

Chapter 6

Development of Radiographic Contrast-Enhancement Masks

Radiographic contrast-enhancement mask (RCM) algorithms were developed to overcome some limitations of general digital radiography (DR). Large attenuation differences of some anatomical regions result in exit radiation having a wide dynamic range. In general radiography, this results in anatomy not being fully visualised in the image or being displayed with suboptimal contrast. Physical tissue compensation filters (TCFs) are used in film/screen (F/S) general radiography to assist in overcoming this limitation. Digital radiographic images have a large dynamic range and hence not all the diagnostic information within this dynamic range can be displayed with acceptable image contrast. In DR, users can alter image brightness and contrast. This and other post-processing functions discussed in Chapter 5 allow users to compensate for large anatomical attenuation differences. These post-processing routines can assist in overcoming such limitations of general DR.

The use of TCFs in DR results in artefactual appearances on the image. However, post-processing routines have their own limitations. Displayed contrast cannot be optimised for the entire image where large anatomical attenuation differences exist. Contrast and brightness adjustments are global operations and act upon the entire image. Viewers manipulate the contrast to visualise various areas within the image at a high displayed contrast. This allows for greater differentiation of subtle density differences within the image. The disadvantage is that other areas in the image will appear black and/or white with high displayed contrast settings. Re-manipulation of these areas is required. Spatial enhancing techniques are also global operations which may act adversely on some areas of the image so that de-optimisation of the image may occur.

6.1 Previous Work

Several approaches similar to the method used to produce digital RCMs have been reported. These approaches were used with digital mammographic images. Giger & MacMahon (1996), in a general discussion of image processing techniques, discussed peripheral enhancement of breast images. The compressed breast in mammography has less thickness in peripheral regions than in the centre of the breast. A density curve is plotted from the centre of the breast image to the periphery. This density plot is used to adjust the density values and increase the peripheral density values. Byng, Critten & Yaffe (1997) adjusted breast density values in the peripheral breast where breast tissue is thinner. Their method was to determine the pixel values of breast tissue in the centre of the breast where tissue is thicker. The difference between peripheral pixel values was calculated and applied as an equalisation value to peripheral pixels. Stefanoyiannis *et al* (2003) used a similar approach. In this case, the correction method depended upon the mean value over iso-distance lines from the periphery to the centre of the breast. The authors reported that this method also improved image contrast in the interior areas of the breast.

More recently, Snoeren & Karssemeijer (2004) modelled the shape of the breast and created tissue thickness maps of the breast tissue. Compressed breast tissue ideally should be uniform in thickness for the mammographic examination. Snoeren & Karssemeijer used the x-ray intensity values to map the thickness variations within the actual image. Corrections were made for peripheral thickness and for the shape of the compressed breast tissue. An intensity map was calculated, and was applied to the breast image to adjust the pixel values and hence equalise contrast across the entire breast image.

6.2 Radiographic Contrast-Enhancement Mask Principles

Digital RCMs are based on contrast manipulation principles. Digital RCMs do not alter the spatial frequencies or sharpness of the image. Only the displayed contrast is altered. Displayed contrast is the difference between displayed pixel values. The transect histogram in Figures 6.1a & b provides a graphical representation of

displayed contrast. The transect histograms (bottom of both images) is a plot of pixel values along the line shown in the image. Figure 6.1a has high displayed contrast and Figure 6.1b has low displayed contrast. The pixel values along the line have greater differences in Figure 6.1a than in Figure 6.1b. A greater range of pixel values implies high contrast. The images in Figure 6.1 are 8 bit depth for display purpose. The same principle applies for 12 bit depth images.

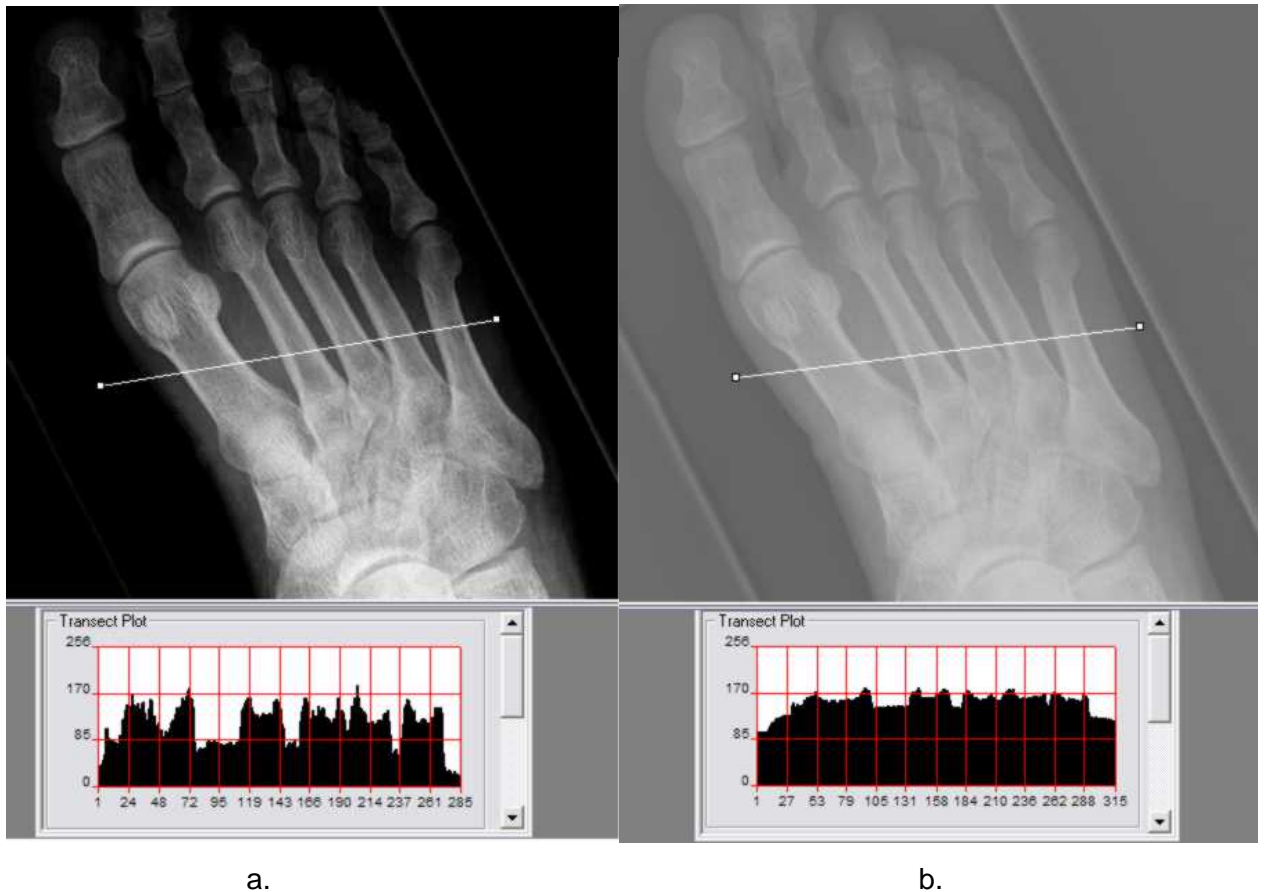


Figure 6.1 Radiographic images and transect plots showing:

- a. High displayed contrast;
- b. Low displayed contrast

The contrast manipulation properties of digital RCMs act locally. Physical TCFs affect local contrast in an image and in DR, areas of anatomy that are highly attenuating have pixel values that are high. Areas of low attenuation appear black on the image and have low pixel values. Physical TCFs attenuate the x-ray beam to produce a non-uniform intensity entrance beam. The non-uniform intensity entrance beam is directed at the anatomy to compensate for high attenuating differences. This

results in a more uniform exit beam. High radiographic contrast in the image can be achieved without over- or under-exposing areas within the image. Over-exposed areas within the image would appear black, and under-exposed areas would appear white.

The principle of digital RCMs is to increase the relative pixel values in one area of the image compared to that of another area. The digital RCM is essentially an intensity map of values shaped to the anatomy to which it is to be applied. The intensity map or digital RCM values vary according to the amount of contrast adjustment required in the individual anatomical region. Each DR image pixel value is multiplied by the corresponding digital RCM value which is overlaid on the image. If no contrast adjustment is required in a region, the digital RCM values are 1. If contrast adjustment is required, the values are greater than 1.

Local area contrast is not affected and neighbouring pixels are multiplied by the same or similar digital RCM value. These pixel values have a contrast that remains constant. Pixels in another anatomical region are multiplied by a different digital RCM value. Thus the relative contrast between the two distant anatomical areas is altered. The result of applying a digital RCM is that a greater uniformity of pixel values throughout the image is achieved. If the RCM is applied appropriately, the dynamic range of the DR image is altered. Standard global contrast manipulation techniques can then be applied across the entire image to maximise displayed contrast without causing some anatomical areas to appear black or white.

Digital RCMs are shaped in the plan or two dimensional view to suit the anatomy that has been imaged. The shapes of the digital RCM were based on the physical TCFs that were reported in the literature and that were in clinical use. Viewers of the image can modify the shape of the digital RCM to the anatomical variations that exist between patients.

Local contrast manipulations are adjustable by the viewer. The third dimension or the height of the digital RCM is the multiplication factor that is used to adjust the contrast. These values range from 1, where there is no alteration of the pixel values, to a maximum value set by the user.

6.3 Development of Digital RCMs

The design of the digital RCMs was based upon characteristics of the physical TCF. Physical TCFs were designed to be used in the radiographic examination of specific anatomical regions. The shape of the physical TCF mimics the shape of the anatomy being examined. The thickness of the physical TCF depends upon two factors, material type and the amount of attenuation needed for the anatomical region. Two general digital RCM shapes, a wedge filter and a boomerang filter, were designed and evaluated (evaluation is detailed in later chapters). A further trough-shaped digital RCM for use with DR images of the chest is discussed in principle only. With these basic shapes, users can further modify the plan-view shape of the digital RCM. The multiplication values or the “thickness” in the third dimension of the digital RCM can also be controlled by the user. An intensity map is the result of applying the thickness components to the plan view shape. The digital RCM is shaped by the user to suit the anatomy.

The numbers of rows and columns of the digital RCM, the x and y dimensions, are the same as in the original image. This was done for ease of applying the digital RCM to the image. Later development of digital RCMs may not require this criterion. The size of the digital RCM being the same as that of the image does not imply that the effect of the applied digital RCM is global. Sections of the digital RCM may have values of 1. These sections will not affect the image.

In areas of the image not to be altered, the digital RCM values are set to 1. In anatomical regions of the image where pixel values are low, the digital RCM values are set to values greater than 1. When the contrast differences that exist in the original image are large, the RCM values used would be typically greater than 2.

Typical medical images consist of approximately 2,000 rows and 2,000 columns of pixels, so-called 2 K resolution. The RCM is mapped over the original image to form a new image. The mapping process multiplies each original image pixel value by the digital RCM value at the same spatial (x, y) location. The general formula for the mapping process is given in Equation 6.1.

$$O(x, y) = I(x, y) * f(x, y) \quad \dots\dots\dots 6.1$$

where: $O(x,y)$ is the new image;
 $I(x,y)$ is the original image;
 $f(x,y)$ is the digital RCM or intensity map.

A suitable personal computer (PC) based program for the development and mapping processes was needed. The mapping of the digital RCM with the image is essentially a linear algebraic process using matrices. A mathematical program designed for use with matrices is Matlab[®] (MathWorks Inc., Natick, USA). Matlab[®] Version 5.1 was originally purchased and has since been upgraded to Version 6.5. Matlab[®] has various toolboxes that can be purchased for additional functionality of the program in specific areas. The Image Processing toolbox and Signal Processing toolbox were purchased. The Image Processing toolbox has functionality that allows images to be read into the program and used as matrices. Various image file formats such as Joint Photographic Expert Group (JPEG), Tag Imaging File Format (TIFF) and Digital Imaging and Communications in Medicine (DICOM) can be read into the program and then be manipulated within the program. The Image Processing toolbox also allows contrast and brightness manipulation and spatial domain processing. The frequency domain functionality of the Signal Processing toolbox was originally considered as an approach within digital RCM design. This approach was subsequently discarded for the simpler contrast manipulation method.

Matlab[®] allows users to develop algorithms. The process of algorithm development is similar to coding in high level computer programming languages. Codes can be developed to allow repetitive processes to be performed; mapping two large matrices is such a process. The algorithms form a Matlab[®] file called an m file. The m files used in this project can be seen in Appendix 2.

Digital RCMs can be considered three dimensional (3D). The two plan view dimensions (x, y) are those of the image and the third dimension or height depicts the values at the (x, y) locations. The development of vertical shapes and the height of the digital RCM was achieved using Matlab[®] vector capabilities. To create the vertical shape of the filter, a function was applied to a vector of a specific length.

This created the desired vertical shape of the digital RCM. Once the vertical shape of the filter had been created, the height could be adjusted. Other vectors of various sizes that consisted of zeros or ones could be added to complete the shape of the digital RCM. This vector was then replicated across the plan view shape to create a three dimensional digital RCM. Design of the specific digital RCMs is detailed in the following sections.

6.4 Wedge Shaped RCM Profiles

Wedge shaped RCMs were the first to be designed. These designs are simpler than boomerang and trough shapes. There are two wedge shapes digital RCMs, a linear wedge and a curved wedge. The cross-sectional shape of the wedge RCM, or the vertical profile, is controlled by user inputs that determine the values within a vector.

The length of the overall profile vector is equal to:-

1. the number of rows in the image, if the user determines that the wedge RCM should be applied from the top to the bottom of the image or from the bottom to the top, *or*
2. the number of columns in the image, if the user determines that the wedge RCM should be applied left to right or right to left, *or*
3. $\sqrt{(\text{no. of rows})^2 + (\text{no. of columns})^2}$, if the user determines the orientation of the RCM is to be at an angle other than a right angle.

The profile vector consists of three smaller sub-vectors. The middle sub-vector consists of the wedge values. The length of each of the three vectors is determined by user input. Varying the length of each small vector allows the user to control the location in the anatomy at which the wedge sections will be applied. It allows users to control the length of the wedge section.

The two end sub-vectors of the profile vector consist of “1”s or “0”s. One end sub-vector values are set at 0 and the other end sub-vector values are set at 1. The middle wedge sub-vector has values ranging from 0 to 1. This section forms the wedge’s vertical shape. The shape of the middle sub-vector is either linear or curved, again

determined by user input. Once the overall profile vector is created, all values are altered. The height of the profile is multiplied by a value equal to the user-defined maximum value minus 1, with the result that the profile height ranges between 0 and the user-defined maximum value minus 1. Following this, all profile vector values are increased by the addition of 1. Thus the zero values of the profile vector become 1. This section of the RCM, when applied to the image, does not alter the image values and hence does not affect local area contrast. The maximum profile vector value is restored to the original user defined value.

The slope of the wedge sub-section of the profile vector will depend upon the length of the wedge sub-section of the profile vector and the maximum value of the vector. Figure 6.2 shows a plot of a linear profile vector with values between 1 and 2. The two end sub-vectors were each set to zero length. The user input for the maximum contrast-enhancing effect of the filter was 2. Figure 6.3 shows a profile vector with the same the maximum contrast-enhancing value of 2. User inputs for the length of the end sub-vectors of the RCM were 20%, where no effect from the RCM will occur, and 35%, where maximum contrast enhancement will occur equally across the image.

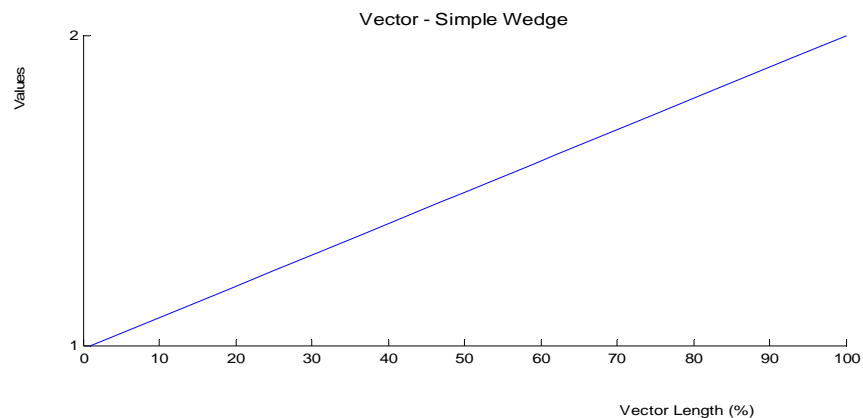


Figure 6.2 Plot of the profile vector that determines the height and length of the RCM

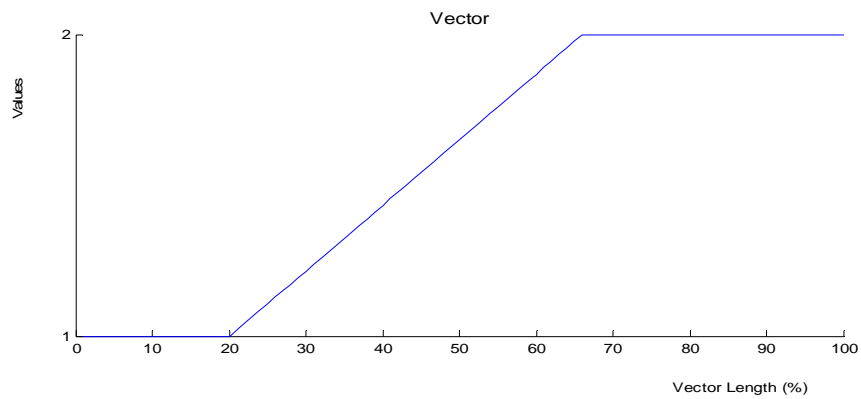


Figure 6.3 Plot of the profile vector that determines the height and length of the RCM. User inputs for the end sections were 20% and 35% of the length

Curved wedge sections were designed to reduce the potential problem of an abrupt change of density values at the ends of the wedge section. The S-shaped curve style has curves that are equal and opposite on either side of the centre of the curve. It is based on the formula in Equation 6.2 from Simon (2003). The b value of the formula is altered to change the shape of the curve.

$$y = \frac{1}{1 + e^{b \cdot x}} \quad \dots\dots\dots 6.2$$

where: $-5 \leq x \leq 5$;

b is a user input value which controls the slope of the curve.

(Simons, 2003)

Plots of Equation 6.2, demonstrating the curve section of the S-shaped profile vector, are shown in Figure 6.4. Values of b in Figure 6.4 are 0.5 – dotted line; 1.0 – dashed line and 2.0 – solid line.

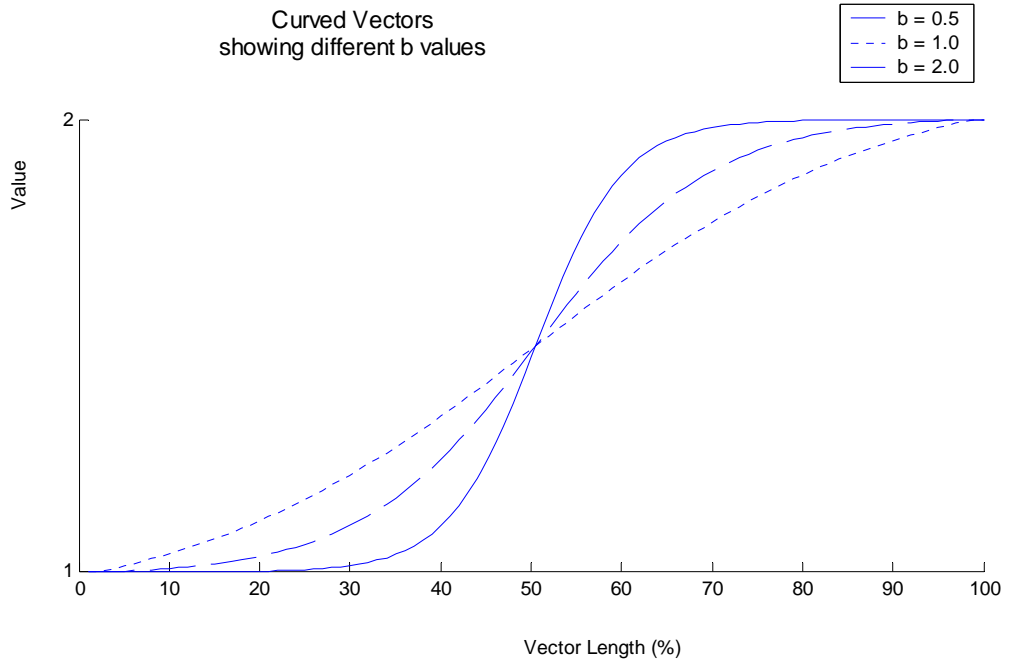


Figure 6.4 Plot of S-shaped curved profile vector using Equation 6.2 with b values of: 0.5 – dotted line; 1.0 – dashed line; 2.0 – solid line.

An alternative curve profile vector formula is based on the Gaussian or normal distribution curve formula obtained from Stockburger (2001). The formula for the normal-shaped profile curve is given in Equation 6.3. User inputs vary the s values to alter the shape of the curve.

$$y = \frac{1}{s \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-x^2}{2 \cdot s^2}} \quad \dots\dots\dots 6.3$$

where: $-8 \leq x \leq 0$;

s is a user input value which controls the slope of the curve.

(Stockburger, 2001)

The formula in Equation 6.3 provides a greater lateral spread of the curve for a smaller change in the s value compared to using the true Gaussian or normal distribution curve formula. The shape of this curve differs from that of the curve given by Equation 6.2 in that the lower end of the slope is more gradual than the

upper end of the curve. Plots of profile vector using Equation 6.3 are shown in Figure 6.5. The values of the profile are normalised between 0 and 1. Values of s shown in Figure 6.5 are:-

- 1.5 – dotted line;
- 2.0 – dashed line;
- 3.0 – solid line.

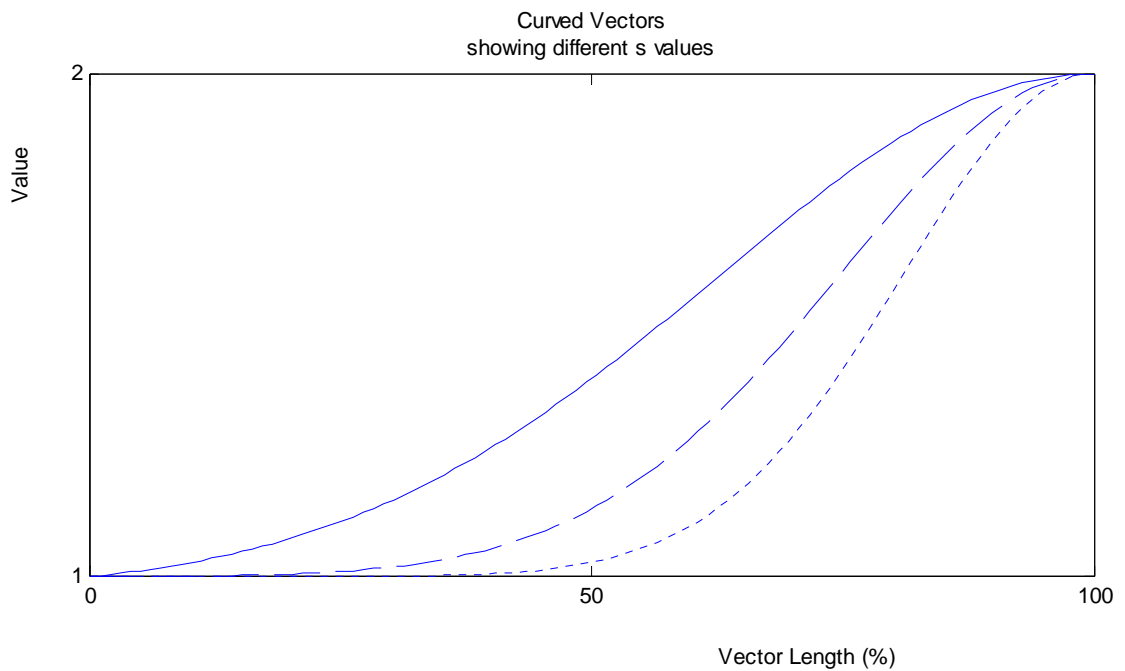


Figure 6.5 Plot of the Gaussian-shaped curved profile vector using Equation 6.3 with s values of: 1.5 – dotted line; 2.0 – dashed line; 3.0 – solid line.

Users can also alter the length of the end vectors when defining the shape of either of the two profile curve shapes described above. This will again affect the slope of the curves. Like the linear profile shape, the curved wedge section can be located at different places within the profile vector by setting different lengths of the end vectors.

6.5 Wedge Shaped RCMs

The 3D shape of the digital RCM is created by replicating the profile vector to equal the width or length of the image, depending on the desired orientation of the RCM. User input can determine the angle of rotation, in the plan view, of the digital RCM. This allows users to orient the digital RCM to match the visualised anatomy in the image.

Figure 6.6 shows a 3D representation of a simple linear wedge shaped RCM. The maximum height of the wedge was set at 1.75. The two end sub-vectors were set at zero.

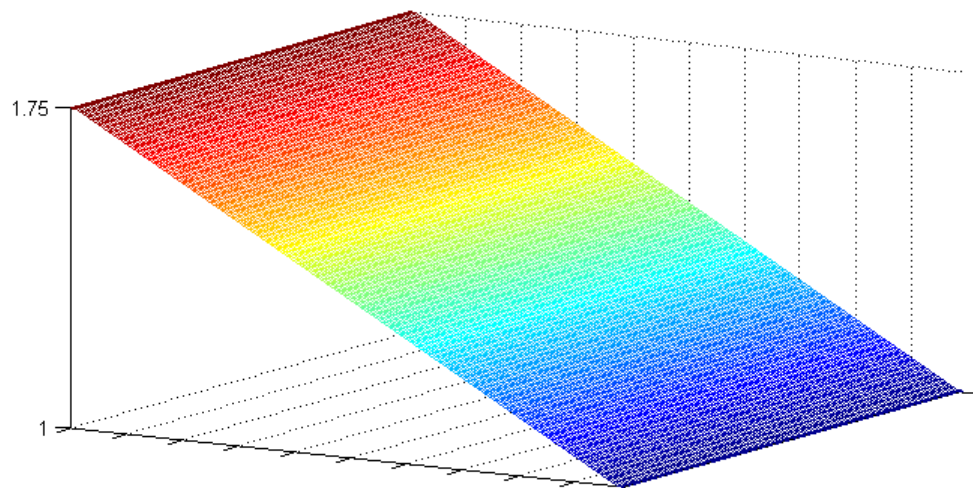


Figure 6.6 3D Representation of a linear wedge RCM. Height is 1.75

Another 3D representation of a wedge shaped RCM is shown in Figure 6.7. In this case the maximum height of the wedge was set at 2. The two end sub-vectors were set at 10% and 40% respectively of the total length of the image.

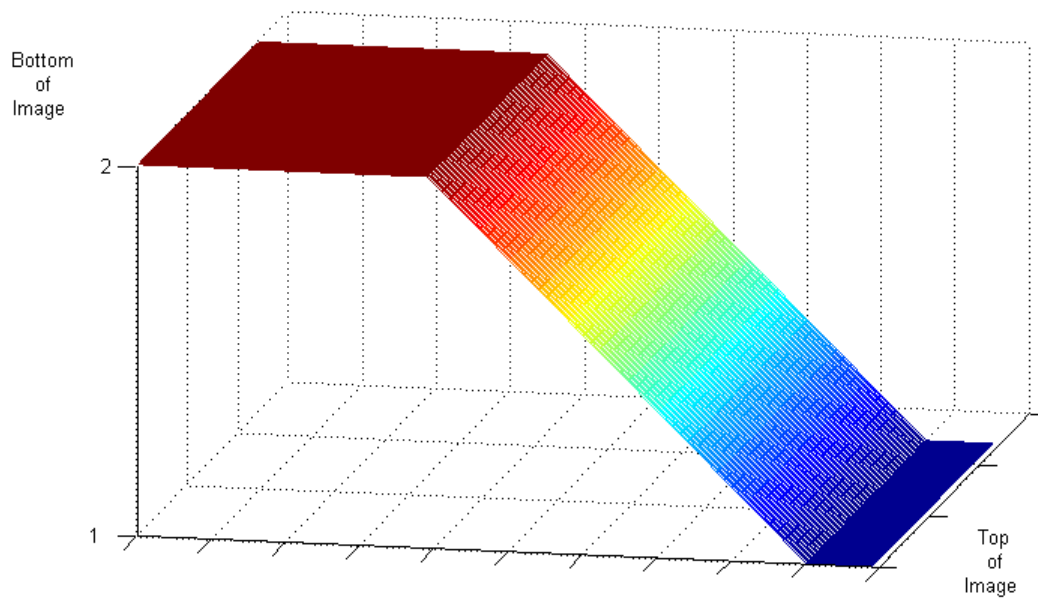


Figure 6.7 3D Representation of a linear wedge RCM. Height is 2. User-defined lengths of uniform sections are 10% at the top of the image and 40% at the bottom of the image

A representation of a user oriented digital RCM is shown in Figure 6.8. In this example, the orientation was set at a rotation of 45° clockwise. The maximum height of the wedge was set at 2 and the two end sub-vectors were set at zero.

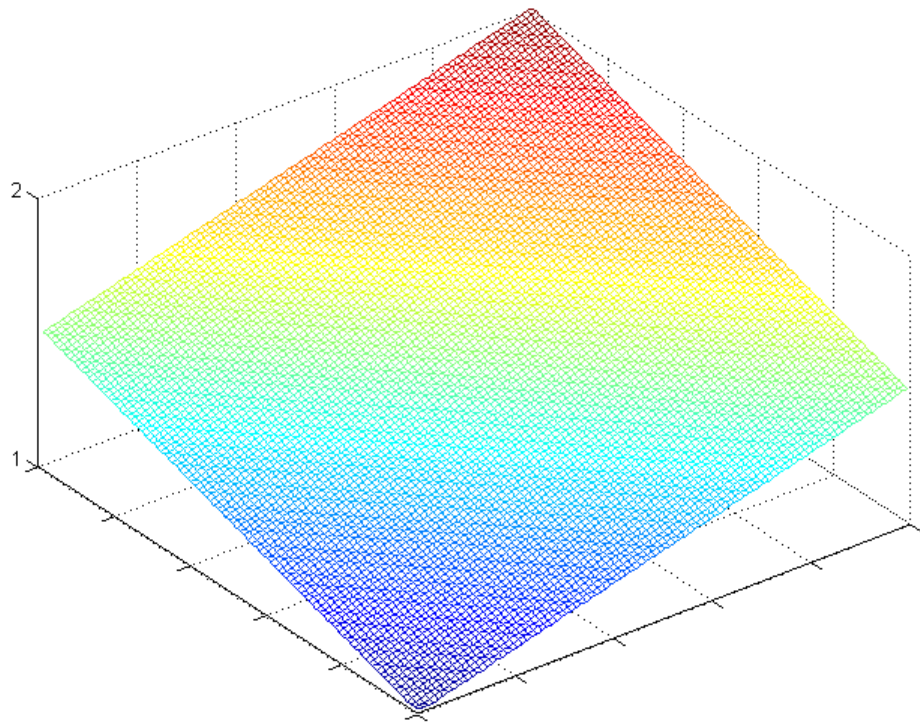


Figure 6.8 3D Representation of a 45° clockwise rotation of a linear wedge RCM. User defined height is 2

Representations of curved digital RCMs can be seen in Figures 6.9 to 6.12. Details of the shapes and orientation of the filters are:

- Figure 6.9 S-shaped curve. Height is 2.
- Figure 6.10 Gaussian-shaped curve. Orientation is 90° clockwise. Height is 2.
- Figure 6.11 S-shaped curve. Orientation is 180°. Height is 2. User-defined length of uniform section at the bottom of the image is 50%.
- Figure 6.12 S-shaped curve. 30° counter-clockwise rotation. Height is 2.

The algorithms for linear and curved wedge shaped RCMs can be found in Appendix 2b.

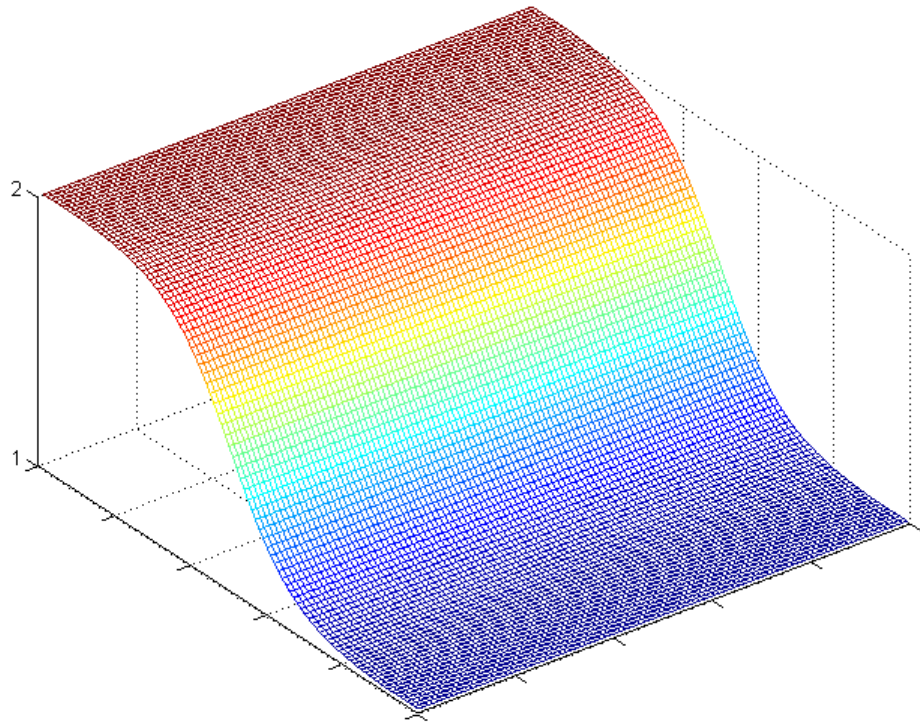


Figure 6.9 3D Representation of an S-shaped curved wedge RCM. Height is 2

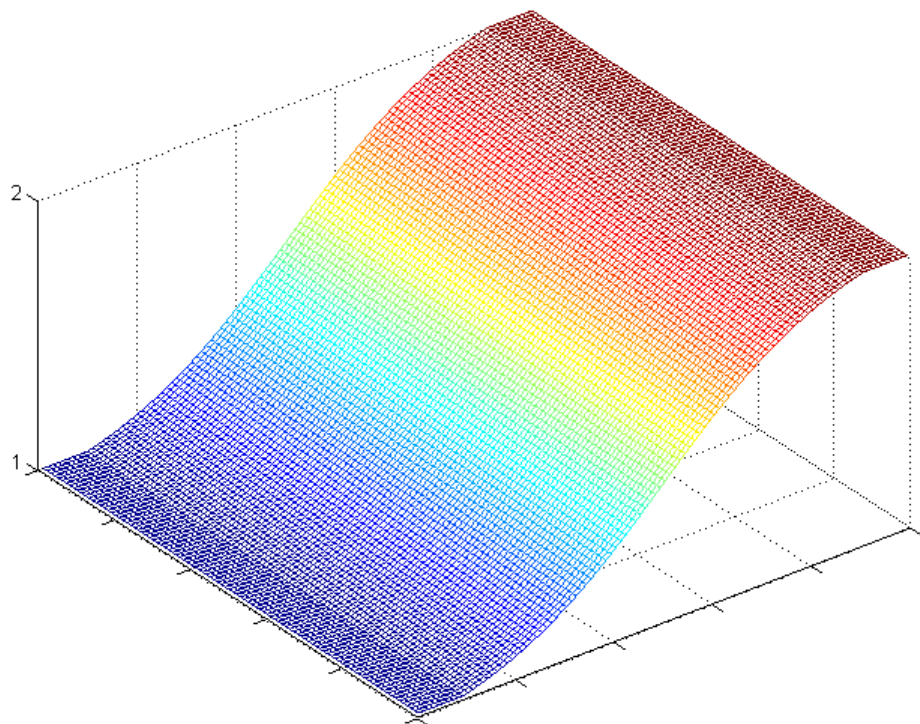


Figure 6.10 3D Representation of a Gaussian-shaped curved wedge RCM. Orientation is 90° clockwise. Height is 2

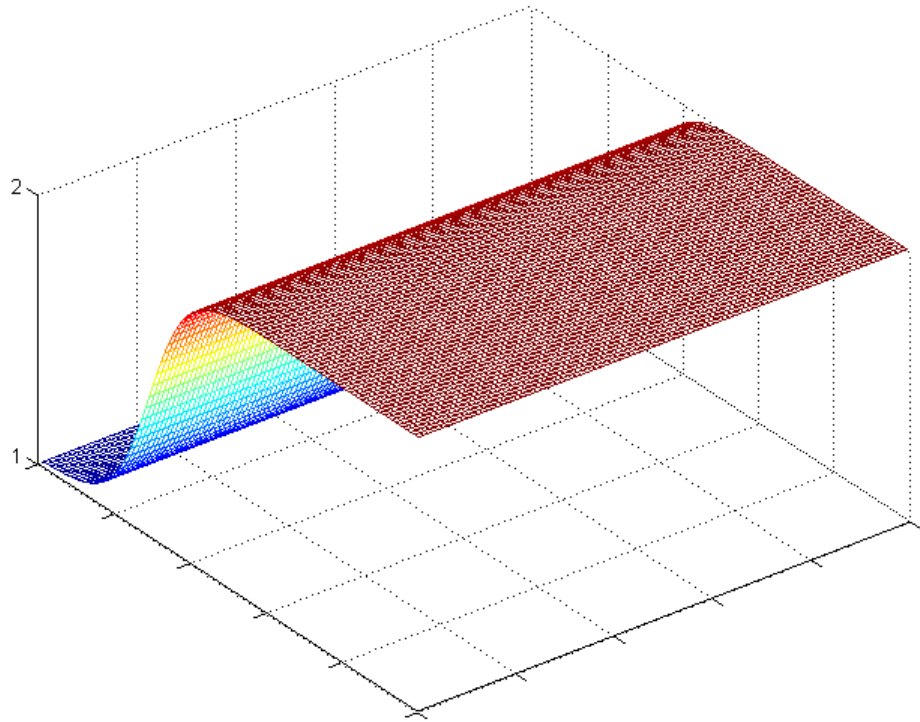


Figure 6.11 3D Representation of an S-shaped curved wedge RCM. Orientation is 180° . Height is 2. User-defined length of uniform section at the bottom of the image is 50%

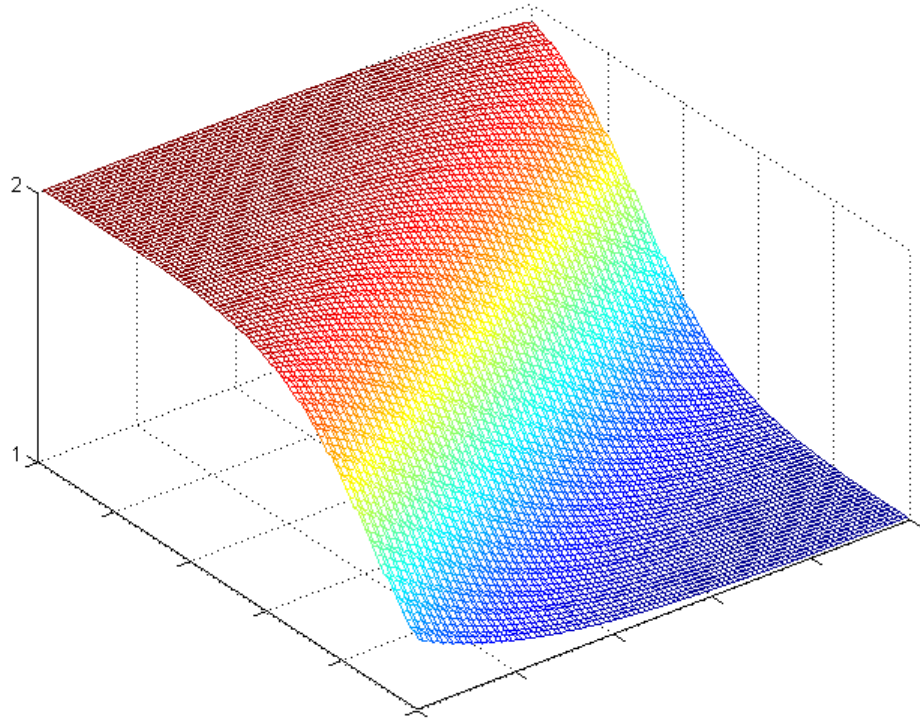


Figure 6.12 3D Representation of a 30° counter-clockwise rotation of an S-shaped wedge RCM

6.6 Boomerang RCMs – Plan View Shape

Boomerang shaped digital RCMs were specifically designed for use with DR images of the shoulder. The design of the boomerang RCM is based on characteristics of the Octostop[®] Boomerang filter described by Vezina (1995). Figure 6.13 (Vezina, 1995) shows the plan view and cross-sectional design of the Octostop[®] Boomerang filter. Unlike their physical counterparts such as those described by Vezina, it is unlikely that there will be a use for the boomerang RCM in other anatomical regions.

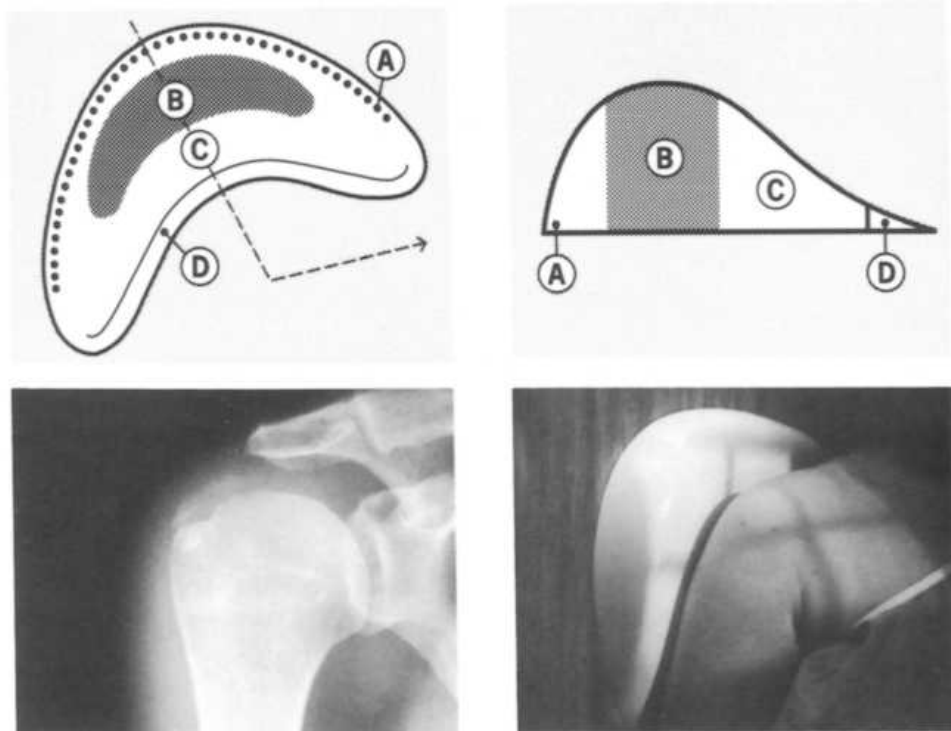


Figure 6.13 Plan view and cross-section of Octostop[®] boomerang filter (Vezina, 1995, p. 5)

Boomerang digital RCMs exhibit many similarities to the wedge shaped RCMs previously described. They are mapped with and act upon the DR image in a similar fashion. The digital RCM is again created as an intensity map or matrix of the same size (row and columns) as the DR image to which it will be mapped.

Plan views of the shape of the outer edge of the boomerang RCM for the right shoulder are shown in Figure 6.14. The lines displayed in Figure 6.14 represent plots of rows and columns or (x, y) coordinates of the outer edge of the digital RCM. The calculation of the edge coordinates was based on the formula for a circle, $r^2 = x^2 + y^2$.

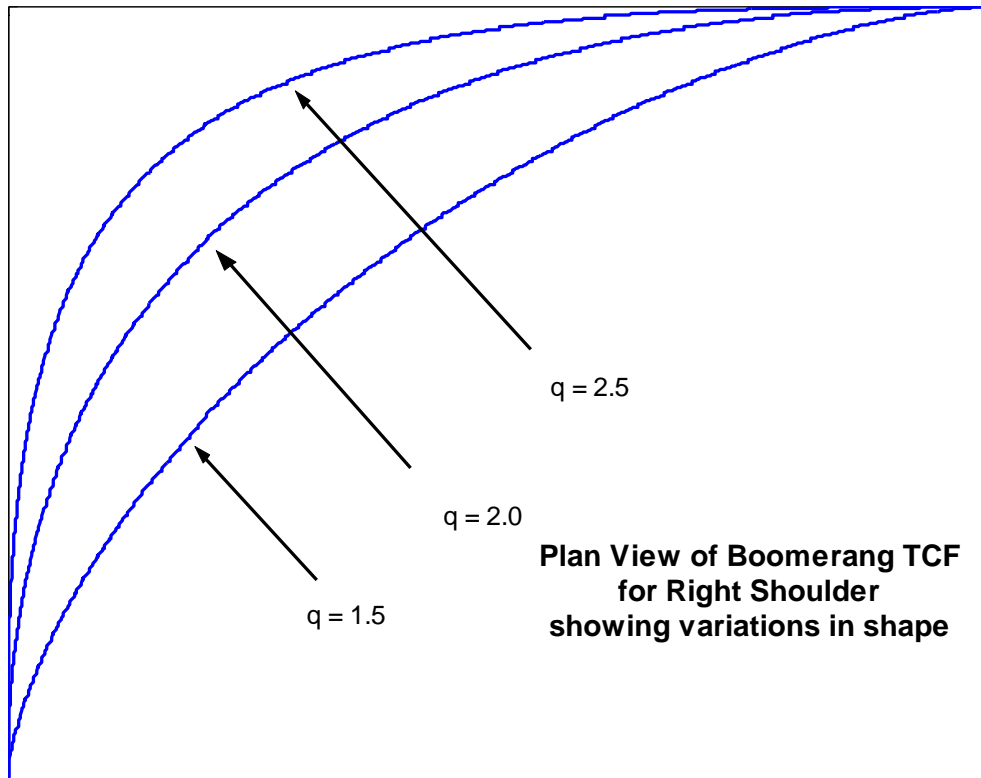


Figure 6.14 Plan view of boomerang RCM edge coordinates. Curves with q values of 1.5, 2.0 and 2.5 are shown

The capability for users to adjust the outer edge shape to suit various shoulder shapes in the image was required. Edge (x, y) coordinates of the shape were calculated. The method of achieving this was to prescribe each row and column in the intensity map or RCM matrix with a value. Digital images, and hence the RCM matrices, can be considered as having M number of rows and N number of columns. Rows and column of the image are numbered from 0 to $M-1$ and from 0 to $N-1$ respectively. Row and column values, labelled r and c respectively, were calculated. Each row of the RCM matrix was prescribed a value, r , incrementally increasing from 0 and 1, with the first row value equal to 0 and the last row value equal to 1. Each column in

the RCM matrix was prescribed a value, c , incrementally decreasing from 1 and 0, with the first column value equal to 1 and the last column value equal to 0. The calculations used to determine the values of r and c were $r = (\text{row number}) / (M - 1)$ and $c = (N - 1 - \text{column number}) / (N - 1)$.

The values r and c were raised to the power q . The user input value q controlled the shape of the edge curve. The r^q and c^q values were converted to row and column or (x, y) coordinates by multiplying these values by the row and column number respectively and rounding the values to the nearest integer value. The formula for the edge coordinates is shown as Equation 6.4.

$$(x, y) = (\text{round}(\text{row_no} \cdot r^q), \text{round}(\text{col_no} \cdot c^q)) \quad \dots\dots 6.4$$

where: row_no is the number of the row in the image,

where $0 \leq \text{row_no} \leq M-1$;

col_no is the number of the column in the image,

where $0 \leq \text{col_no} \leq N-1$;

$r = (\text{row_no}) / (M-1)$;

$c = (N - 1 - \text{col_no}) / (N-1)$;

q is a user input value which controls the shape of the edge curve.

Equation 6.4 requires the number of rows and columns to be equal and the matrix square. However, as image matrices in DR are usually rectangular, Equation 6.4 was modified for rectangular image matrices. The total number of (x, y) edge coordinates calculated was the total number of rows + the total number of columns. r and c values were calculated by creating a vector of integers, I , between 0 and $n-1$ where $n = \text{total number of rows} + \text{the total number of columns}$. The calculations used to determine the values of r and c were $r = I \text{ value} / n$ and $c = n - I \text{ value} / n$. The r and c values were raised to the power q to gain the curved edge shape. Edge (x, y) coordinate values were then calculated by using Equation 6.5.

$$(x, y) = \left(\text{round} \left[\left(\frac{I_i}{n} \right)^q .n \right], \text{round} \left[\left(\frac{n-I_i}{n} \right)^q .n \right] \right) \quad \dots\dots 6.5$$

where: I_i is the i th values of a vector with n values equally spaced between 0 & $n - 1$;

n is the number of rows + number of columns in the image;

q is a user input value which controls the shape of the edge curve.

These calculations create an inverted matrix, flipped top to bottom, of Figure 6.14. The (x, y) coordinates are reoriented to match the edge shape of a right shoulder image. The (x, y) coordinates are stored for later use. When $q = 1$, the (x, y) coordinates define a straight diagonal line from one corner to the opposite corner of the matrix. When $q > 1$, the (x, y) coordinates define a curved diagonal line from one corner to the opposite corner of the matrix as shown in Figure 6.14. Higher q values will result in a greater degree of curvature towards the top left corner of the RCM matrix as seen in Figure 6.14.

The (x, y) coordinates are used to define an edge of the profile shape of the boomerang RCM (discussed in the next section). When the coordinates created from Equation 6.5 were used, artefacts appeared on the modified image. The artefact appearance was typically a line radiating from the edge approximately one third of the distance towards the bottom right corner. The artefacts resulted from “gaps” in the RCM.

The (x, y) coordinates calculated using Equation 6.5 did not represent a combination of every row and column in the image. The coordinate map of a 16 x 11 image, seen in Figure 6.15, provides an example of edge coordinates created using Equation 6.5. The coordinate map plots the position of the pixels in each row and column. The diamond shapes represent the (x, y) coordinates. Gaps in the edge exist where a (x, y) coordinate’s nearest neighbour on either side is not at an orthogonal location. An example of a gap in the edge can be seen in Figure 6.15. The diamond shape at coordinates of (0, 10) has its nearest neighbour to the left at (1, 9).

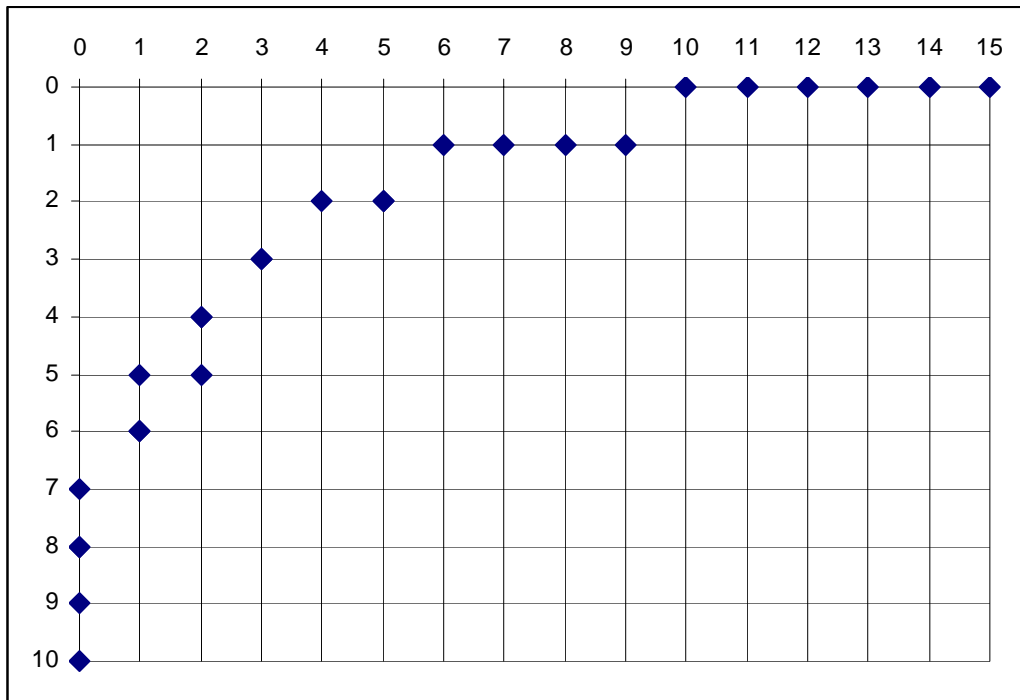


Figure 6.15 Image coordinate map of a 16 x 11 image showing edge (x, y) coordinates. Gaps in the edge can be seen

A method to overcome this problem was based on the Bresenham's line algorithm described by Hoff (1995). The algorithm is essentially an interpolation method for (x, y) coordinates. In this example the algorithm starts at a coordinate point at the top right of the matrix. It then checks to ensure there is a neighbouring coordinate at an orthogonal location. If there is such a neighbouring orthogonal coordinate, it moves to that coordinate point and repeats the process in the forward direction. If there is not a neighbouring orthogonal coordinate, it seeks out nearest neighbour at a non-orthogonal location and creates a coordinate point between the two neighbouring points at an orthogonal location from the first point. The process is then repeated from this new point. Figure 6.16 is an image coordinate map with the Bresenham's line algorithm applied to the coordinates in Figure 6.15. The empty orthogonal coordinate point between (0, 10) and (1, 9) from Figure 6.15 has been filled. Other such gaps have also been filled.

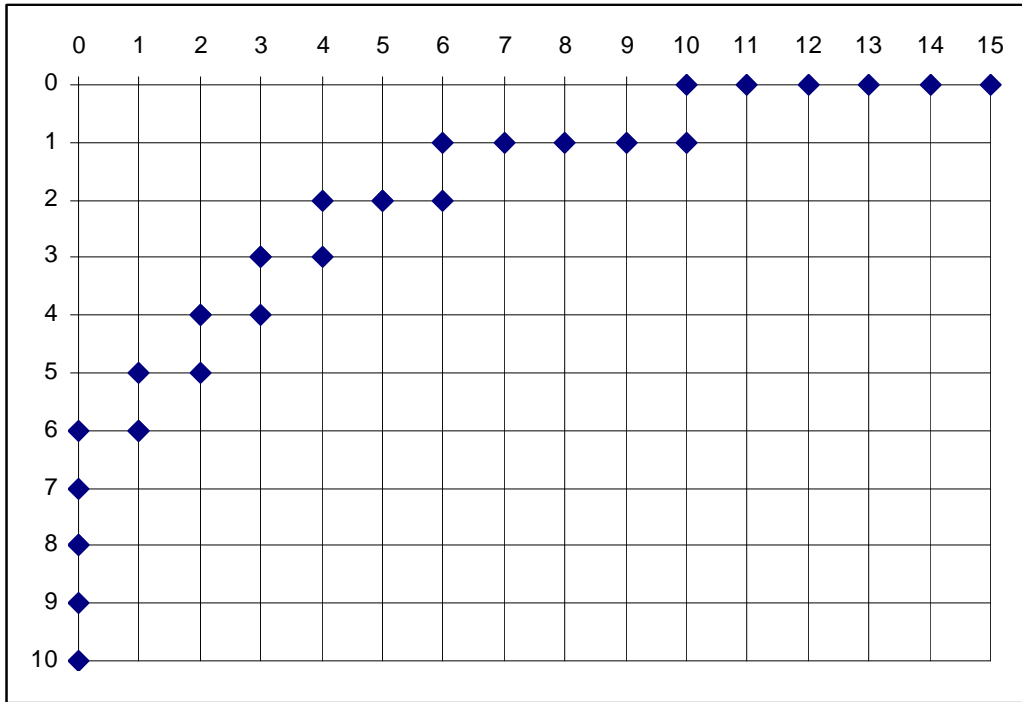


Figure 6.16 Image coordinate map of a 16 x 11 image showing edge (x, y) coordinates. Gaps in the edge of Figure 6.15 are now filled by the Bresenham's line algorithm

6.7 Boomerang RCM Profiles

The boomerang RCM profile is again based on the formula for Gaussian or normal distribution curves. The formula used for this profile is given in Equation 6.3. The range of x values used in this profile has been changed to $-1 \leq x \leq 10$. The width of the Gaussian shape of the profile is determined by the s value. Various profile shapes that result from different s values can be seen in Figure 6.17. The height of the profile is normalised between 0 and 1 with a user input then used to determine the maximum value of the profile. Figure 6.17 has a maximum value of 2. s values of 1.5, 2.0 and 3.0 are displayed.

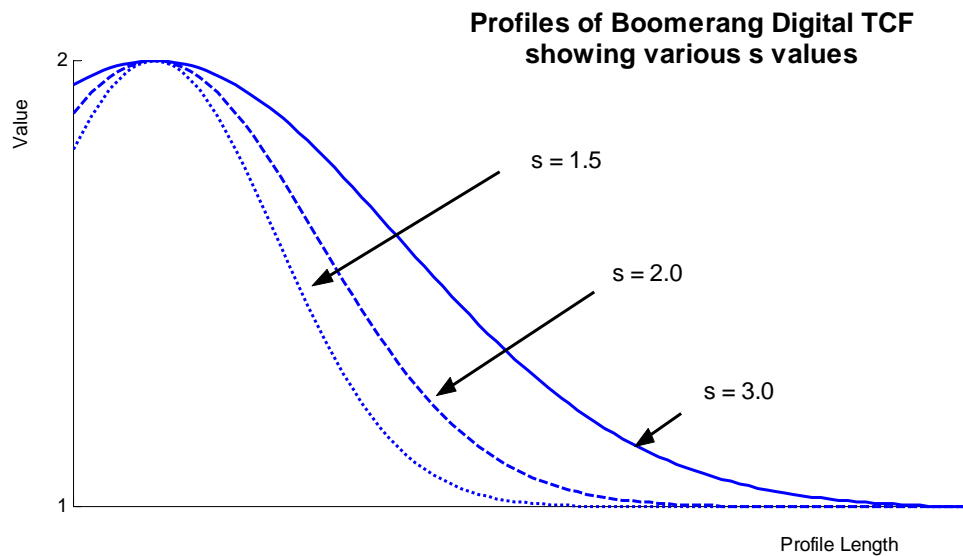


Figure 6.17 Profile shapes of boomerang RCM. Profile shape values are s equal to 1.5, 2.0 and 3.0. Maximum height of the profile is 2

6.8 Boomerang RCMs

The boomerang digital intensity map or digital RCM is again created with the same dimensions as the image. All of its values are initially set to 1. A boomerang RCM

profile is then mapped to the intensity map from each stored edge (x, y) coordinate to the bottom right corner of the matrix as seen in Figure 6.13, an (x, y) coordinate of $(M-1, N-1)$. The profile value replaces the original intensity map matrix value along the line between the edge coordinate and $(M-1, N-1)$. The use of the modified Bresenham's line algorithm allowed the boomerang RCM profile to be applied to create the intensity map without "gaps". Without the use of the modified Bresenham's line algorithm, intensity map matrix values might have been missed and hence the matrix value at that point would differ greatly from its neighbours. In this case when the RCM algorithm was mapped with the image, an artefact was created.

The 3D shape of the RCM results from mapping each profile from the edge to the corner. The length of each profile is calculated prior to the calculation of the profile shape. All the profile lengths differ. The length of each profile is the Euclidean distance between the edge coordinate and $(M-1, N-1)$. Figure 6.18 shows a 3D plot of intensities (bottom) and an intensity map (top) of a boomerang RCM. In this example, factors selected were $q = 2$; $s = 3$ and height = 2.

The intensity map in Figure 6.18 (top) has a maximum value of 2 which is represented by white. The minimum value, 1, is represented by black, and values between 1 and 2 by shades of grey.

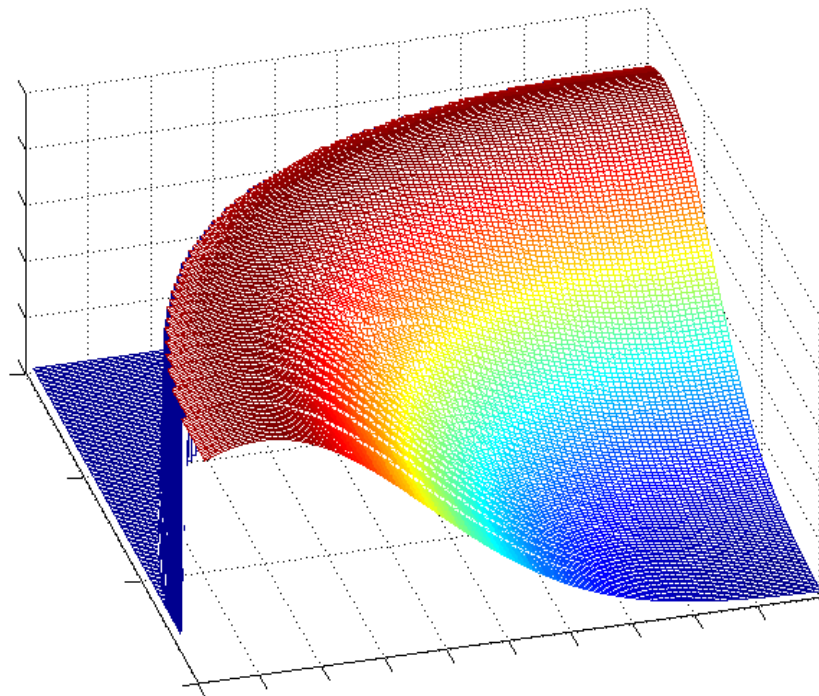
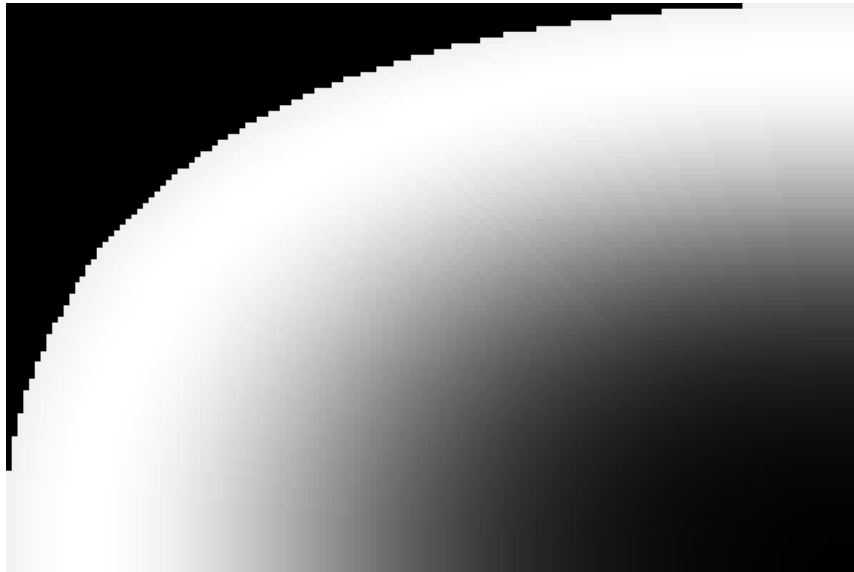


Figure 6.18 Intensity map (top) and 3D plot (bottom) of a boomerang RCM. User input values are $q = 2$, $s = 3$, and height = 2

The width of the Gaussian shape of the boomerang RCM profile, determined by the s value, controls the area of the image that is contrast adjusted. Figure 6.19 shows an intensity plot and 3D plot with factors of $q = 2$, $s = 3$ and height = 2. In this example, the area of contrast adjustment is narrower than in Figure 6.18 and the plan view curvature is extended further towards the top left corner.

Users are able to select to which side shoulder the boomerang RCM will be applied. This is achieved by creating the boomerang RCM and flipping the RCM from right to left. Figure 6.20 shows an intensity map and 3D plot for a left shoulder. User input values are $q = 1.8$, $s = 2.5$ and height = 2.

Artefact lines are noted in the intensity maps of Figures 6.18 – 6.20. These are due to the reduced size of these digital RCMs compared to the actual size that would be used with DR images. The artefact appearances are similar to those that would be visualised in an image without the use of Bresenham's line algorithm to fill in the "gaps" of the edge coordinates of the RCM. The size of the digital RCM used for display purposes in Figures 6.18 – 6.20 is 100 rows by 150 columns. A typical DR shoulder image has 2000 rows and 2500 columns of pixels.

Algorithms for boomerang RCMs can be found in Appendix 2c.

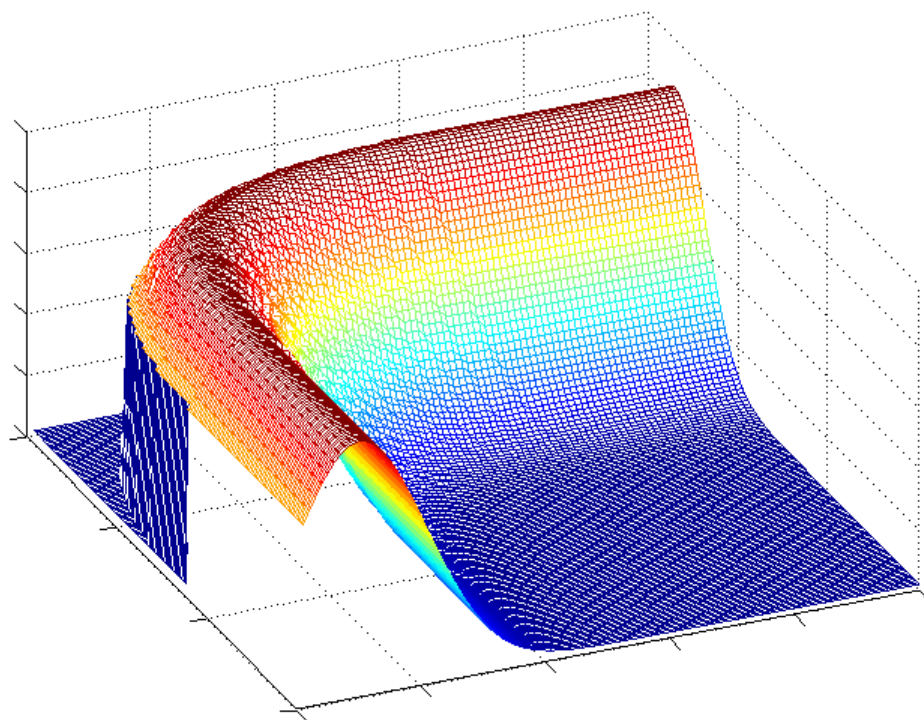
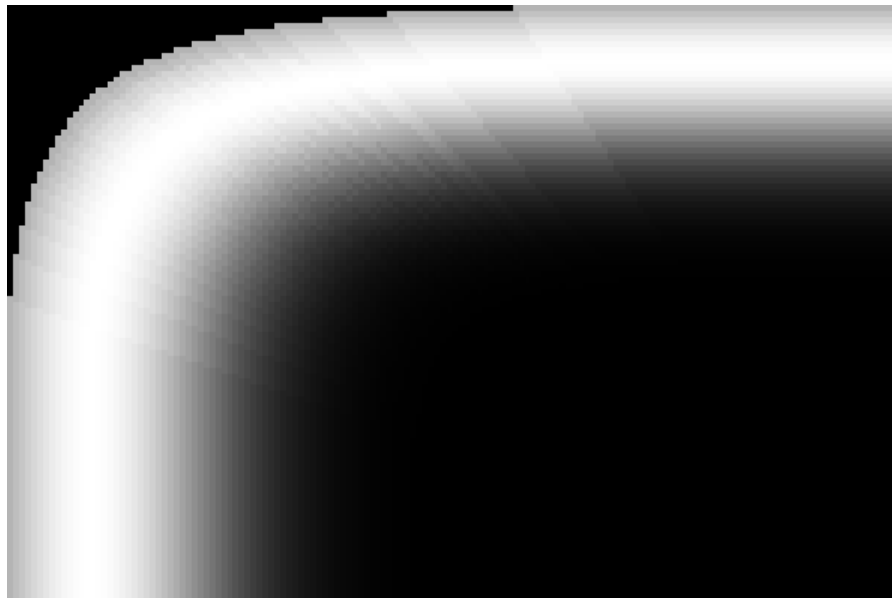


Figure 6.19 Intensity map (top) and 3D plot (bottom) of a boomerang RCM. User input values are $q = 3$, $s = 1.2$ and height = 2

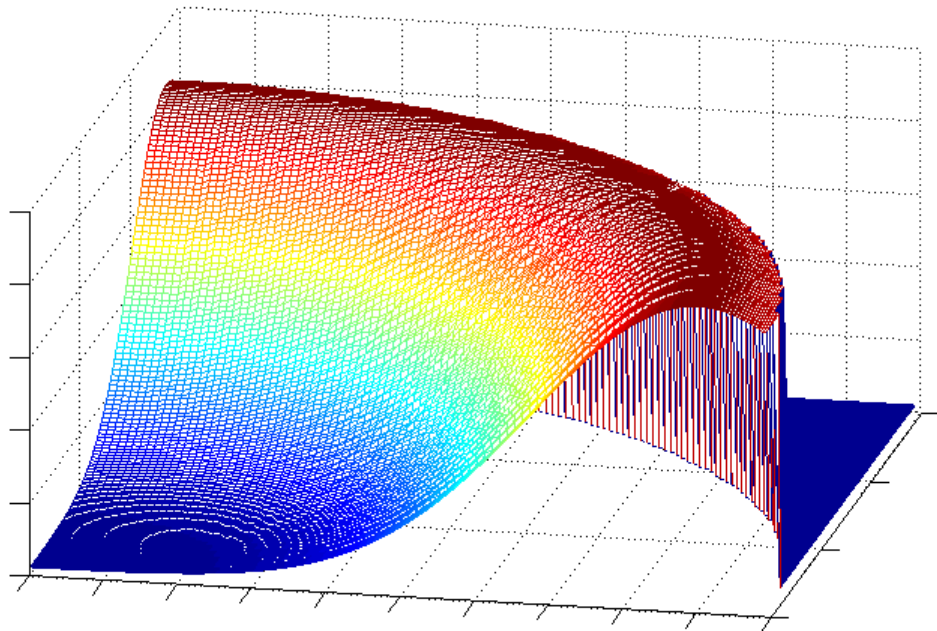
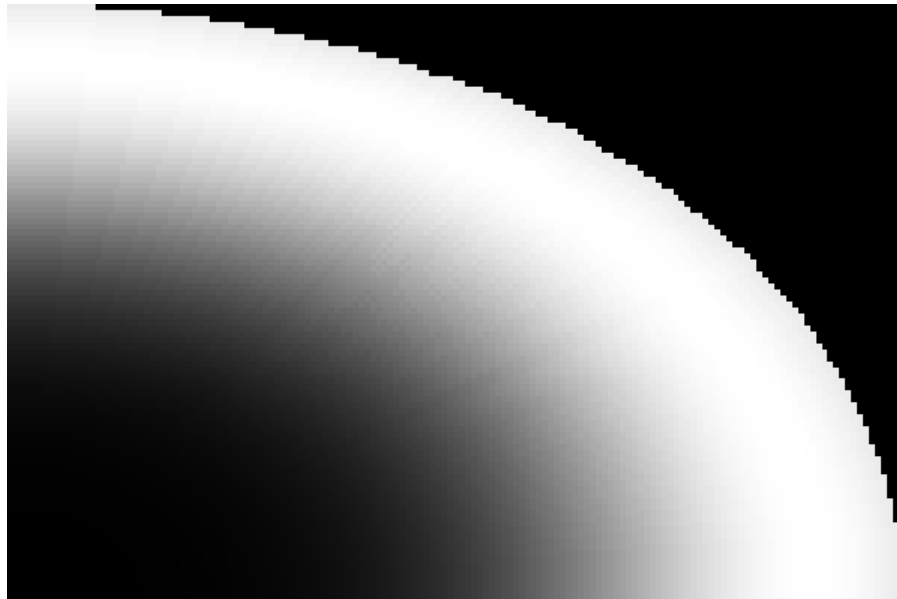


Figure 6.20 Intensity map (top) and 3D plot (bottom) of a boomerang RCM for a left shoulder image. User input values are $q = 1.8$, $s = 2.5$ and height = 2

6.9 Chest RCMs

Both wedge shaped and boomerang RCMs were applied to clinical DR images and the resultant images were evaluated by clinicians. Chapters 8 and 9 detail the survey method used for evaluation and the results of the survey. A further group of digital RCMs are chest digital RCMs. Initial development of chest RCMs is discussed here. Chest RCMs have not yet been applied to clinical images for evaluation.

Chest RCMs were designed to compensate for the large density value difference between the mediastinum and the lungs. The design was based on physical TCFs. The shapes of the trough filter described by Bushong (2001) and the chest TCF described by Müller *et al* (1996c) were used.

A profile that was considered for a chest RCM is shown in Figure 6.21. This profile was calculated by modifying Equation 6.3. By including a u value in Equation 6.6, the centre of the trough can be shifted right or left. Only one section vector is required to produce this profile. The vector width is same width as the chest RCM or the DR image. The values of the profile were calculated using the range of x values - $10 \leq x \leq 10$. The s value was 2 and the height was set at 1.5.

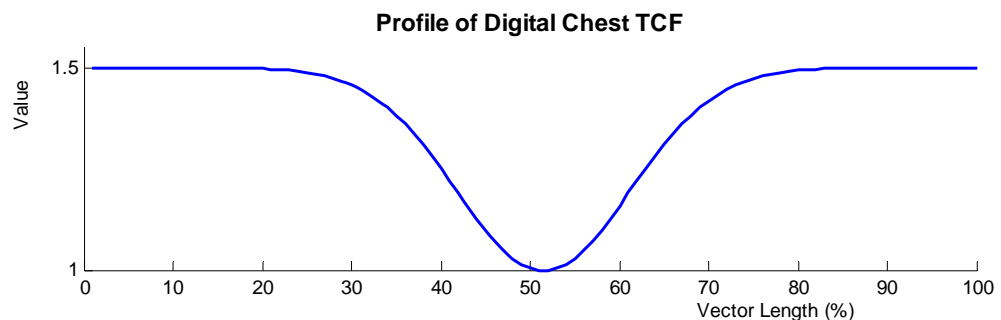


Figure 6.21 Profile of a chest RCM. s value = 2

$$y = \frac{1}{s \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-x-u^2}{2 \cdot s^2}} \quad \dots\dots\dots 6.6$$

where: $-8 \leq x \leq 0$;

s is a user input value which controls the slope of the curve.

u is a user input value which controls the central location of the curve.

An alternative profile for a chest RCM can be seen in Figure 6.22. The profile consists of four sections. These are two outer sections and two inner sections. The shapes of the two inner sections are based on Equation 6.2, with the left inner section being a copy of the right inner section that has been flipped from left to right. The slope of these curves can be altered by user input. The b value of Equation 6.2 again alters the slope of these two curves. In Figure 6.22 the length of each outer sections is 20% of the total length of the profile vector. The centre of the trough can be offset left or right by individually varying the size of the two outer sections.

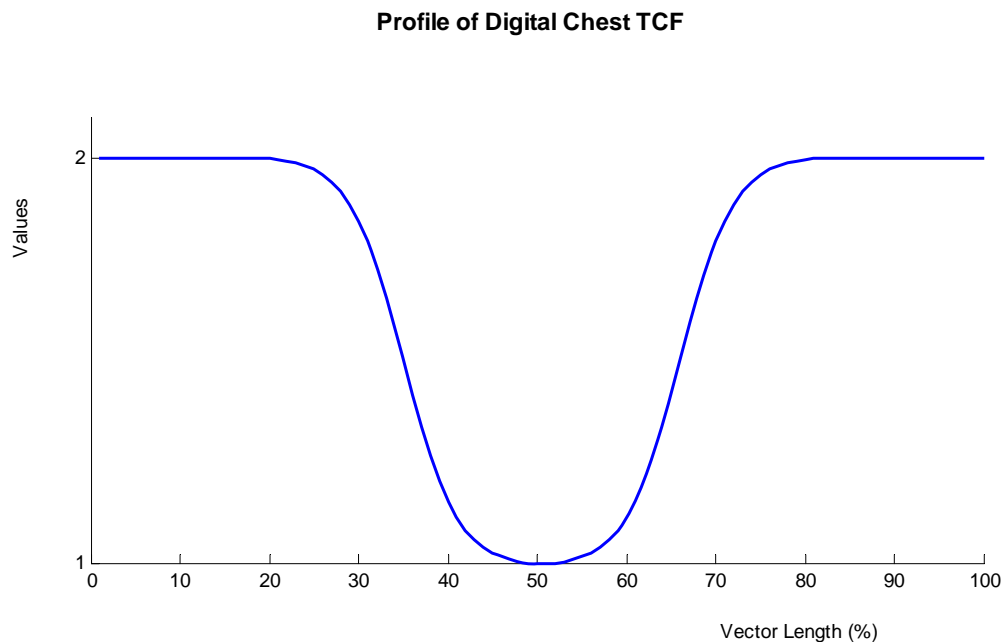


Figure 6.22 Profile of a chest digital RCM. b value = 1. Outer vector lengths = 20% each

The resulting intensity map and 3D plot from the profile in Figure 6.22 are shown in Figure 6.23. The trough has a uniform width from the top to the bottom of the intensity map. In trough section there will be only a small change of contrast in the DR image. This corresponds to the mediastinum of the chest. The mediastinum of the chest, in plan view, is not uniform in width from the top to the bottom of the image. The profile thickness of the chest and mediastinum also varies from the superior to inferior aspects of the chest. Altering the width and depth of the trough of the digital chest RCM, from the top to the bottom of the image, will be the next area of development of the digital chest RCM.

Further evaluation of digital trough RCMs and their profiles will be undertaken. The development will take into account the plan view shape of the mediastinum and profile thicknesses. Once a suitable digital chest RCM is determined, it will be applied to images and clinically evaluated.

Clinical uses for RCMs are discussed in Chapter 7. Chapter 8 objectively evaluates RCM-enhanced DR images and various other dynamic range control methods. Medical images such DR images are subjectively evaluated in clinical practice. Chapters 8 and 9 detail the survey method and results of subjective evaluation of the RCM method.

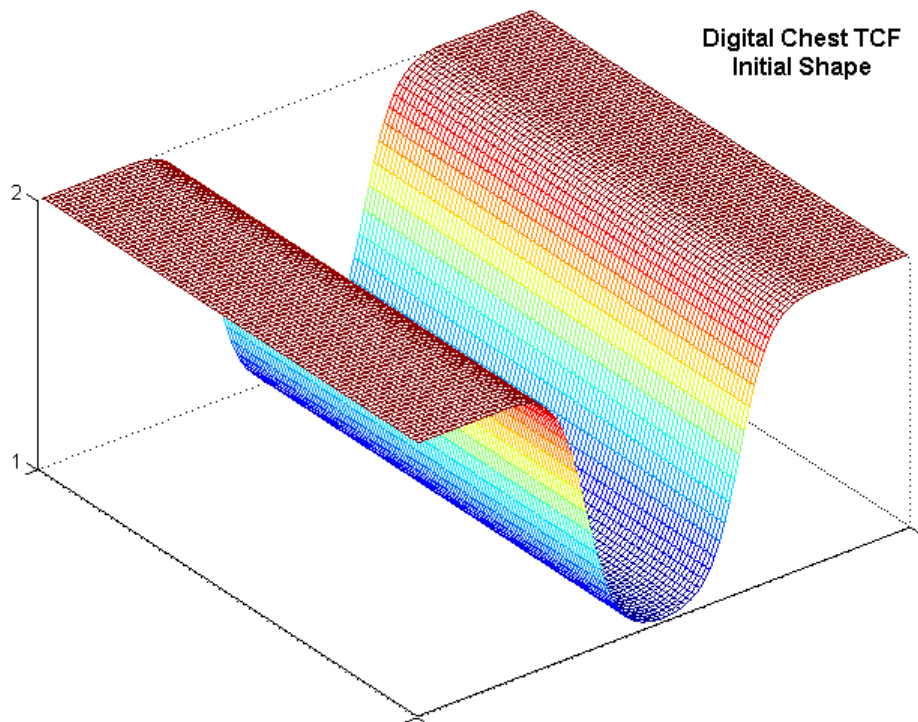
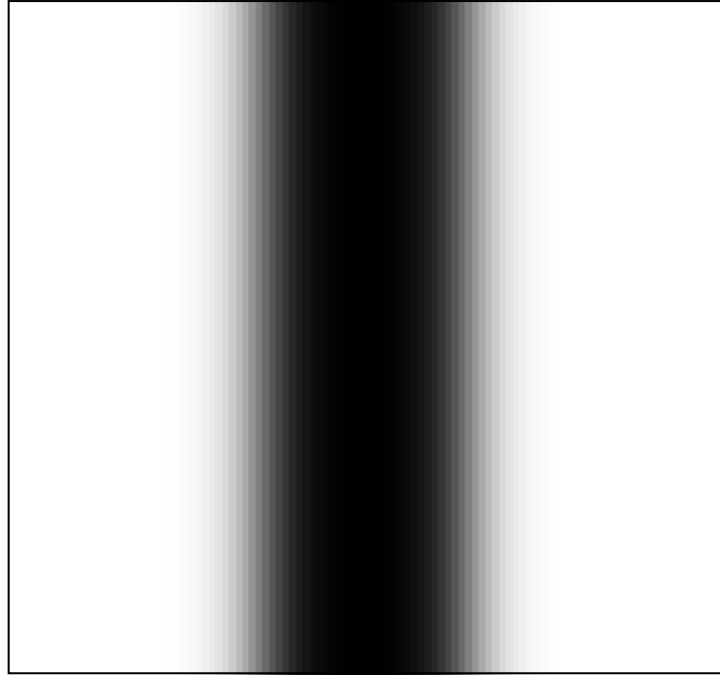


Figure 6.23 Intensity map (top) and 3D plot (bottom) of a chest RCM. User input value of $b = 1$. Outer vector lengths = 20% each