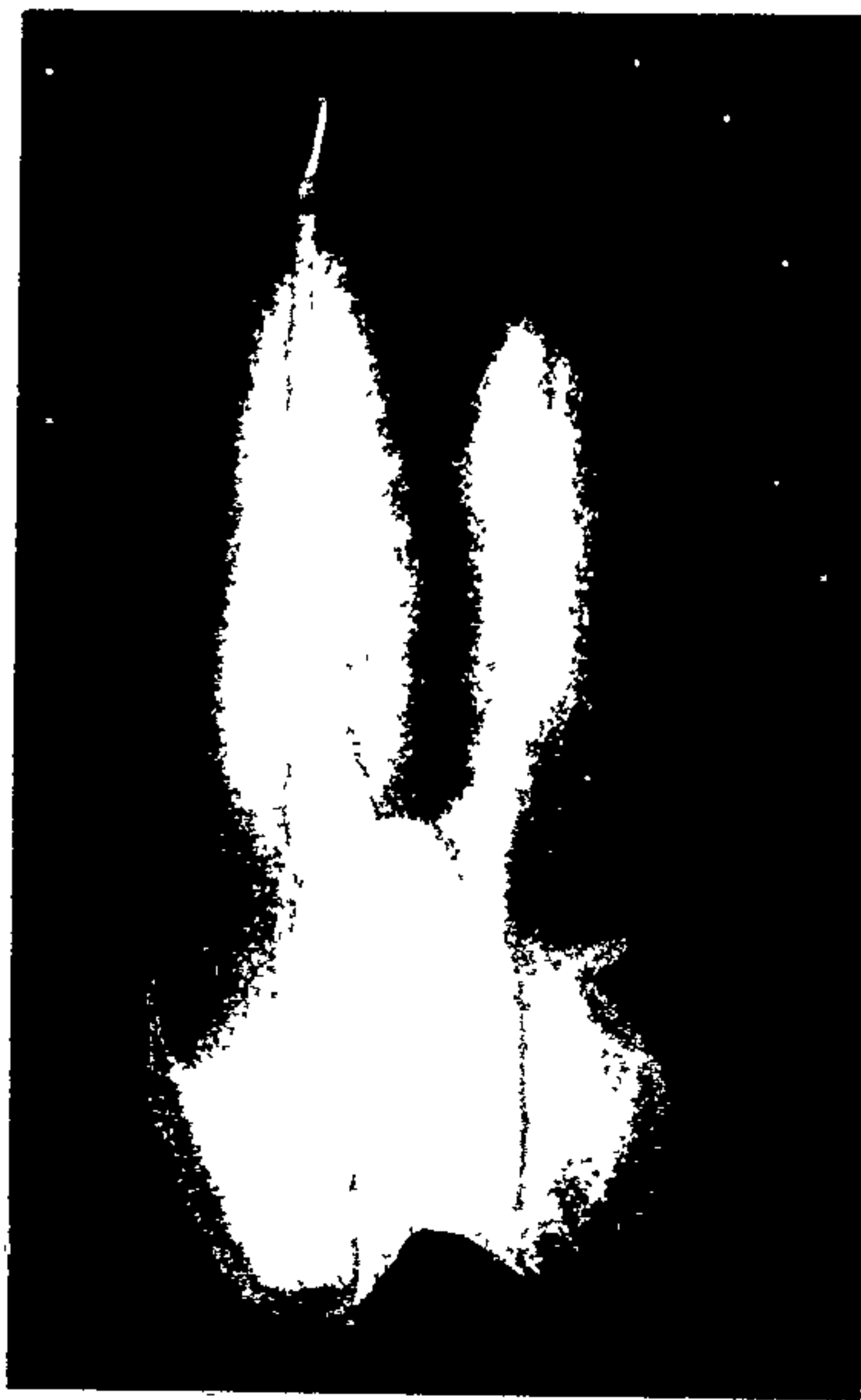
One of the specimens (a mandibular second molar) was

eliminated from the experiment due to the repeated fracture of instruments. The mesio-buccal canal caused 2.0mm of a number 10 K file to fracture at the apical end. This was by-passed with another number 10 K file thence a number 15 and following this a 20 K file was worked through the apical end. In the mesio-lingual canal, 14.0mm of a number 30 K file fractured leaving 2.0mm projecting into the pulp chamber. This was grasped with forceps and removed. Although the specimen was not used in later experimental procedures it could be argued it would not be a lost cause in the clinical situation. Regarding instrument failure, Ingle ⁽¹²⁾ states "Actually, this (Washington) study would indicate that the broken instrument is not the desperate situation it is often considered. During the eight years of the study, a great number of instruments were broken, yet the fact that only one failure case involving a broken instrument occurred out of all the number on record, attests to the fact that a broken instrument will serve as an adequate root canal filling".

Although not part of this experiment, radiographic analysis of the results of the canal preparations ⁽¹³⁾ showed six teeth where instruments had fractured, in three cases unbeknown to the operator (Fig.7). In two of the six cases of instrument fracture recorded, the fragments were by-passed with other instruments and in addition, there was the case mentioned above where multiple problems occurred causing the removal of that specimen from further experimentation.

Two other observations are of note although no statistical material was garnered for analysis.

Fig. 7



Maxillary first premolar showing a fragment of K file measuring approximately 1.5mm which had fractured in the buccal canal. This was not noted and recorded at the time of canal preparation but showed in subsequent radiographs.

- (i) The use of E.D.T.A. appeared to lessen the potential for instrument failure possibly because the effectiveness of the chelate in softening canal walls allowed for less work to be performed by each instrument.
- (ii) Kerr K files were found to be superior to Cord K files in that they were much less likely to "unwind" during use.

Results

The length of each tooth and the largest file used to create an apical funnel was recorded. These figures have been arranged in groups according to the denominations of the teeth and appear in Tables 1 and 2. Other information such as the canals which were not negotiable for their complete length and those which were not negotiable to the desired 1.0mm from the apical foramen has also been included.

Discussion

The longest canal encountered was that of a mandibular canine (29.5mm) and there were five out of nine specimens in this group which measured 27.0mm or greater. Maxillary canines were also generally long, four of the six measuring 26.0mm or more with the longest measuring 28.5mm. The shortest canals found were in a very short maxillary second premolar and the mesio-palatal canal of a maxillary first molar, each being a mature tooth and measuring 15.0mm.

The clinical information which may be deduced from a study of the tooth length figures so presented is that the variation from minimum to maximum within the range pertaining to a particular group of teeth is great and in the case of

TABLE I Maxillary Tooth Lengths and Canal Dimensions

Tooth	Canal	No. Studied	Canal Patency *			Canal length (nearest 0.5mm)			"K" file used at apex		
			F	C	S	Max.	Min.	Variation	Max.	Min.	Variation
1	-	14	14	-	-	25.0	20.0	5.0	110	50	60
2	-	6	5	1	-	24.0	17.0	7.0	80	30	50
3	-	6	6	-	-	28.5	20.0	8.5	60	45	15
4	B	13	12	1	-	26.0	19.5	6.5	120	25	95
	P	12	12	-	-	26.0	19.5	6.5	120	25	95
5	Single	9	9	-	-	24.5	15.0	9.5	120	30	90
	B	15	13	2	-	24.5	18.0	6.0	100	30	70
	P	14	12	2	-	24.5	18.0	6.0	80	30	50
6	MB	9	7	1	1	21.5	16.5	5.0	40	25	15
	MP	8	4	2	2	21.5	15.0	6.5	40	20	20
	DB	9	9	-	-	23.0	16.5	6.5	40	25	15
	P	9	9	-	-	23.5	17.0	6.5	80	40	40
7	MB	12	11	1	-	22.0	17.0	5.0	55	25	30
	MP	4	1	-	3	21.0	20.0	1.0	30	25	5
	DB	10	9	1	-	23.5	18.0	5.0	50	25	25
	P	12	12	-	-	23.0	19.5	3.5	80	40	40
8	Single	2	2	-	-	18.0	16.5	1.5	90	60	30
	MB	10	7	3	-	21.0	17.0	4.0	55	25	30
	MP	1	1	-	-	17.0	-	-	30	-	-
	DB	8	3	1	4	21.0	16.0	5.0	30	20	10
	P	10	7	2	1	23.0	16.0	7.0	90	25	65

* F denotes canal negotiable to apical foramen
 C " " " " clinically acceptable level (1.0mm from apical foramen)
 S " " " " level short of clinically acceptable level

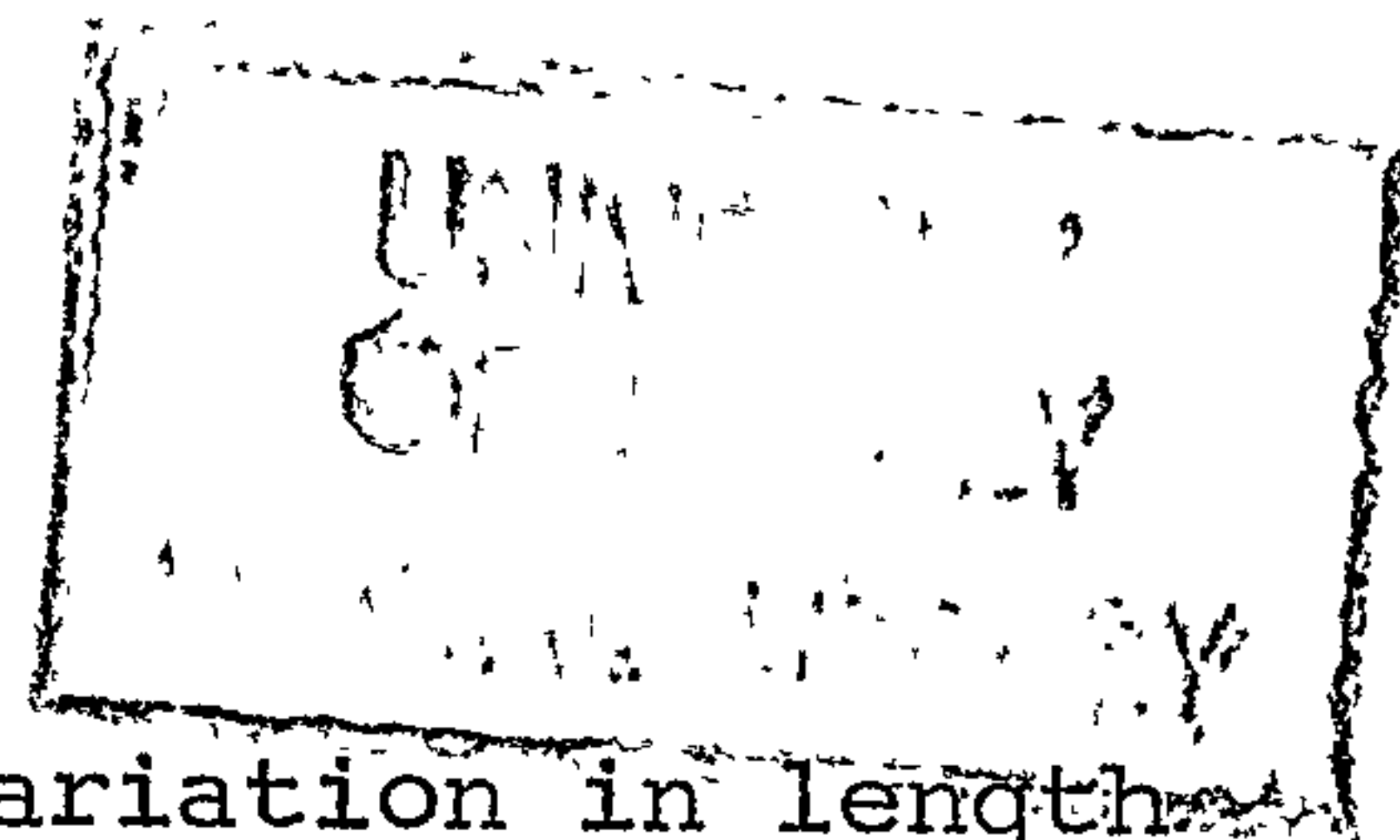
TABLE II Mandibular Tooth Lengths and Canal Dimensions

Tooth	Canal	No. Studied	Canal Patency*			Canal length (nearest 0.5 mm)			"K" File used at apex		
			F	C	S	Max.	Min.	Variation	Max	Min.	Variation
1	Single	2	2	-	-	22.0	20.0	2.0	40	30	10
	B	4	4	-	-	23.0	22.0	1.0	35	25	10
	L	2	2	-	-	22.0	22.0	-	25	25	-
2	Single	3	3	-	-	25.5	20.0	5.5	55	25	30
	B	4	4	-	-	24.0	22.0	2.0	30	25	5
	L	4	4	-	-	24.0	22.0	2.0	30	25	5
3	Single	8	8	-	-	29.5	22.0	7.5	50	35	15
	B	1	1	-	-	24.5	-	-	25	-	-
	L	1	1	-	-	24.0	-	-	25	-	-
4	Single	12	10	1	1	26.0	20.5	5.5	110	30	80
	B	4	4	-	-	24.0	20.5	3.5	110	30	80
	L	4	4	-	-	23.0	20.5	2.5	80	30	50
5	Single	11	10	-	1	26.0	19.0	7.0	90	30	60
	B	1	1	-	-	23.0	-	-	25	-	-
	L	1	1	-	-	22.5	-	-	25	-	-
6	MB	3	3	-	-	23.0	18.5	4.5	35	25	10
	ML	3	3	-	-	23.0	18.5	4.5	35	25	10
	D	2	2	-	-	24.0	18.0	6.0	70	45	25
	DB	1	1	-	-	20.5	-	-	30	-	-
	DL	1	1	-	-	20.5	-	-	25	-	-
7	M	1	1	-	-	14.0	-	-	30	-	-
	MB	11	10	1	-	22.5	18.0	4.5	45	25	20
	ML	11	10	1	-	23.0	18.0	5.0	45	25	20
	D	10	10	-	-	23.0	16.0	7.0	80	45	35
	DB	2	2	-	-	20.5	18.5	2.0	60	30	30
	DL	1	1	-	-	18.5	-	-	30	-	-
8	M	1	1	-	-	16.5	-	-	30	-	-
	MB	2	1	1	-	22.0	18.5	3.5	30	25	5
	ML	2	2	-	-	22.5	18.5	4.0	30	25	5
	D	3	2	1	-	22.0	16.5	5.5	40	25	15

*F denotes canal negotiable to apical foramen

C " " " clinically acceptable level (1.0mm from apical foramen)

S " " " level short of clinically acceptable



maxillary second premolars was 9.5mm. The variation in length was also marked in the case of maxillary canines (8.5mm), maxillary lateral incisors (7.0mm), mandibular second premolars (7.0mm), the palatal root canals of maxillary third molars (7.0mm) and the distal root canals of mandibular second molars (7.0mm). These figures are comparable with those reported by Bjorndal et al⁽¹⁴⁾ who in conducting a survey of extracted teeth found wide variations in tooth lengths for each type of tooth. In twenty four groups of fifty one studied there was a variation of 5.0mm or more between the shortest and the longest canal. This was more evident in the case of maxillary teeth where sixteen groups in twenty one showed this variation.

The habit of working to average tooth lengths rather than utilising the more established radiographic methods of determining the correct working lengths for instruments must be suspect. Developments in the use of the electronic root canal probe⁽¹⁵⁾ may obviate some of the problems encountered during radiographic interpretation, not the least being observer bias⁽¹⁶⁾. For the present however, it would seem entirely reasonable for the clinician to always work from radiographs, both pre-operative and operative to determine canal length, using a marked radiopaque guide within the root canal in conjunction with the tactile sense imparted by instruments for a correct assessment to be made. To utilise average figures to the extent of total reliance must on the one hand be hazardous to the integrity of the periapical tissues or on the other, leave an unknown portion of the canal untreated.

As previously mentioned, all canals were widened at the

apical end with K files to a maximum of two sizes beyond that which first commenced to cut the canal walls at the predetermined length. When fine canals were entered it was intended to form an apical funnel to at least a size 25 K file as clinical experience has proven this to be the minimum diameter into which a gutta percha cone will readily seat without deformation. It is possible to condense gutta percha into canals of smaller dimensions, however, this may serve to confirm the skill and determination of a particular clinician rather than support a technique which may be universally applied.

The maximum instrument size used in this study was a number 120 K file and in each case these instruments were required to prepare the canals of partially developed maxillary premolar teeth which had been extracted for orthodontic reasons. The minimum apical preparations were those which were achieved with number 20 K files and these occurred in the mesio-palatal canal of a maxillary first molar and the disto-buccal canals of two maxillary third molars. Of a total of three hundred and nine canals prepared, all except the three mentioned were negotiated to a size 25 K file or greater.

The degree of success attained in canal preparation to the desired depth was not so great. In all, thirty five canals of three hundred and nine were not negotiable to the apical foramen and thirteen of these were prepared to a distance greater than 1.0mm from the apical foramen. Of those prepared "short", six were prepared to within 2.0mm of the root end and although less than ideal these cases may be considered as clinically acceptable when a realistic viewpoint is adopted⁽¹⁷⁾.

This means seven of the three hundred and nine canals treated were prepared short by greater than 2.0mm.

It was found that those canals which proved to be troublesome in this respect were mainly located in the mesio-buccal roots of maxillary first and second molars and the disto-buccal roots of maxillary third molars. In the case of the former this appeared to relate to the small diameters encountered and to aberrations in canal form. In the latter, excessive root curvature was quite often the main difficulty which presented.

The maxillary teeth under review were far more likely to present problems in "treatment" than were those from the mandibular arch. Most of the problem canals regarding the achievement of the correct depth of canal preparation were maxillary teeth. When this fact is added to the small number of buccal canals of maxillary molars which were unable to be negotiated to the "optimal" size (25 K file or greater) it would appear the canals of maxillary molars are the most difficult to successfully instrument.

A later study⁽¹³⁾ based upon these results together with the radiographs obtained from contrast infused pre- and post-instrumented canals does not support this conclusion. The later composite study must be considered as giving a more complete analysis of the effectiveness of canal preparation and this will be reported in another paper.

Summary

One hundred and sixty four extracted human teeth were subjected to canal preparations to determine the likelihood of achieving adequate shaping of the canals for the employment of

a lateral condensation technique in obturation. Three hundred and nine canals representative of all roots were prepared, allowing for the discarding of one specimen in which repeated instrument fracture occurred.

The lengths of all canals were recorded as were the sizes to which the apical ends were prepared. The variations in dimensions were large and a note of caution has been given regarding the reliance by clinicians upon a knowledge of average tooth lengths during canal preparation. Certain factors related to canal preparation, in particular the use of chelates, the compacting of canal debris in an apical direction and the potential for instrument failure have been observed.

In most cases the desired depth of canal penetration was achieved (1.0mm from the apical foramen) and this was also the case regarding the establishment of an acceptable diameter at the apical end (25 K file or greater). In all cases, canals were able to be flared coronally from an apical constriction and a technique for the achievement of this feature has been presented.

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ENDODONTIC MORPHOLOGY IVA Comparative Study

When the condition of the pulp or the periapical tissues necessitates endodontic treatment, the prognosis is largely dependent upon the ability of the operator to successfully enter and negotiate the canal system prior to its obliteration with suitable root filling materials⁽¹⁾. Although clinical treatment which falls short of the ideal is often successful^(2,3,4) this may relate more to the ability of the patient's tissues to survive despite the treatment rather than because of the treatment. Notwithstanding this the degree of predictability of endodontic success appears to be directly related to the observance of the principles of modern endodontic practice throughout the performance of the treatment⁽⁵⁾.

Clinically, the means of observing success or failure are limited. Radiographic surveys^(6,7,8) of endodontically treated teeth where there have been known histories have been undertaken whereby large numbers of cases have been included in each study. These present a variety of problems ranging from the high fallout rate of those patients recalled for the interpretation of results^(6,7,8,9) to the method of interpretation^(10,11). Some attribute success to the diminution in size of an apical area of bone rarefaction^(11,12) whilst others require its complete elimination^(8,11,13).

The present in-vitro study was undertaken to determine the potential for endodontic success by comparing the canal morphology of a number of specimens after canal preparation with that which prevailed prior to canal preparation. The

material gathered from previous studies^(14,15,16) was utilised along with the technique of infusion of the canal system under vacuum by the use of a water soluble radiopaque contrast medium⁽¹⁴⁾. This provided a means for comparing the canal systems of one hundred and sixty-three extracted teeth before and after canal preparation.

Method and Materials

The same one hundred and sixty-three teeth which had been infused with water soluble radiopaque contrast medium, radiographed and subsequently subjected to canal preparation, were used in this study. The coronal openings were sealed with zinc oxide and eugenol cement (U.S.P.) which was allowed to dry for one week.

Each specimen was immersed into a 70% solution of sodium iothalamate^{*} and subjected to a vacuum at twenty nine inches of mercury to ensure the entire canal system had been permeated with contrast. The specimens were then carefully washed with water, dried and radiographed^{**} from the proximal, oblique and buccal surfaces with the contrast medium in situ within the canal systems, in accordance with the procedure previously described⁽¹⁴⁾. Following this the contrast was cleared from each canal system by forcing water through the tooth under hand pressure with the aid of a large syringe fitted to the tooth at the cervical opening. By reversing the procedure using a small venturi sucker fitted to the same opening, water was reverse flushed through the canal system upon immersing the specimen in water. Each tooth was radiographed again from the buccal aspect.

^{*}

Conray 420, May and Baker Ltd., Dagenham, England

^{**} Kodak Periapical Ultra-Speed Dental X-Ray Film, Eastman Kodak Company, Rochester, N.Y., U.S.A. 14650.

It was noted after twenty two specimens had been cleared of contrast that not all canals were patent at the apical end. A prerequisite for the acceptance of all specimens in the earlier experiments^(14,15) was that the apical openings be patent. The method of test was the creation of a "jet effect" at the apex of each root when water was forced through the canal system under pressure from a hypodermic syringe fitted to the cervical opening. The remaining one hundred and forty one teeth were then assessed at the canal clearance stage to determine which roots contained patent or stenosed canals at the apical ends (Table I).

The radiographs were processed strictly according to the procedure recommended by the manufacturers and filed in parallel with those previously taken for each specimen prior to the canals being entered⁽¹⁴⁾. Comparisons were made between the two sets of radiographs utilising the known details which accrued from the mechanics of canal preparation⁽¹⁶⁾.

Results

Apical Patency

One hundred and forty one teeth were examined for apical patency to water forced through the canal systems by hand pressure. Single roots with multiple canals were given a single assessment (e.g. mesial roots of mandibular molars) except in the case of premolars where a differential assessment for the buccal and lingual canals could generally be made. A total of two hundred and thirty two canal orifices or root

TABLE I Apical Patency following Canal Preparations

a. Maxillary Teeth

Tooth	Root	Root ends studied (total)	Patent				Not Patent			
			Root ends	Max. File	Min. File	Average File	Root ends	Max. File	Min. File	Average File
1	Single	11	4	80	70	73 (>)	7	80	50	64 (<)
2	Single	6	2	60	50	55 (=)	4	80	30	53 (=)
3	Single	5	2	55	50	53 (=)	3	60	50	55 (=)
4	B	7	4	100	45	65 (>)	3	55	25	37 (<)
	P	7	3	100	30	63 (>)	4	55	25	43 (<)
5	Single	9	3	120	60	87 (>)	6	90	30	51 (<)
	B	14	8	100	30	63 (>)	6	50	30	43 (<)
	P	13	7	80	30	60 (>)	6	50	30	40 (<)
6	MB	7	2	30	30	30 (=)	5	40	25	29 (=)
	DB	7	3	40	25	30 (=)	4	40	25	30 (=)
	P	7	2	70	40	55 (=)	5	55	50	54 (=)
7	MB	11	2	50	25	38 (=)	9	55	25	41 (=)
	DB	9	1	25	25	25 (<)	8	50	25	34 (>)
	P	11	4	60	40	50 (<)	7	80	45	63 (>)
8	Single	1	1	60	60	60				
	MB	10	4	55	25	38 (>)	6	35	25	28 (<)
	DB	8	3	30	20	25 (=)	5	30	20	25 (=)
	P	10	3	60	25	40 (>)	7	50	25	32 (<)
Totals		153	58 (37.9%)	120	20	8 (>) 7 (=) 2 (<)	95 (62.1%)	90	20	2 (>) 7 (=) 8 (<)

Note : (>) average file size greater than comparison group
 (<) average file size less than comparison group
 (=) average file size equal to comparison group (less than 0.05mm variation)

TABLE I Apical Patency following Canal Preparation

b. Mandibular Teeth

Tooth	Root	Root ends studied (total)	Patent				Not Patent			
			Root ends	Max. File	Min. File	Average File	Root ends	Max. File	Min. File	Average File
1	Single	6	4	40	25	31(=)	2	35	25	30(=)
2	Single	7	2	30	30	30(=)	5	55	25	32(=)
3	Single	8	1	50	50	50(>)	7	50	35	46(<)
	B	1					1	25	25	25
	L	1					1	25	25	25
4	Single	10	6	100	45	73(>)	4	90	30	51(<)
	B	3					3	55	30	43
	L	3					3	35	30	32
5	Single	10	4	90	40	54(>)	6	70	30	46(<)
	B	1	1	25	25	25				
	L	1	1	25	25	25				
6	M	2	1	25	25	25(<)	1	35	35	35(>)
	D	2	2	70	25	50				
7	M	9	6	35	25	30(<)	3	45	25	37(>)
	D	9	5	80	30	47(<)	4	60	45	56(>)
8	M	3	2	30	25	28(=)	1	30	30	30(=)
	D	3	1	40	40	40(>)	2	30	25	28(<)
Totals		79	36 (45.6%)	100	25	4(>) 3(=) 3(<)	43 (54.4%)	90	25	3(>) 3(=) 4(<)

Note: (>) average file size greater than comparison group

(<) average file size less than comparison group

(=) average file size equal to comparison group (less than 0.05mm variation)

TABLE I Apical Patency following Canal Preparation
c. Maxillary and Mandibular Teeth (Composite table)

Tooth	Root	Root ends studied (total)	Patent				Not Patent			
			Root ends	Max. File	Min. File	Average File	Root ends	Max. File	Min. File	Average File
Maxillary		153	58	120	20	8(> 7(= 2(<	95	90	20	2(> 7(= 8(<
Mandibular		79	36	100	25	4(> 3(= 3(<	43	90	25	3(> 3(= 4(<
Totals		232	94 (40.5%)	120	20	12(> 10(= 5(<	138 (59.5%)	90	20	5(> 10(= 12(<

Note : (>) number of groups where average file size greater than comparison group

(<) number of groups where average file size less than comparison group

(=) number of groups where average file size equal to comparison group (less than 0.05mm variation)

ends were checked for patency and of these only ninety four (40.5%) were so, the remaining one hundred and thirty eight (59.5%) being either completely or partially blocked. In the latter cases a small bead of water was often able to be extruded from the root end when heavy hand pressure was applied to the syringe. Sometimes the blockage could be cleared by reverse flushing (aspiration) however these were all recorded as being stenosed.

The maximum and minimum sizes for files used in the apical portion of each canal were recorded and there appeared to be a wide degree of inconsistency in canal dimensions regarding clearance or blockage at the apical end. Large and small canals were seen to relate to both blocked and open apices, appearing to be so at random. The largest canal demonstrating apical patency was a maxillary second premolar (size 120 K file) and the smallest to do so was the disto-buccal canal of a maxillary third molar (size 20 K file). The largest canals where the apical foramina were blocked were in a maxillary second premolar and a mandibular first premolar (size 90 K file) and the smallest demonstrating this feature was in the disto-buccal root of a maxillary third molar (size 20 K file).

Notwithstanding this, the size of the canal at the level of the apical seat may have had some significance. The canal sizes at this level were averaged for each group of teeth under review according to the largest file allowed to penetrate to

the correct working length in each case. It was noted that canals with large diameters appeared to clear marginally more efficiently than those with small diameters. Of twenty seven groups of teeth averaged as such which were available for comparison, twelve of the "cleared" groups showed larger diameters than those which were blocked, five of the "cleared" groups showed smaller diameters than those which were blocked whilst ten "cleared" and "blocked" groups had canal sizes which were substantially the same (variation less than .05mm).

Apical ramifications and lateral canals were often demonstrated by a jet of water being emitted from the root surface in the manner previously described in this paper. In some instances where the main canal was blocked at the apical end and a lateral canal was present the jet effect was quite pronounced. In one specimen, a maxillary second molar, a fine jet of water escaped in this manner from a point in the furca between the disto-buccal and palatal roots, indicating the presence of a furcation canal. This was also seen in the perfusion radiographs although it was found the accessory canal arose from the palatal canal and not the pulp chamber⁽¹⁵⁾. This was the only evidence of accessory canals in the furcation region which was encountered in the entire series of experiments utilising one hundred and sixteen posterior teeth of which fifty two were molars.

Interpretation of Radiographs

Canal Form :

During the preparation of each canal⁽¹⁶⁾ it had been the author's intent to produce a continuous taper from the coronal opening to the apical region where an apical funnel was to be

developed, with or without an apical shoulder. The resultant canal form was designed to allow a master cone of gutta percha to bind in the apical region at the predetermined level, leaving a residual space around the master cone coronally, for the packing of subsidiary cones by lateral condensation.

The radiographic picture of each anterior tooth following canal preparation was examined for continuity of taper, shoulder establishment and evidence of "creep back" (the withdrawal of instruments from the predetermined depth of penetration of the canal preparation), see Table II.

Continuity of Taper -

In most cases this was achieved although eleven of fifty five canals entered showed irregularities in the canal walls following preparation. In some instances where canals presented with broad bucco-lingual diameters, this could have been obviated by a more radical extension of the coronal access to the lingual (Figs. 1,2).

Shoulder Establishment -

In the roots which contained single canals it was generally found an apical shoulder could be readily established (Figs. 3,4). This was most evident in the case of maxillary incisors and canines where the relative simplicity of canal form allowed this feature to be developed in all cases. It was not so with the mandibular incisors studied. Out of twenty three main canals present in thirteen roots, only nineteen were entered and prepared and of those an apical shoulder was defined in twelve.

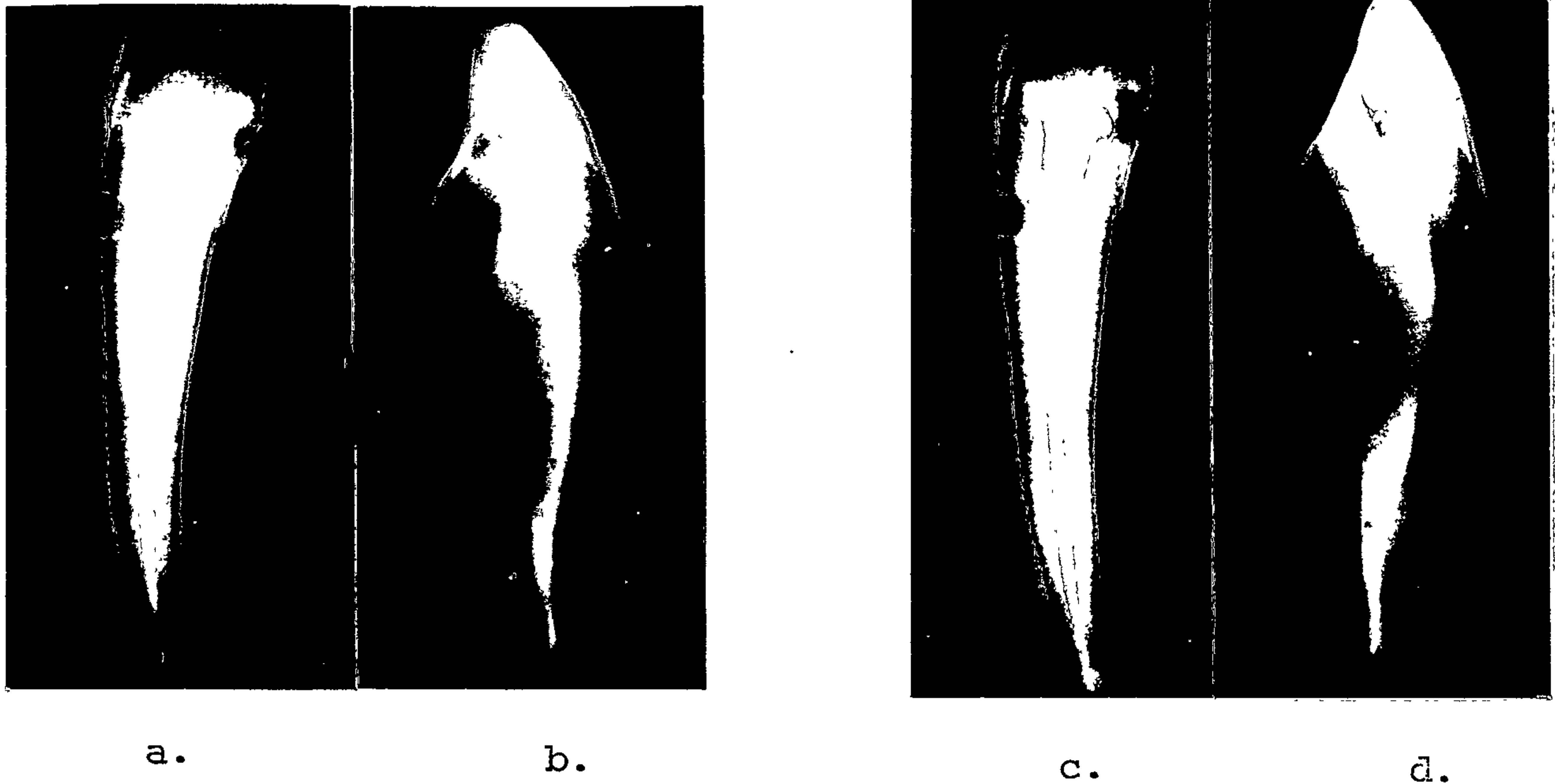
TABLE II Comparison of pre and post-filing Radiographs and Clinical Records
a. Maxillary and Mandibular Incisors and Canines

Tooth	Number of Specimens	Number of Canals				
		Present	Prepared	Continuous Taper	Apical Shoulder	Creep-back
Max.1	14	14	14	9	14	0
Max.2	6	6	6	2	6	0
Max.3	6	6	6	4	6	0
Mand.1	6	11	8	8	5	1
Mand.2	7	12	11	11	7	0
Mand.3	9	10	10	10	10	1
Totals	48	59	55	44	48	2

b. Maxillary and Mandibular Molars

Tooth	Number of Specimens	Canals Present	Canals Prepared	Problem Roots				
				M.B.	D.B.	P.	M.	D.
Max.6	9	36	35	3	2	0	0	0
Max.7	12	39	38	1	1	0	0	0
Max.8	12	31	31	0	2	0	0	0
Mand.6	3	10	10	0	0	0	0	0
Mand.7	12	37	36	0	0	0	0	1
Mand.8	3	8	8	0	0	0	0	0
Totals	51	161	158	4	5	0	0	1

Fig. 1



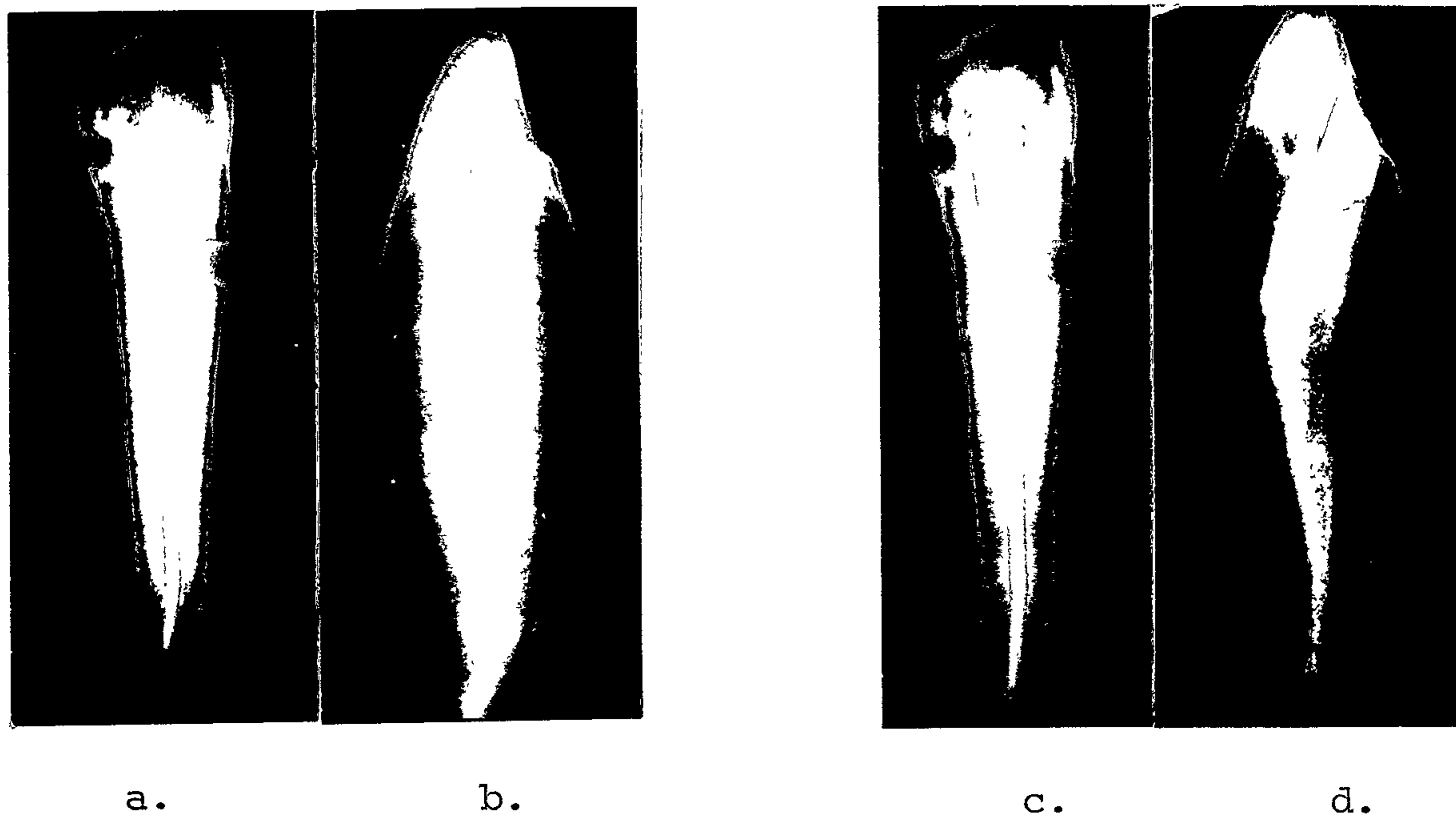
Figs. 1a,b

Pre-canal preparation radiographs of a contrast infused mandibular canine showing a broad labio-lingual canal width. Note the apical delta and the large pulp horn.

Figs. 1c,d

Post-canal preparation radiographs of the contrast infused specimen shown in 1a and b. The access cavity has not been extensive enough thus allowing overhangs to remain on the lingual wall of the canal. The opening should also extend further incisally to expose the tip of the pulp horn.

Fig. 2



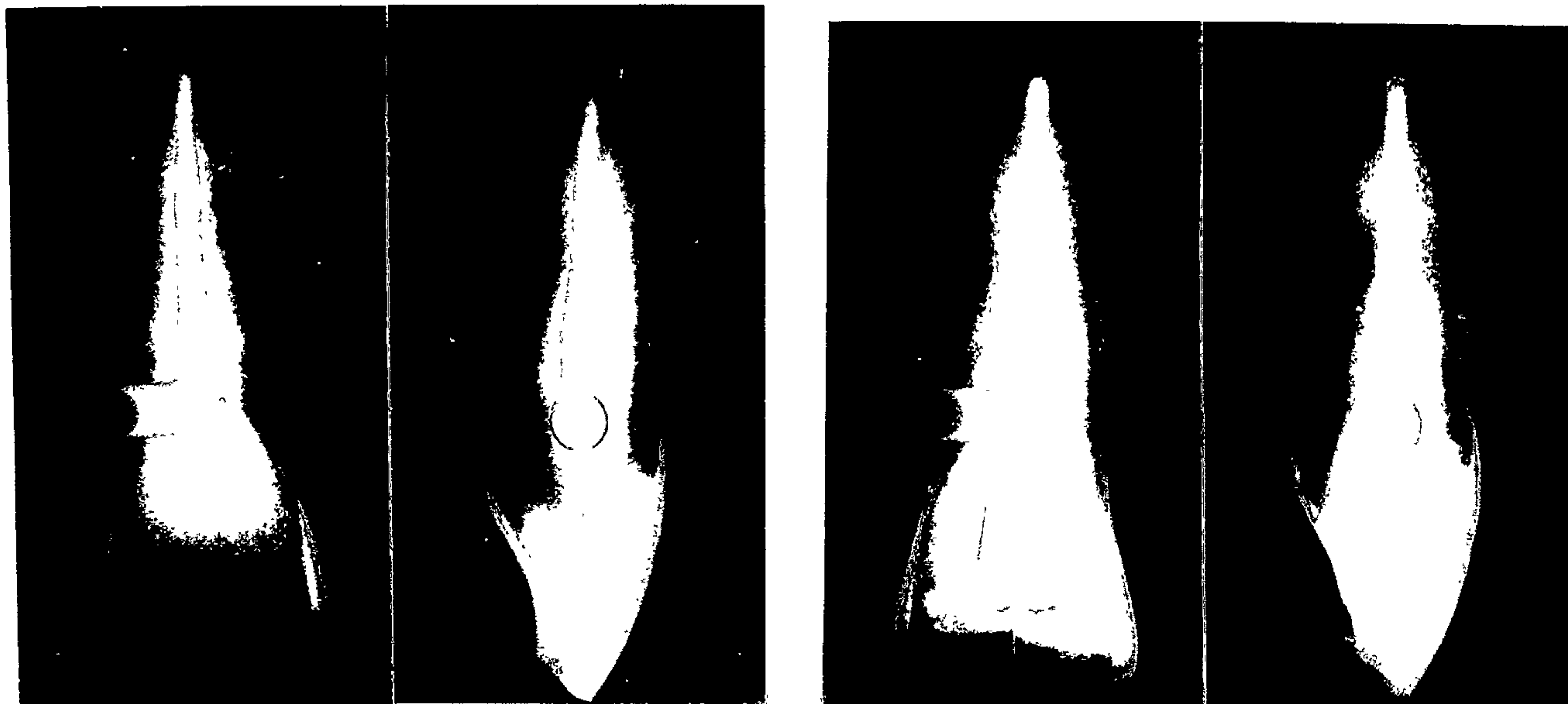
Figs. 2a,b

Pre-canal preparation radiographs of a contrast infused mandibular canine, similar in form to that shown in Fig. 1.

Figs. 2c,d

Post-canal preparation radiographs of the contrast infused specimen shown in 2a and b. Adequate lingual extension of the access cavity has allowed for the development of a smooth lingual wall. The same defect applies regarding incisal extension as in the case shown in Fig. 1.

Fig. 3



a.

b.

c.

d.

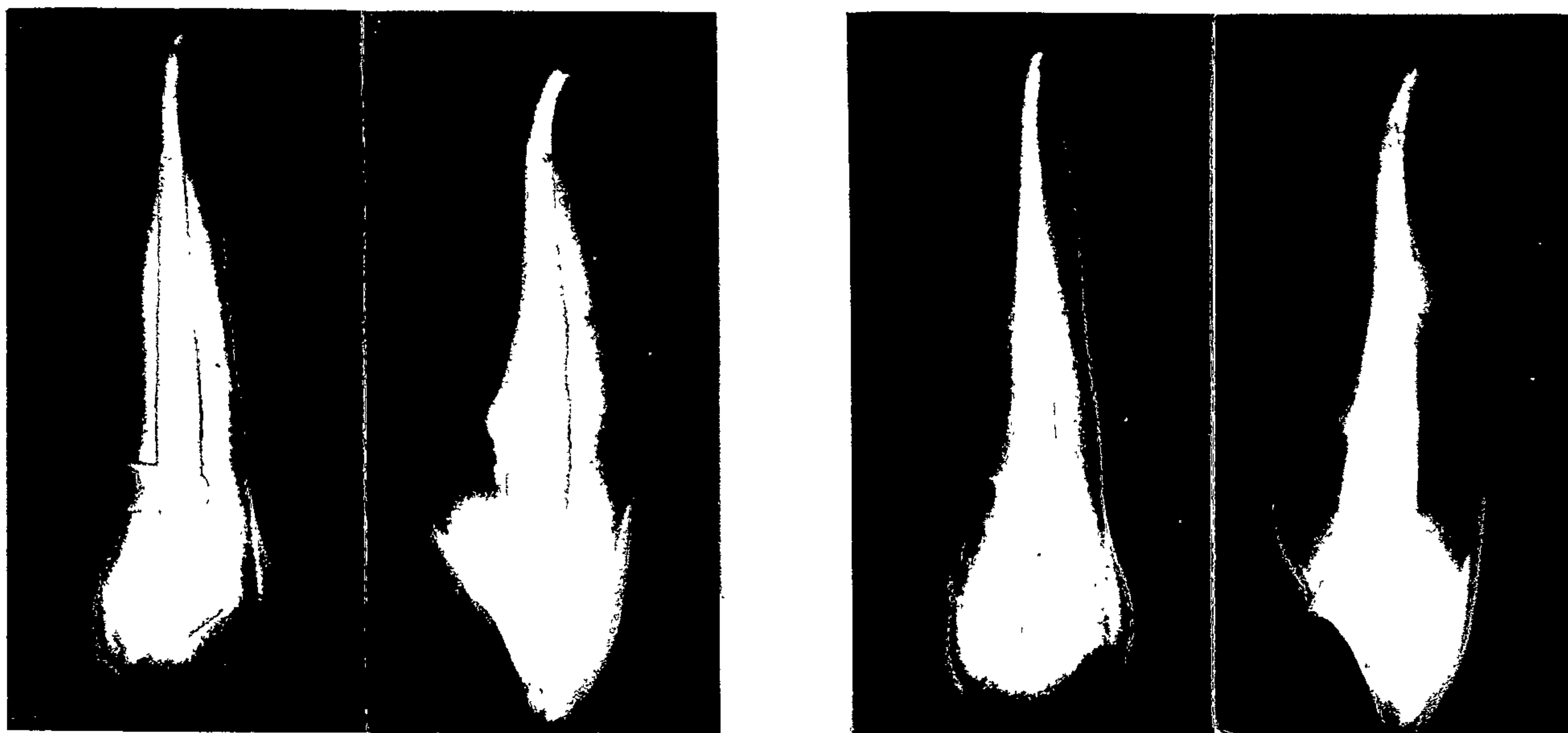
Figs. 3a,b

Pre-canal preparation radiographs of a contrast infused maxillary central incisor containing a straight root canal.

Figs. 3c,d

Post-canal preparation radiographs of the contrast infused specimen seen in 3a and b showing the shoulder established in the apical region.

Fig. 4



a.

b.

c.

d.

Figs. 4a,b

Pre-canal preparation radiographs of a contrast infused maxillary canine containing a curved root canal.

Figs. 4c,d

Post-canal preparation radiographs of the contrast infused specimen seen in 4a and b showing modified shoulder form.

Creep Back -

The post-canal preparation radiographs of all maxillary and mandibular incisors and canines were examined for evidence of this phenomenon. It was found the initial depth of canal preparation by instruments was maintained throughout the procedure in all but two of the fifty five canals prepared (Fig.5).

Radiopaque Debris:

Radiographic examination disclosed the presence of a dense "powdered" material in the canal systems of eight of the one hundred and sixty three teeth studied (Fig.6). This material was greater in contrast than the medium which had been perfused through the teeth and it had the radiographic appearance of amalgam alloy. In each of the teeth in which this material was present there had been an alloy restoration in situ prior to opening through the crown to effect canal preparation. It is thus reasonable to assume the presence of alloy particles within the root canals in such cases, the material being readily carried from the pulp chambers to the canals by the action of instruments.

Fractured Instruments:

Radiographic examination showed five canals which contained fragments of fractured instruments although only two cases were recorded as such during the preparation of the canals. The three which were unrecorded at that time contained small fragments (0.5 - 1.5mm) of what appeared to be No. 10 K files, one being in the apical region of a maxillary lateral incisor (Fig.6), the second in the apical region of the buccal root of

Fig. 5



a.

Pre-canal preparation radiograph of a contrast infused mandibular canine with two roots. The canals are fine and the labial root has an accessory canal arising level with the angle in the canal.

Post-canal preparation radiograph of the contrast infused specimen seen in 5a. Note the degree of creep-back during instrumentation in the labial canal.



b.

Fig. 6



a.

Post-canal preparation radiograph of a contrast infused maxillary second molar showing variation in density of the contrast medium in the canals of the mesio-buccal root.

Post-canal preparation radiograph of the tooth seen in 6a following clearance of the contrast medium from the canal system. Particles of dense radiopaque material consistent with amalgam alloy may be seen to correspond with that appearing in 6a. A large alloy restoration was present in the crown prior to commencement.



b.

a maxillary first premolar and the third in the body of the canal system of a maxillary second premolar.

Comparison of Pre- and Post-Preparation Canal Systems :

A comparative study of the radiographs demonstrating the morphology of the pre- and post-preparation canal systems was made for each specimen (Table III). The results were grouped according to nomenclature and tabulated, showing the number of canals known to be present and the number successfully prepared with endodontic instruments. The potential for clinical acceptance for each prepared canal was recorded and these have been expressed as totals and as percentages for each group of teeth studied. Additional information such as shoulder establishment (maxillary and mandibular incisors and canines) and "problem" roots (maxillary and mandibular molars) was collected and this necessitated a further grouping of teeth (Table II).

The method of scoring used here was rather harder than that which would normally be applied in the clinical situation. It was considered reasonable, however, to utilise it under the circumstances prevailing, if for no other reason than to provide a base against which future clinical performance may be judged. In each case the fracture of an instrument, either known or unknown at the time of canal preparation, was assessed as a failure although clinical experience may contra-indicate this "hard line" approach⁽¹⁷⁾. Likewise despite the union of two canals apically, where only one was negotiated this was also marked as a failure. There were of course other instances evident where failure would be expected to follow endodontic treatment in the clinical situation. Such clear cut issues as the non-negotiation of a separate canal must be considered

TABLE III Comparison of pre and post-filing Radiographs and Clinical Records

a. Maxillary Incisors and Canines

Tooth	Number of Specimens	Number of Canals		Clinical Acceptance		Successful (%)		Failures (teeth)
		Present	Prepared	Canals	Teeth	Canals	Teeth	
1	14	14	14	14	14	100	100	0
2	6	6	6	6	6	100	100	0
3	6	6	6	6	6	100	100	0
Totals	26	26	26	26	26	100	100	0

b. Mandibular Incisors and Canines

Tooth	Number of Specimens	Number of Canals		Clinical Acceptance		Successful (%)		Failures (teeth)
		Present	Prepared	Canals	Teeth	Canals	Teeth	
1	6	11	8	8	3	72.7	50.0	** ϕ
2	7	12	11	11	6	91.7	85.7	*
3	9	10	10	10	9	100	100	0
Totals	22	33	29	29	18	87.9	81.8	4

c. Maxillary and Mandibular Incisors and Canines (Composite table)

Tooth	Number of Specimens	Number of Canals		Clinical Acceptance		Successful (%)		Failures (teeth)
		Present	Prepared	Canals	Teeth	Canals	Teeth	
Max. 1, 2, 3	26	26	26	26	26	100	100	0
Mand. 1, 2, 3	22	33	29	29	18	87.9	81.8	4
Totals	48	59	55	55	44	93.2	91.4	4

TABLE III Comparison of pre and post-filing Radiographs and Clinical Records
d. Maxillary and Mandibular Premolars

Tooth	Number of Specimens	Number of Canals		Clinical Acceptance		Successful (%)		Failures (teeth)
		Present	Prepared	Canals	Teeth	Canals	Teeth	
Max.4	12	25	25	24	11	96.0	91.7	β
Max.5	24	39	38	37	21	92.3	83.3	$\alpha\Delta^*$
Mand.4	16	22	20	20	15	90.9	93.8	ϕ
Mand.5	12	13	13	13	12	100	100	o
Totals	64	99	96	94	59	94.9	91.2	5

e. Maxillary and Mandibular Molars

Tooth	Number of Specimens	Number of Canals		Clinical Acceptance		Successful (%)		Failures (teeth)
		Present	Prepared	Canals	Teeth	Canals	Teeth	
Max.6	9	36	35	35	8	97.2	88.8	ϕ
Max.7	12	39	38	37	10	94.9	83.3	$+\alpha$
Max.8	12	31	31	31	12	100	100	o
Mand.6	3	10	10	10	3	100	100	o
Mand.7	12	37	36	36	11	97.3	91.6	*
Mand.8	3	8	8	8	3	100	100	o
Totals	51	161	158	157	47	97.5	92.1	4

TABLE III Comparison of pre and post-filing Radiographs and Clinical Records

f. All Teeth (Composite table)

Tooth	Number of Specimens	Number of Canals		Clinical Acceptance		Successful (%)		Failures (teeth)
		Present	Prepared	Canals	Teeth	Canals	Teeth	
1, 2, 3	48	59	55	55	44	93.2	91.7	4
4, 5	64	99	96	94	59	94.9	91.2	5
6, 7, 8	51	161	158	157	47	97.5	92.1	4
Totals	163	319	309	306	150	95.9	92.0	13

Table III Legend

- * Root containing multiple canals with common apical opening where only one canal successfully negotiated
- ∅ Root containing multiple canals with separate apical openings where less than the total number were successfully negotiated
- ⌵ Root containing fractured instrument successfully by-passed
- β Root containing fractured instrument undetected during canal preparation
- Δ Extensive apical ramifications producing questionable clinical prognosis without surgical intervention
- + Unable to negotiate canal with instruments

unarguable in this respect and these were scored accordingly.

DISCUSSION

Apical Patency

The lack of apical patency following canal preparation in more than half of the number of specimens, despite the earlier selection process being dependent upon this feature, was a surprising piece of information which came to hand quite accidentally. It has been previously recorded⁽¹⁶⁾ that apical openings were seen to emit portions of canal contents (canal filings and flotation medium) during canal preparation. It has also been specified that all canals were irrigated with sodium hypochlorite (4%), hydrogen peroxide (3%), sodium hypochlorite (4%) and water, in that order, at the completion of canal preparation. This is a process which has been recommended⁽¹⁸⁾ and these medicaments have been used in clinical practice by the author during and following canal preparation for a number of years. It is believed⁽¹⁸⁾ the effervescent action of hydrogen peroxide in conjunction with sodium hypochlorite is sufficient to allow debris to escape from the canal in a coronal direction.

The potential for the elimination of extraneous matter from the apical portion of the root canal has been claimed⁽¹⁹⁾ to be enhanced by the use of R.C. Prep.* followed by irrigation with sodium hypochlorite, the urea peroxide contained in the material being carried apically within the vehicle during instrumentation. It would appear in this case the material was not always completely reduced by the sodium hypochlorite

*R.C. Prep., Premier Dental Products Co., Philadelphia, Pa.19107.

and washed free from the canals. As all canals prepared during this study were previously cleared of their contents by enzyme action⁽¹⁴⁾ it would seem the apical blockages were caused by dentine shavings, R.C. Prep, or a combination of the two. This feature has recently been confirmed by Zurbriggen and Brady⁽²⁰⁾ who were able to demonstrate the retention of quantities of carbon 14 labelled EDTA - urea peroxide - carbowax mixtures in root canals following their use during instrumentation and after irrigation with sodium hypochlorite.

It may be argued, fine canals present a definite problem in introducing irrigants to the apical third due to the canal lumen restricting entry to the needle of the syringe and in this respect a considerable number of canals prepared during this study were limited in diameter to that of a number 20 to 30 K file at the apical end. It was therefore surprising to note the rather random nature of the results regarding apical patency compared with canal size. This was also found to be the case by Zurbriggen and Brady⁽²⁰⁾ who discovered no significant difference in the quantities of material retained in relation to canal size. Many canals which were quite large in diameter (size 80-90 K file) at the apical end were blocked whilst some of the finest encountered (size 20-25 K file) were not (Table I). It is not known why this was so however the possibility of debris not only being forced through the root apex but becoming impacted into the apical region of the canal during canal preparation⁽²¹⁾ must be a distinct possibility. Unless such debris is removed by the action of instruments and

irrigants it may remain in situ, compressed between the apical tissues and the root filling material. Until further study is made to determine the manner in which this material is best removed, the technique of irrigation used in this experiment must remain suspect.

Canal Form

Continuity of Taper :

In this experiment, despite attempts during canal preparation to produce a continuous taper within the canal from apex to crown there was evidence of irregularity in the canal walls. As the degree of irregularity was slight and as it was generally related to the coronal end, it could be reasoned the clinical significance of this feature is of little consequence.

Shoulder Establishment :

Where attempted, it was relatively easy to establish an apical shoulder against which a master cone could be readily fitted. This related in the main to canals with sizes in the order of a number 50 K file or greater in the apical region, although smaller sizes (35 K file) allowed this shape to be created, provided that the degree of taper in the body of the canal was great enough to give freedom of movement of the instrument. In other cases a tapered apical form was achieved and this was the goal in all fine canals.

Creep Back :

The low number of cases recorded where this phenomenon was in evidence was heartening, although it has been the author's experience that the inadvertent lack of penetration of instruments

to the correct depth during canal preparation is a fact which occurs from time to time in clinical practice. The incremental variations in instrument size predispose towards a regression of the tips of the larger instruments from the correct working depth. Great care must therefore be exercised to guard against this possibility and the success achieved here may have been due to the good access which an inert and hand-held specimen affords rather than that which prevails in the mouth.

Radiopaque Debris

The inclusion of fine particles of radiopaque material within the canals of some of the specimens was of interest as it appears to confirm a suspicion of the author that alloy particles may be carried into the root canals from the coronal opening during instrumentation. In this experiment, in each case where these fragments were detected, an alloy restoration had been cut through in forming the access cavity into the pulp chamber. All of the specimens which showed this phenomenon contained fine fragments of very dense radiopaque material, consistent with the appearance of alloy.

The method of introduction of this material into the canals may be active (by the use of flotation medium and instruments) or passive (by gravity). The material may have been present in the floor of the pulp chamber as residue from the coronal opening, or fresh filings may have been introduced from the alloy side walls of the access cavity where contacted by endodontic instruments. Whichever may be the case, frequent irrigation during the canal preparation phase as well as at the

completion may serve to reduce the potential for the retention of this material within the canal system. It may be further argued, a thorough debridement of the coronal access cavity by irrigation and vacuum prior to canal preparation being commenced would reduce the likelihood for this to occur.

Fractured Instruments

Of the five canals which showed fractured instruments two had been recorded as such during canal preparation and the other three fractures were unknown until seen in the post preparation radiographs. The problems presented by the two fractures detected during canal preparation were able to be overcome in a standard clinical fashion, each fragment being by-passed⁽²²⁾ by other instruments to an acceptable size (No.30 K file) to permit canal obturation. In one of these cases the instrument fragment was a small portion of a No. 10 K file whilst in the other, three separate instruments fractured (Nos. 10, 15 and 40 K files) before they were by-passed (No. 30 K file). In each case however, they were recorded as failures although in clinical practice a by-passed instrument which allows the canal to be filled to the correct level would hardly jeopardize the tooth. The likelihood of clinical failure following such treatment (slight though it may be resulting from the fracture alone) could conceivably be lessened by surgical intervention in many cases^(22,23,24).

The other three fractures were each of small (No. 10 or 15 K files) instruments and each was a small fragment. One of these was at the apical end of a fine maxillary first premolar canal and the case was recorded as a failure despite the potential for obliteration up to and around the remnant by root filling

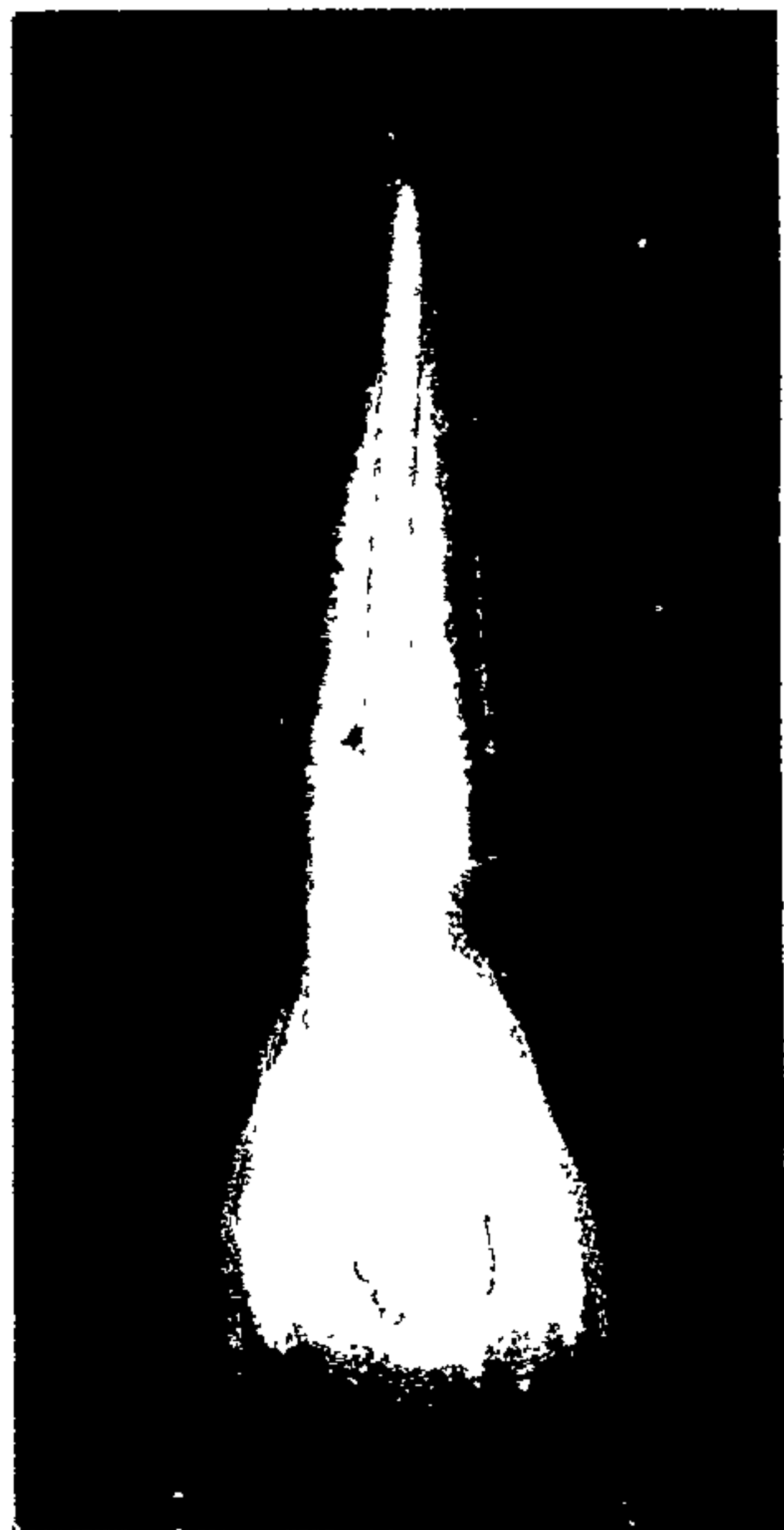
material. An other was included in the middle of a maxillary second premolar root and that case was considered a potential success as the apical region of the canal was remote from the remnant. The third was the case shown in Fig.7 where it would be unlikely that failure would result in the clinical situation from the retention of such a remnant.

There were two further canals which presented problems during the canal preparation phase and in each, instruments fractured and bound with no possibility of removal or by-passing them⁽¹⁶⁾. The tooth in question (a mandibular second molar), being of no further use for the infusion of radiopaque contrast, was discarded from the experimental procedures which followed and it has not been recorded in the details appearing in Table III. The clinical problems produced by such a tooth may not be so great as endodontists have generally believed as the repair rate following the leaving of fractured instruments in situ appears to be rather high⁽¹⁷⁾. It would seem the lack of control of the situation may cause a deal of embarrassment to the clinician which is far in excess of that warranted. The instrument failure in this case was, however, a fact and it should be borne in mind as such when results are being assessed.

The Comparative Study

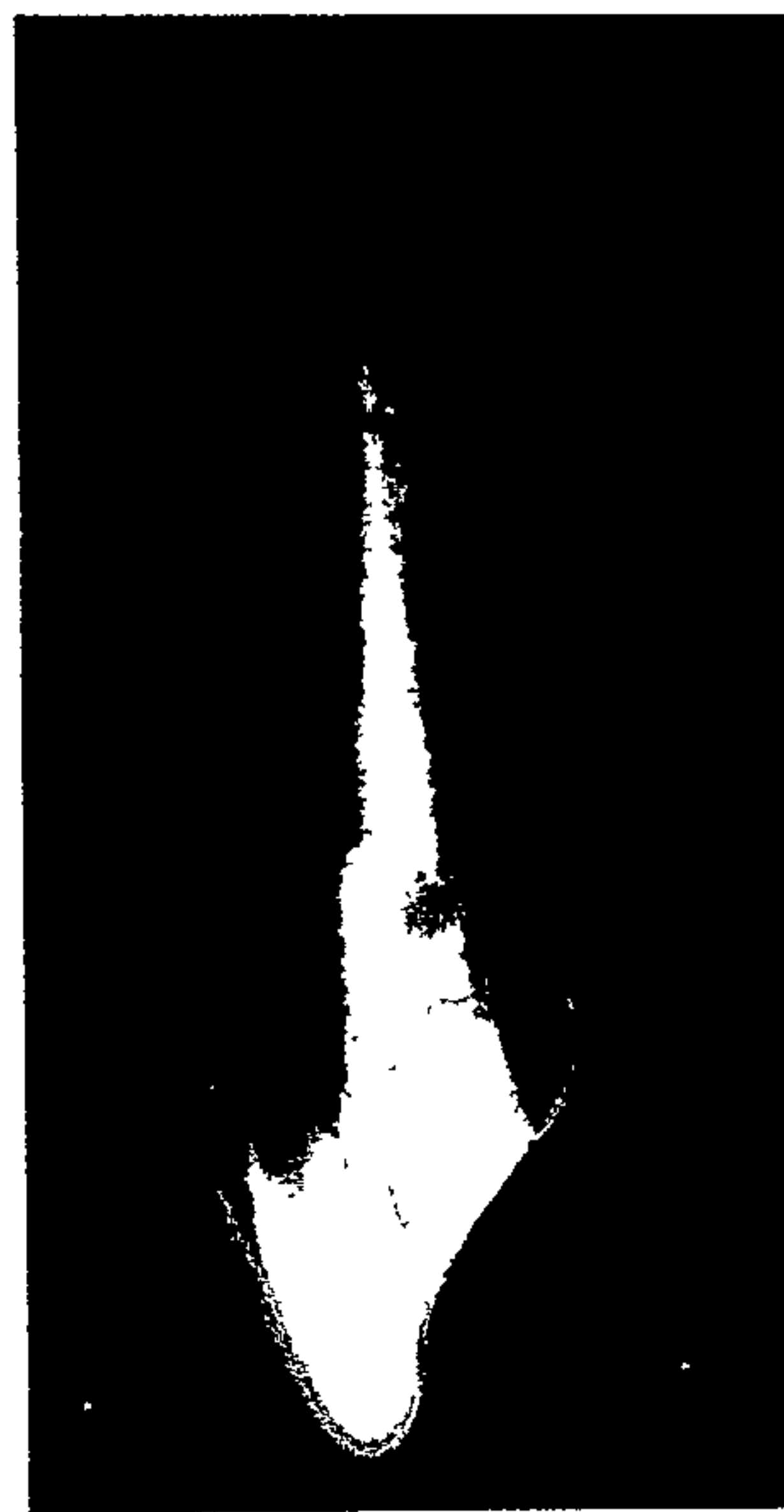
The results disclosed by a detailed comparison of radiographs as described (Tables II and III) give some indication of the potential for endodontic success by conservative means, in a broad cross section of human teeth. The rather hard system of marking undertaken to project successful or unsuccessful results has given a base figure for each group of teeth in the

Fig. 7



a.

Post-canal preparation radiographs of a contrast infused maxillary lateral incisor. A small fragment of fractured K file may be seen in the canal at the apical shoulder. Note the variation in canal diameter throughout, when viewed from the proximal, indicating insufficient flare created during canal preparation.



b.

survey. Problems which occurred during canal preparation such as instrument fractures which may have been in part overcome by a by-pass technique⁽²²⁾ (as used in clinical practice), have been marked down as failures. Likewise, one case where adequate canal preparation had been performed but detailed study of radiographs disclosed a network of complex apical ramifications (which it could be argued may predispose toward subsequent failure), was marked as a failure. There were other cases where only one of two canals which joined apically were negotiated. This may very well occur in the clinical situation unbeknown to the operator. Such cases, although not necessarily being doomed to failure as conservative procedures^(25,26) were considered to be so for the purposes of this experiment.

Provided the operator is able to manipulate endodontic instruments in vivo as they have been in this in vitro study the potential for endodontic success should parallel that indicated here. For those cases which have been classified as failures it would remain to be seen what reaction the body defence processes may take in similar cases in vivo. In the event of failure there is always the possibility of undertaking endodontic surgery, even in the case of maxillary and mandibular posterior teeth⁽²⁷⁾ although the close proximity of important anatomical features or the presence of an unsatisfactory crown/root ratio may sometimes preclude this form of treatment⁽²³⁾. It is of interest here to note the only problem canals occurring in the roots of maxillary molars were buccal ones, which are fortunately conveniently placed for surgical treatment. There were no palatal roots which gave problems. There was only one

canal in fifty five mandibular molar canals which presented a problem in that it was not found clinically, although subsequent radiographic examination revealed it joined apically with another (successfully negotiated) in the same root.

The most successful group treated were the maxillary and mandibular molars, where 97.5% of all canals present were adequately prepared (157 of 161 canals in 51 teeth) and 92.1% of those teeth (47 of 51) had canal preparations performed which would be expected to lead to successful obturation by the lateral condensation technique. This was slightly better than the score for the maxillary and mandibular incisors and canines (93.2% of all canals and 91.7% of all teeth successfully prepared) and the maxillary and mandibular premolars (94.9% of all canals and 91.2% of all teeth successfully prepared). This result produced somewhat of a surprise as apart from the widely held belief that molars are difficult to treat there were a considerable number of teeth with canals exhibiting defalcation and dilaceration included in this study, more for the sake of checking the efficacy of the infusion technique used in the earlier work than for the purpose of indicating the results which may accrue from the use of endodontic instruments.

The figures which relate to the incisors and canines are somewhat misleading because of the grouping of the maxillary and mandibular teeth together. A brief perusal of Table IIIC shows a 100% score for the twenty six maxillary incisors and canines used in the study whereas Table IIIB shows the mandibular incisors as the reason for the poor score when all anterior teeth are considered collectively. The high failure rate with mandibular incisors was due to the presence of sufficient specimens containing complex canal systems which are not only

difficult to detect in vivo but were unable to be satisfactorily negotiated in this series of experiments. The results in this study for successfully prepared mandibular incisors and canines (81.8%) must therefore be considered when clinical endodontics is being performed on these teeth. It has been reported⁽²⁵⁾ 41.4% of mandibular incisors contain two clinically separate canals although nearly all of these show apical confluence. In the latter, obturation of one canal at a level which seals the other may well provide the basis for the success presently enjoyed by clinicians. Suffice to say however, when this is not so, failure would be expected to follow due to the presence of an open canal. In the case of mandibular incisors the need for post-operative clinical and radiographic assessment cannot be too highly stressed.

Summary

One hundred and sixty four extracted human teeth of all denominations were subjected to radiographic study following their canal systems being prepared with endodontic instruments and perfused with a water soluble radiopaque contrast medium. The same specimens had been studied prior to endodontic instrumentation by utilising the same technique and a comparison of the two sets of radiographs was made. Results of this comparative study were combined with information gained during the instrumentation procedures and an analysis of the success rate for each group of specimens has been given.

The overall rate of success was high (92%) being highest in the case of maxillary incisors and canines (100%) and lowest in mandibular incisors and canines (81.8%). The belief that molar canals present more difficulties than those of other teeth

was not substantiated in this experiment, the success rate for maxillary and mandibular molars being 92.1%.

The potential for the packing of debris into the apical ends of root canals during instrumentation, the presence of residual traces of alloy found within canals after canal preparation and the known and unknown fractures of endodontic instruments which occurred has been discussed.

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APPENDIX A

Data Recorded During Canal Preparations

Maxillary Teeth

1. Maxillary Central Incisors

Specimen Number	Actual Length (mm)	Length Filed (mm)	Max. K. File Size
8	25.0	24.0	110
17	22.0	21.0	80
20	21.5	20.5	60
123	24.0	23.0	50
124	23.0	22.0	60
125	20.0	19.0	55
135	23.0	22.0	80
136	21.0	20.0	70
145	22.5	21.5	70
149	24.0	23.0	70
150	21.0	20.0	70
151	21.0	20.0	80
153	21.0	20.0	80
154	23.5	22.5	55

2. Maxillary Lateral Incisors

Specimen Number	Actual Length (mm)	Length Filed (mm)	Max. K. File Size
121	17.0	16.0	50
122	24.0	23.0	60
134	23.0	22.0	80
147	23.0	22.0	30
161	23.0	22.0	50
164	22.5	21.5	50

3. Maxillary Canines

Specimen Number	Actual Length (mm)	Length Filed (mm)	Max. K. File Size
9	20.0	19.0	45
19	23.5	22.5	55
126	26.5	25.5	50
132	28.5	27.5	60
148	28.0	27.0	50
156	26.0	25.0	55

4. Maxillary First Premolars

Specimen Number	Actual Length(mm)		Length Filed(mm)		Max. K. File Size	
	B	P	B	P	B	P
5	22.5	23.0	21.5	22.0	40	40
11	26.0	26.0	25.0	25.0	60	60
14 ^{**}	24.5	24.0	23.5	23.0	25	35
	24.5		23.5		25	
16	23.0	23.0	22.0	22.0	110	110
18	19.5	19.5	18.5	18.5	120	120
27	23.0	23.0	22.0	22.0	60	60
33	23.0	23.0	22.0	22.0	30	30
34	21.5	21.0	20.5 [*]	20.0	25	25
47	22.5	22.0	21.5	21.0	45	45
49	20.0	20.0	19.0	19.0	100	100
51	21.0	21.0	20.0	20.0	55	55
70	20.0	20.5	19.0	19.5	55	45

* Unable to negotiate total length of canal with instrument.

** Two buccal canals and one palatal canal.

5. Maxillary Second Premolars

Specimen Number	Actual Length (mm)		Length Filed (mm)		Max. K. File Size	
	B	P	B	P	B	P
13	23.5	23.0	22.5	22.0	30	30
26**	24.0	-	23.0	-	50	-
28	20.0	20.0	19.0	19.0	80	60
29**	20.5	-	19.5	-	35	-
30	18.0	18.0	17.0	17.0	60	55
39**	24.5	-	23.5	-	90	-
40	22.5	22.0	21.5	21.0	80	70
43	23.0	23.0	22.0	22.0	30	30
45**	21.0	-	20.0	-	30	-
46**	21.0	-	20.0	-	120	-
55	24.0	24.0	23.0	23.0	45	45
56**	22.0	-	21.0	-	50	-
58	19.5	19.5	18.5	18.5	40	40
60**	22.5	-	21.5	-	60	-
75	21.5	21.5	20.5	20.5	80	80
79	21.5	21.5	21.0*	21.0*	50	50
88	20.5	20.5	19.5	19.5	100	80
95**	20.5	-	19.5	-	50	-
96	20.0	19.0	19.0	18.0	30	30
101	22.5	22.5	21.5*	21.5*	45	45
106	20.0	20.5	19.0	19.5	50	35
111	19.5	20.5	18.5	19.5	40	40
114**	15.0	-	14.0	-	80	-
118***	17.0	-	16.0	-	30	-

* Unable to negotiate total length of canal with instrument.

** One canal present.

*** Unable to enter palatal canal, only buccal canal negotiated
(disclosed in post-preparation infusion radiographs)

6. Maxillary First Molars

Specimen Number	Actual Length (mm)				Length Filed (mm)				Max.K.File Size			
	MB	MP	DB	P	MB	MP	DB	P	MB	MP	DB	P
3	21.0	21.0	22.0	22.0	20.0	20.0	21.0	21.0	35	35	35	80
22	17.0	17.0	17.5	20.5	16.0	16.5*	16.5	19.5	30	30	30	50
25	20.0	15.0	20.0	22.0	19.0	14.0	19.0	21.0	25	25	25	55
36	20.5	16.5	20.0	20.5	18.5*	15.5*	19.0	19.5	25	25	25	40
41	20.5	20.5	19.0	21.5	19.5	19.5	18.0	20.5	30	30	40	70
54	21.5	21.5	23.0	23.5	20.5	19.0*	22.0	22.5	30	20	25	55
62**	17.0	17.5	18.0	20.0	16.0	16.5	17.0	19.0	40	40	40	55
65	18.5	18.5	20.5	20.5	18.0*	16.0*	19.5	19.5	25	25	25	55
78***	16.5	-	16.5	17.0	15.5	-	15.5	16.0	30	-	30	50

* Unable to negotiate total length of canal with instrument.

** Post-preparation infusion radiographs showed two separate canals (with separate apical openings) in disto-buccal root, there being five canals all told (two mesio-buccal, two disto-buccal and one palatal). Only one disto-buccal canal was negotiated with instruments.

*** Three canals (mesio-buccal, disto-buccal and palatal).

7. Maxillary Second Molars

Specimen Number	Actual Length (mm)				Length Filed (mm)				Max.K.File Size			
	MB	MP	DB	P	MB	MP	DB	P	MB	MP	DB	P
6	20.5	20.5	23.0	21.0	19.5	19.5	22.0	20.0	30	30	25	70
24***	21.5	-	21.5	21.0	20.5	-	20.5	20.0	30	-	30	45
31	21.0	21.0	22.5	23.0	20.0	20.0	21.5	22.0	25	25	25	50
44***	20.0	-	19.0	20.0	19.0	-	18.0	19.0	50	-	25	80
57**	22.0	-	-	22.5	21.5*	-	-	21.5	55	-	-	55
61***	18.5	?	19.0	19.5	17.5	13.5*	18.0	18.5	35	30	40	55
63	20.0	20.0	20.0	21.0	19.0	18.0*	19.0	20.0	25	25	25	40
66***	21.0	-	20.5	22.5	20.0	-	19.5	21.5	40	-	35	60
67	20.5	20.5	20.5	23.0	19.5	19.0*	20.0*	22.0	30	30	30	55
73***	18.5	-	21.0	21.0	17.5	-	20.0	20.0	50	-	40	70
83***	17.0	-	18.0	20.0	16.0	-	17.0	19.0	50	-	50	80
86**	21.0	-	-	22.0	20.0	-	-	21.0	50	-	-	50

* Unable to negotiate total length of canal with instrument.

** Two canals (buccal and palatal)

*** Three canals (mesio-buccal, disto-buccal and palatal).

8. Maxillary Third Molars

Specimen Number	Actual Length (mm)				Length Filed (mm)				Max.K. File Size			
	MB	MP	DB	P	MB	MP	DB	P	MB	MP	DB	P
21 ϕ	-	-	-	18.0	-	-	-	17.0	-	-	-	90
48 $\blacktriangle$	21.5	-	21.5	20.5	20.5	-	20.5	19.5	25	-	25	25
53**	22.0	-	-	22.5	21.0	-	-	21.5	55	-	-	35
69 $\blacktriangle$	20.5	-	23.0	23.0	19.5	-	21.0*	22.0*	25	-	25	25
82***	18.0	-	18.5	19.5	17.0	-	18.0*	18.5	30	-	25	40
85***	22.5	-	22.5	22.5	20.0*	-	18.0*	21.5	25	-	20	25
91***	21.0	-	21.0	21.0	19.5*	-	17.5*	20.0*	25	-	25	25
97***	20.5	-	20.5	20.5	18.0*	-	18.0*	18.0*	25	-	20	25
99 ϕ	-	-	-	16.5	-	-	-	15.5	-	-	-	60
100***	20.5	-	20.5	21.0	19.5	-	19.5	20.0	45	-	30	60
105	18.0	18.0	17.0	16.0	17.0	17.0	16.0	15.0	30	30	30	50
119**	18.0	-	-	17.5	17.0	-	-	16.5	35	-	-	35

* Unable to negotiate total length of canal with instrument.

** Two canals (buccal and palatal).

*** Three canals (mesio-buccal, disto-buccal and palatal).

ϕ One canal only.

$\blacktriangle$ Three canals (one buccal and two palatal).

APPENDIX B

Data Recorded During Canal Preparations

Mandibular Teeth

1. Mandibular Central Incisors

Specimen Number	Actual Length(mm)		Length Filed(mm)		Max.K.File Size	
	B	L	B	L	B	L
130 ^{**}	23.0	-	22.0	-	30	-
139 ^{**}	22.0	22.0	21.0	21.0	25	25
140 [*]	22.0	22.0	21.0	21.0	30	30
142 ^{***}	22.0	22.0	21.0	21.0	25	25
157 [*]	20.0	-	19.0	-	40	-
159 ^{**}	22.0	-	21.0	-	35	-

* One canal present.

** Two canals present.

*** Three canals present (disclosed in post-preparation infusion radiographs).

2. Mandibular Lateral Incisors

Specimen Number	Actual Length (mm)		Length Filed (mm)		Max. K.File Size	
	B	L	B	L	B	L
131 [*]	24.0	-	23.0	-	25	-
138 ^{**}	22.0	22.0	21.0	21.0	25	25
141 [*]	20.0	-	19.0	-	30	-
143 ^{**}	24.0	24.0	23.0	23.0	25	25
152 ^{***}	23.5	23.5	22.5	22.5	30	30
158 [*]	25.5	-	24.5	-	55	-
162 ^{**}	23.0	23.0	22.0	22.0	30	30

* One canal present.

** Two canals present.

*** Three canals present (disclosed in post-preparation infusion radiographs).

3. Mandibular Canines

Specimen Number	Actual Length (mm)		Length Filed (mm)		Max.K. File Size	
	B	L	B	L	B	L
127	28.5	-	27.5	-	35	-
128	27.0	-	26.0	-	50	-
129	29.5	-	28.5	-	45	-
137	27.0	-	26.0	-	50	-
144	26.0	-	25.0	-	50	-
146**	24.5	24.0	23.5	22.5	25	25
155	29.0	-	28.0	-	45	-
160	23.5	-	22.5	-	50	-
163	22.0	-	21.0	-	50	-

** Two roots and two canals present.

4. Mandibular First Premolars

Specimen Number	Actual Length (mm)		Length Filed (mm)		Max.K. File Size	
	B	L	B	L	B	L
1	26.0	-	25.0	-	70	-
2**	24.0	23.0	23.0	22.0	110	80
12	23.0	-	22.0	-	110	-
35	21.0	-	20.0	-	90	-
37	24.0	-	23.0	-	80	-
50**	23.0	23.0	22.0	22.0	55	35
76	25.5	-	24.5	-	80	-
89***	23.5	-	22.0*	-	30	-
103	20.5	-	19.5	-	60	-
107	24.0	-	23.0	-	45	-
109▲	21.5	20.5	21.0	20.0	30	30
110	23.0	-	22.0	-	50	-
112**	20.5	20.5	19.5	19.5	45	30
116	23.0	-	22.0	-	70	-
117	25.0	-	24.0*	-	35	-
133	20.5	-	19.5	-	100	-

* Unable to negotiate total length of canal with instrument.

** Two canals present in one root.

*** Three canals present in one root (disclosed in post-preparation infusion radiographs).

▲ Distinct apical branching negotiable with instruments.

5. Mandibular Second Premolars

Specimen Number	Actual Length (mm)		Length Filed (mm)		Max.K. File Size	
	B	L	B	L	B	L
15	22.0	-	21.0	-	70	-
71	26.0	-	25.0	-	70	-
74	22.0	-	21.0	-	45	-
81	21.5	-	20.5	-	60	-
87	22.0	-	21.0	-	35	-
90	25.0	-	24.0	-	30	-
92	24.5	-	23.0*	-	40	-
94**	23.0	22.5	22.0	21.5	25	25
104	22.0	-	21.0	-	90	-
108	24.0	-	23.0	-	40	-
113	19.0	-	18.0	-	40	-
115	21.0	-	20.0	-	40	-

* Unable to negotiate total length of canal with instrument.

** Two canals present in one root.

6. Mandibular First Molars

Specimen Number	Actual Length (mm)				Length Filed (mm)				Max. K. File Size			
	MB	ML	DB	DL	MB	ML	DB	DL	MB	ML	DB	DL
10	23.0	23.0	24.0	-	22.0	22.0	23.0	-	30	30	45	-
72	18.5	18.5	18.0	-	17.5	17.5	17.0	-	35	35	70	-
80	19.5	19.5	20.5	20.5	18.5	18.5	19.5	19.5	25	25	30	25

7. Mandibular Second Molars

Specimen Number	Actual Length (mm)				Length Filed (mm)				Max.K.File Size			
	MB	ML	DB	DL	MB	ML	DB	DL	MB	ML	DB	DL
4	22.5	23.0	23.0	-	21.5	22.0	22.0	-	25	25	45	-
7	18.5	18.5	17.5	-	17.5	17.5	16.5	-	25	25	70	-
23	19.0	19.5	19.0	-	18.0	18.5	18.0	-	30	30	70	-
32	19.0	19.0	17.5	-	18.0	18.0	16.5	-	25	25	45	-
38	Eliminated from experiment due to repeated instrument fracture.											
42	18.0	18.0	19.0	-	17.0	17.0	18.0	-	30	30	80	-
52	20.0	20.0	20.0	-	19.0*	19.0	19.0	-	25	25	45	-
59	18.5	18.5	18.5	18.5	17.5	17.5	17.5	17.5	25	25	30	30
64▲	19.0	19.0	20.5	-	18.0	18.0	19.5	-	40	40	60	-
68	18.5	18.5	17.0	-	17.5	17.5	16.0	-	35	35	60	-
84**	14.0	-	16.0	-	13.0	-	15.0	-	30	-	30	-
93	18.5	18.5	18.5	-	17.5	17.5*	17.5	-	35	35	50	-
102	18.0	18.0	19.5	-	17.0	17.0	18.5	-	45	45	60	-

* Unable to negotiate total length of canal with instrument.

** Two canals present (mesial and distal).

▲ Post-preparation infusion radiographs disclosed two canals in the distal root, only one of which was negotiated.

8. Mandibular Third Molars

Specimen Number	Actual Length(mm)				Length Filed(mm)				Max.K.File Size			
	MB	ML	DB	DL	MB	ML	DB	DL	MB	ML	DB	DL
77	22.0	22.5	22.0	-	21.0	21.5	21.0	-	30	30	30	-
98**	16.5	-	16.5	-	15.5	-	15.5	-	30	-	40	-
120	18.5	18.5	17.5	-	17.5*	17.5	16.5*	-	25	25	25	-

* Unable to negotiate total length of canal with instrument.

** Two canals present (mesial and distal).

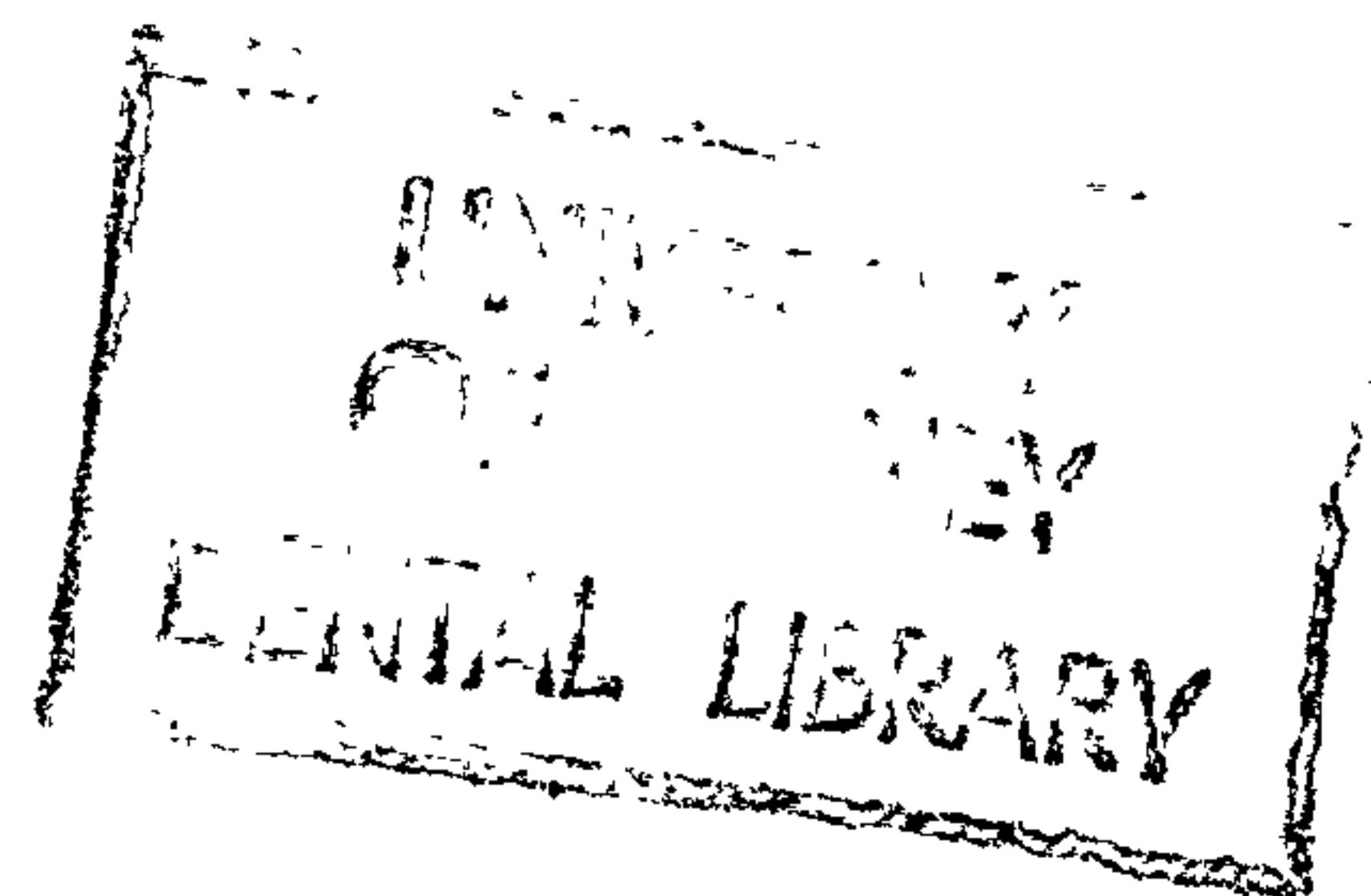
APPENDIX C

Comparison of Pre-filing and Post-filing
Radiographs and Clinical Assessments

Maxillary Teeth

1. Maxillary Central Incisors

Specimen Number	Canals Present	Canals Filed	Continuous Taper	Shoulder Formation	Creep Back	Clinical Acceptance
8	1	1	✓	✓	-	✓
17	1	1	✓	✓	-	✓
20	1	1	✓	✓	-	✓
123	1	1	✓	✓	-	✓
124	1	1	✓	✓	-	✓
125	1	1	-	✓	-	✓
135	1	1	-	✓	-	✓
136	1	1	-	✓	-	✓
145	1	1	-	✓	-	✓
149	1	1	✓	✓	-	✓
150	1	1	-	✓	-	✓
151	1	1	✓	✓	-	✓
153	1	1	✓	✓	-	✓
154	1	1	✓	✓	-	✓



2. Maxillary Lateral Incisors

Specimen Number	Canals Present	Canals Filed	Continuous Taper	Shoulder Formation	Creep Back	Clinical Acceptance
121	1	1	-	✓	-	✓
122	1	1	✓	✓	-	✓
134	1	1	-	✓	-	✓
147	1	1	-	✓	-	✓*
161	1	1	-	✓	-	✓**
164	1	1	✓	✓	-	✓

* Foreign body seen in canal presumed to be alloy particle.

** Fractured instrument, undetected during instrumentation procedure.

3. Maxillary Canines

Specimen Number	Canals Present	Canals Filed	Continuous Taper	Shoulder Formation	Creep Back	Clinical Acceptance
9	1	1	-	✓	-	✓
19	1	1	✓	✓	-	✓
126	1	1	-	✓	-	✓
132	1	1	✓	✓	-	✓
148	1	1	✓	✓	-	✓
156	1	1	✓	✓	-	✓

4. Maxillary First Premolars

Specimen Number	Canals Present	Canals Filed	Clinical Acceptance	
			B	P
5	2	2	✓	✓
11	2	2	✓	✓
14	3	3	✓	✓
16	2	2	✓	✓
18	2	2	✓	✓
27	2	2	✓	✓
33	2	2	X*	✓
34	2	2	✓	✓
47	2	2	✓	✓
49	2	2	✓	✓
51	2	2	✓	✓
70	2	2	✓	✓

* Fractured instrument, undetected during instrumentation procedure.

5. Maxillary Second Premolars

Specimen Number	Canals Present	Canals Filed	Clinical Acceptance	
			B	P
13	2▲	2	✓	✓*
26	1	1	✓	-
28	2	2	✓	✓
29	1	1	✓	-
30	2▲	2	✓	✓
39	1	1	✓	-
40	2▲	2	✓	✓
43	2▲	2	✓	✓
45	1	1	X**	-
46	1	1	✓	-
55	2▲	2	✓	✓
56	1	1	✓	-
58	2	2	✓	✓
60	1	1	✓	-
75	2▲	2	✓	✓
79	2▲	2	✓	✓
88	2	2	✓	✓
95	1	1	✓	-
96	2	2	✓	✓
101	2	2	✓	✓
106	2	2	✓	✓
111***	2	2	✓	X
114	1	1	✓	-
118∅	2▲	1	✓	X

* Fractured instrument fragment, undetected during instrumentation procedure.

** Nos. 10, 15 and 40 K files fractured during instrumentation and by-passed with No. 30 K file - possibly acceptable clinically.

*** Apical ramifications could preclude clinical acceptance unless resected.

∅ Possibly acceptable clinically due to common canal in apical third.

▲ Apical confluence of canals.

6. Maxillary First Molars

Specimen Number	Canals Present	Canals Filed	Problem Roots			Clinical Acceptance
			MB	DB	P	
3	4	4	-	-	-	✓
22	4	4	-	-	-	✓
25	4	4	X ^{**}	X ^{**}	-	✓
36	4	4	X ^{**}	-	-	✓
41	4	4	-	-	-	✓
54	4	4	X ^{***}	-	-	✓*
62	5	4	-	X [▲]	-	X
65	4	4	X ^{**}	-	-	✓*
78	3	3	-	-	-	✓

* Traces of foreign material seen in canals, presumed to be alloy particles.

** Canals prepared short of desired level (within 3.0 mm from apex).

*** Mesio-palatal canal only able to be prepared to size 20 K file.

▲ Two canals present in disto-buccal root (each with separate apical foramen) and only one prepared.

7. Maxillary Second Molars

Specimen Number	Canals Present	Canals Filed	Problem Roots			Clinical Acceptance
			MB	DB	P	
6	4	4	-	-	-	✓
24	3	3	-	-	-	✓
31	4	4	-	-	-	✓
44	3	3	-	-	-	✓
57	2	2	-	-	-	✓
61	4	3	X [*]	-	-	X ^{***}
63	4	4	-	-	-	✓
66	3	3	-	-	-	✓ ^{***}
67	4	4	-	X ^{**}	-	X
73	3	3	-	-	-	✓ ^{***}
83	3	3	-	-	-	✓
86	2	2	-	-	-	✓

* Mesio-palatal canal of indeterminate length and unable to be completely negotiated. Resection and retro-fill necessary for mesio-buccal root in clinical situation.

** Known fracture of 1.0 mm of No. 10 K file (during instrumentation) at apex and unable to be by-passed.

*** Traces of foreign material seen in canals, presumed to be alloy particles.

8. Maxillary Third Molars

Specimen Number	Canals Present	Canals Filed	Problem Roots			Clinical Acceptance
			MB	DB	P	
21	1	1	-	-	-	✓
48	3	3	-	X [*]	-	✓
53	2	2	-	-	-	✓
69	3	3	-	-	-	✓
82	3	3	-	-	-	✓
85	3	3	-	-	-	✓
91	3	3	-	-	-	✓
97	3	3	-	X ^{**}	-	✓
99	1	1	-	-	-	✓
100	3	3	-	-	-	✓
105	4	4	-	-	-	✓
119	2	2	-	-	-	✓ ^{***}

* Creep back evident during instrumentation.

** Disto-buccal canal only able to be prepared to size 20 K file.

*** Traces of foreign material seen in canals, presumed to be alloy particles.

APPENDIX D

Comparison of Pre-filing and Post-filing
Radiographs and Clinical Assessments

Mandibular Teeth

1. Mandibular Central Incisors

Specimen Number	Canals Present	Canals Filed	Continuous Taper	Shoulder Formation	Creep Back	Clinical Acceptance
130	2 ▲	1	✓	-	-	X*
139	2 ▲	2	✓	-	-	✓
140	1	1	✓	✓	-	✓
142	3	2	✓	✓	-	X**
157	1	1	✓	✓	-	✓
159	2 ▲	1	✓	✓	✓	X*

▲ Apical confluence of canals.

* Possibly acceptable clinically due to common canal in apical region.

** Three canals with separate apical openings, only two of which were instrumented.

2. Mandibular Lateral Incisors

Specimen Number	Canals Present	Canals Filed	Continuous Taper	Shoulder Formation	Creep Back	Clinical Acceptance
131	1	1	✓	✓	-	✓
138	2▲	2	✓	✓	-	✓
141	1	1	✓	✓	-	✓
143	2▲	2	✓	-	-	✓
152	3▲	2	✓	✓	-	X*
158	1	1	✓	✓	-	✓
162	2	2	✓	-	-	✓

▲ Apical confluence of canals.

* Three canals present and only two negotiated with instruments. Possibly acceptable clinically due to apical confluence of canals.

3. Mandibular Canines

Specimen Number	Canals Present	Canals Filed	Continuous Taper	Shoulder Formation	Creep Back	Clinical Acceptance
127	1	1	✓	✓	-	✓
128	1	1	✓	✓	-	✓
129	1	1	✓	✓	-	✓
137	1	1	✓	✓	-	✓
144	1	1	✓	✓	-	✓
146	2	2	✓	✓	✓*	✓
155	1	1	✓	✓	-	✓
160	1	1	✓	✓	-	✓
163	1	1	✓	✓	-	✓

* Evidence of creep back seen in lingual canal.

4. Mandibular First Premolars

Specimen Number	Canals Present	Canals Filed	Clinical Acceptance	
			B	L
1	1	1	✓	-
2	2	2	✓	✓
12	1	1	✓	-
35	1	1	✓	-
37	1	1	✓	-
50	2	2	✓	✓
76	1	1	✓	-
89	3	1*	X	X
103	1	1	✓	-
107	1	1	✓	-
109	2	2	✓	✓
110	1	1	✓	-
112	2	2	✓	✓
116	1	1	✓	-
117	1	1	✓	-
133	1	1	✓	-

* Three canals present with separate apical openings, only one being instrumented.

5. Mandibular Second Premolars

Specimen Number	Canals Present	Canals Filed	Clinical Acceptance	
			B	L
15	1	1	✓	-
71	1	1	✓	-
74	1	1	✓	-
81	1	1	✓	-
87	1	1	✓*	-
90	1	1	✓	-
92	1	1	✓	-
94	2	2	✓	✓
104	1	1	✓	-
108	1	1	✓	-
113	1	1	✓	-
115	1	1	✓	-

* Traces of foreign material seen in apical accessory canal and apical portion of main canal, presumed to be alloy particles.

6. Mandibular First Molars

Specimen Number	Canals Present	Canals Filed	Problem Roots		Clinical Acceptance
			M	D	
10	3	3	-	-	✓
72	3	3	-	-	✓
80	4	4	-	-	✓

7. Mandibular Second Molars

Specimen Number	Canals Present	Canals Filed	Problem Roots		Clinical Acceptance
			M	D	
4	3	3	-	-	✓
7	3	3	-	-	✓
23	3	3	-	-	✓
32	3	3	-	-	✓
38*	-	-	X	-	X
42	3	3	-	-	✓
52	3	3	-	-	✓
59	4	4	-	-	✓
64	4	3	-	X**	X
68	3	3	-	-	✓
84	2	2	-	-	✓
93	3	3	-	-	✓
102	3	3	-	-	✓

* Eliminated from experiment due to repeated failure of instruments during canal preparation:

- (i) Mesio-buccal canal:- 2.0 mm of No. 10 K file fractured at apical end, by-passed with another 10 K file, 15 K file. Fragment forced through apex when 20 K file used to continue enlargement.
- (ii) Mesio-lingual canal:- 14.0 mm of No. 30 K file fractured with new instrument after incremental instrumentation from 10 K file, the fragment binding at the apical end leaving 2.0 mm standing in the pulp chamber. A section of the mesio-buccal wall of the crown was removed, the fragment grasped with "splinter forceps" and extracted from the canal.

** Root containing two canals with common apical opening where only one canal instrumented.

8. Mandibular Third Molars

Specimen Number	Canals Present	Canals Filed	Problem Roots		Clinical Acceptance
			M	D	
77	3	3	-	-	✓
98	2	2	-	-	✓
120	3	3	-	-	✓

APPENDIX E

Specimens Showing Patency of Apical Openings

Following Canal Preparation

Specimen Number	Tooth	K. File Size Used	Specimen Number	Tooth	K. File Size Used
27	<u>4</u>	30	99	<u>8</u>	60
28	<u>5</u>	60	100	<u>8</u>	30
30	<u>5</u>	55	103	<u>4</u>	60
32	<u>7</u>	25	104	<u>5</u>	90
37	<u>4</u>	80	107	<u>4</u>	45
40	<u>5</u>	70	113	<u>5</u>	40
41	<u>6</u>	30	114	<u>5</u>	80
42	<u>7</u>	30	115	<u>5</u>	40
43	<u>5</u>	30	116	<u>4</u>	70
46	<u>5</u>	120	118	<u>5</u>	30
49	<u>4</u>	55	122	<u>2</u>	60
53	<u>8</u>	35	130	<u>1</u>	30
55	<u>5</u>	45	133	<u>4</u>	100
59	<u>7</u>	25	136	<u>1</u>	70
60	<u>5</u>	60	139	<u>1</u>	25
74	<u>5</u>	45	140	<u>1</u>	30
75	<u>5</u>	80	141	<u>2</u>	30
76	<u>4</u>	80	148	<u>3</u>	50
80	<u>6</u>	25	149	<u>1</u>	70
84	<u>7</u>	30	150	<u>1</u>	70
85	<u>8</u>	20	151	<u>1</u>	80
86	<u>7</u>	50	156	<u>3</u>	55
88	<u>5</u>	80	157	<u>1</u>	40
93	<u>7</u>	35	160	<u>3</u>	50
94	<u>5</u>	25	162	<u>2</u>	30
98	<u>8</u>	30	164	<u>2</u>	50

4 Maxillary first premolar.

4 Mandibular first premolar.

(147)

APPENDIX F

Specimens Lacking Patency of Apical Openings

Following Canal Preparation

Specimen Number	Tooth	K. File Size Used	Specimen Number	Tooth	K. File Size Used
19	<u>3</u>	55	65	<u>6</u>	25
24	<u>7</u>	30	66	<u>7</u>	35
25	<u>6</u>	25	67	<u>7</u>	30
26	<u>5</u>	50	68	<u>7</u>	35
29	<u>5</u>	35	69	<u>8</u>	25
31	<u>7</u>	25	70	<u>4</u>	60
33	<u>4</u>	25	71	<u>5</u>	70
34	<u>4</u>	45	72	<u>6</u>	35
35	<u>4</u>	90	73	<u>7</u>	40
36	<u>6</u>	25	77	<u>8</u>	30
39	<u>5</u>	90	78	<u>6</u>	30
44	<u>7</u>	25	79	<u>5</u>	50
45	<u>5</u>	30	81	<u>5</u>	60
47	<u>4</u>	100	82	<u>8</u>	25
48	<u>8</u>	25	83	<u>7</u>	50
50	<u>4</u>	35	87	<u>5</u>	35
51	<u>4</u>	45	89	<u>4</u>	30
52	<u>7</u>	25	90	<u>5</u>	30
54	<u>6</u>	20	91	<u>8</u>	25
56	<u>5</u>	50	92	<u>5</u>	40
57	<u>7</u>	55	95	<u>5</u>	50
58	<u>5</u>	40	96	<u>5</u>	30
61	<u>7</u>	30	97	<u>8</u>	20
62	<u>6</u>	40	101	<u>5</u>	45
63	<u>7</u>	25	102	<u>7</u>	45
64	<u>7</u>	40	105	<u>8</u>	30

Legend: See overleaf.

Specimen Number	Tooth	K. File Size Used	Specimen Number	Tooth	K. File Size Used
106	<u>5</u>	30	134	<u>2</u>	80
108	<u>5</u>	40	135	<u>1</u>	80
109	<u>4</u>	30	137	<u>3</u>	50
110	<u>4</u>	50	138	<u>2</u>	25
111	<u>5</u>	40	142	<u>1</u>	25
112	<u>4</u>	30	143	<u>2</u>	25
117	<u>4</u>	35	144	<u>3</u>	50
119	<u>8</u>	35	145	<u>1</u>	70
120	<u>8</u>	25	146	<u>3</u>	20
121	<u>2</u>	50	147	<u>2</u>	30
123	<u>1</u>	50	152	<u>2</u>	30
124	<u>1</u>	60	153	<u>1</u>	80
125	<u>1</u>	55	154	<u>1</u>	55
126	<u>3</u>	50	155	<u>3</u>	45
127	<u>3</u>	35	158	<u>2</u>	55
128	<u>3</u>	50	159	<u>1</u>	35
129	<u>3</u>	45	161	<u>2</u>	50
131	<u>2</u>	25	163	<u>3</u>	50
132	<u>3</u>	60	-	-	-

4 Maxillary first premolar.

4 Mandibular first premolar.

ADDENDUM

Upon the completion of this study there has been time to read the material afresh and to reflect upon its merit. The obvious question which poses itself is "what has been the nett product of the work?".

There are many items of note which have become evident. Some, which in the past have been taken for granted by clinicians bear further consideration, whilst others pose questions which are even now only partly answered although they may open the way for subsequent investigation. It was an appreciation of the latter which stimulated the presentation of this thesis in the form it now enjoys. Such a presentation was readily adaptable for publication within the realms of international dental literature, thus exposing the material for discussion and (hopefully) continued study. The four chapters which form this thesis have been accepted for publication, thereby realising in part the ideal expressed above.

In answer to the rhetorical question asked in the opening paragraph, the results of the study may be summarised as follows :

(ii)

1. An alternative technique has been developed whereby the internal anatomy of extracted teeth may be studied.
2. The technique may be utilised on the same specimen prior to and following endodontic instrumentation, thus allowing for a comparison to be made between the original and the prepared canal systems.
3. Utilising this technique, the canal systems of one hundred and sixty four specimens (involving three hundred and nine negotiable canals) were examined prior to and following canal preparation.

Of note were -

- a) the high incidence of lateral canals found in maxillary incisors,
- b) the high incidence of apical ramifications found in maxillary molars,
- c) the paucity of furcation canals evident when using this technique,
- d) the complexity of the canal systems found in mandibular incisors and premolars,

and of particular note,

- e) the presence of two canals found in each of the mesio-buccal roots of eight of the nine maxillary first molars examined.

(iii)

4. During the endodontic preparation of the three hundred and nine canals the following were observed :

- a) "Average" tooth lengths bear little resemblance to the length determination which must be made by a clinician during endodontic treatment. In all cases a careful assessment of tooth length, utilising the established methods should be employed.
- b) The use of chelates was found to be a positive aid to canal entry and preparation. In certain cases they were deemed essential to adequately effect instrumentation. In particular, 5.5% E.D.T.A. was the material of choice.
- c) The very process of canal preparation as currently performed tends to compact canal debris into the apical portion of the canal.
- d) In more than half of the teeth examined, the previously cleared canals exhibited apical stenosis following preparation, even though they had all been irrigated by the alternate use of 4.0% sodium hypochlorite and 3.0% hydrogen peroxide.
- e) Instrument failures, sometimes undetected, may arise during canal preparation despite the efforts of the operator to avoid such occurrences.

(iv)

- f) The desired depth of preparation and shaping of the canal may be achieved in nearly all cases.

5. A comparison of pre- and post-canal preparation radiographs in the same specimens showed -

- a) The presence of metallic fragments which were identified as remnants of fractured files where in certain instances there had been no record of instrument failure, and
- b) The presence of minute radiopaque particles which resembled the appearance of finely ground fragments of amalgam alloy. In all cases the tooth in question contained an amalgam restoration.

6. Using a system of assessment based upon clinical experience and reasoned judgement, the overall success rate for teeth with all canals successfully prepared was 92.0%.

The most successful group were maxillary incisors and canines (100%).

The least successful group were mandibular incisors and canines (81.8%).

Those teeth which are least often endodontically treated (largely due to their supposed difficulty of canal negotiation) are maxillary and mandibular molars. Using the above method of assessment it is notable that the canals of these teeth were

successfully prepared in 92.1% of cases.

In all, it would appear canal preparation may be successfully performed in most cases, provided the operator has a sound knowledge of endodontic morphology, including the possible variations which may occur. It is also suggested, the careful use of chelates combined with the principles of instrumentation as outlined in the texts which were used as references to support this thesis and within this thesis itself, should lead to the successful conclusion of endodontic treatment in the clinical situation.