THE USE OF MULTIPLE SURVIEWS OF A COMPUTED TOMOGRAPHY SCANNER TO DETERMINE THE 3D COORDINATES OF EXTERNAL CRANIAL MARKERS

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ABSTRACT

Determining the positions of intracerebral lesions for various medical procedures, using computed tomography (CT) scanners, is a well documented procedure. Such medical procedures include stereotactic biopsies so that the tissue type of the lesion can be ascertained and followed by the treatment of malignant lesions with proton therapy for example. For such procedures the position of the lesion has to be known in relation to external reference markers placed directly on the scalp, or attached to a reference frame that, when replaced on the head, retains the same relationship to the skull and therefore to the intracranial lesion.

The relationship between the lesion and the external reference markers has traditionally been determined using the CT scanner's Cartesian slice coordinate system. It has been shown that the 3D coordinates of external reference markers can be calculated using the conventional plan views of the CT scanner, i.e. the anterior-posterior and lateral surviews, and a two dimensional projective transformation algorithm. Such a transformation has to be employed as surviews are somewhat analogous to X-rays, with the exception that the central projection only applies to the horizontal axis of the surview.

Modern CT scanners can scan oblique surviews from any position on the 360 degree circle of the CT gantry. This paper will show that multiple surviews can be used to calculate 3D coordinates by utilising the two dimensional projective transformation algorithm. The accuracy of such a 3D coordinate determination falls within the measuring resolution of the CT scanner.

3D coordinate determination of external reference markers using multiple surviews provides an overdetermined solution. Although the overdetermined solution does not improve the overall accuracy, it does, however, provide a very important check for blunders, without increasing the overall scanning time.

1. INTRODUCTION

Computed tomography (CT), first described by Hounsfield in 1973, has made a remarkable difference to many medical procedures. Positions of intracranial lesions, that previously had to be inferred from shifts of the ventricular system or blood vessels, can now be visualised and measured in relation to other intracranial structures and cranial landmarks. The measuring system of modern day CT scanners is based on a Cartesian coordinate system, where each point in space is defined in three dimensions. The ability to use the CT scanner as an accurate 3D measuring device has been utilised in various medical techniques.

The CT scanner at the Department of Radiotherapy, University of Cape Town (UCT), for example has been used to provide 3D information for subsequent proton beam radiotherapy, to irradiate intracerebral lesions, and for stereotactic neurosurgery. It's role in both these treatments is to determine the position of the lesion in relation to external reference markers attached to the patient's head (Levin et al, 1993, Adams et al, 1995).

Traditionally when the CT scanner has been used as a measuring device, 3D coordinates of reference markers and intracranial targets have been determined using CT slices (Figure 2). CT pilot or surviews (Figure 2) were only utilised for CT slice planning purposes. CT surviews are an unusual form of X-ray and the anterior-posterior (AP) and lateral (LAT) surviews can be utilised to determine three dimensional CT "slice" coordinates using a two dimensional projective transformation algorithm (van Geems et al 1995).

Modern day CT scanners however are not restricted to AP and LAT surviews, but can scan oblique surviews from any position on the 360 degree circle of the CT gantry. The aim of this paper is to show that multiple surviews can be used to determine 3D coordinates of external cranial markers using the two dimensional projective transformation algorithm.

2. THE CT SCANNER AND IT'S ROLE IN STEREOTACTIC NEUROSURGERY

To undertake a stereotactic biopsy of an intracerebral lesion external reference markers, corresponding to a stereotactic instrument, are attached to the head. The markers are made of radio-opaque material to ensure that they will image on the CT images. The markers are either mounted directly onto the scalp or onto some type of stereotactic frame which is then affixed to the skull. These markers must remain in the same relation to the skull, and therefore to the lesion, from the time the CT scan is undertaken until the medical procedure, e.g. surgery or irradiation, has been completed. Where removable markers / frames are used, these have to be correctly replaced so that the overall geometry is maintained.

The CT scanner in the UCT Radiotherapy Department is being utilised as a measuring device for the ongoing development of a simple stereotactic device - the Cape Town stereotactic pointer. The aim of any stereotactic device is to reconstruct the vector / path that the neurosurgeon's instrument, e.g. a biopsy needle, must follow to reach the centre of a lesion. The Cape Pointer's three contact points with the scalp have to be marked. These points are marked with small ball bearings, with a diameter of approximately 1.5 to 2mm. This procedure transfers the Cape Pointer's reference system to the patient's head. An entry point, if so desired, can be selected and marked by the neurosurgeon. The external reference markers and the target within the intracerebral lesion have conventionally been coordinated in the CT slice coordinate system. These coordinates enable the neurosurgeon to correctly set the Cape Pointer (Adams et. al. 1995). By replacing the Cape Pointer back on to the reference markers on the scalp, the neurosurgeon, utilising the Pointer's guide, can insert a biopsy needle into the intracranial lesion and remove a tissue sample. From the tissue sample analysis the correct course of action can be decided upon.

Utilising AP and LAT surviews to coordinate external reference markers arose from procedures initially required to set the Cape Pointer. The development of multiple surviews, to determine 3D CT coordinates, has been done to ascertain whether it could be utilised in the coordination of the external reference markers pertaining to the Cape Pointer.

3. THE CT SCANNER - 3D MEASURING DEVICE

The 3D coordinates of external reference markers are conventionally determined by the CT slice system. With the patient lying in the supine position (on his back) on the CT bed, the X, Y and Z axes increase positively from the patient's right to left, from posterior to anterior, and from inferior to superior respectively (Figure 1). As the CT gantry is static, the change in Z is achieved by moving the CT bed, and therefore the patient, along the Z axis. (All information in this paper pertains to the CT scanner at the UCT Radiotherapy Department, and may differ from other CT scanners.)

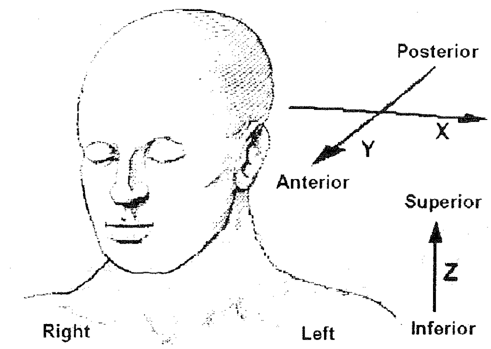

Figure 1: CT scan slice coordinate system

CT slices (Figure 2) are transverse sections through the body, i.e. in the XY plane, with a minimum slice thickness / width of 2mm. The measuring resolution in the XY plane is 1mm, with an overall expected accuracy of target fixation of 1.5mm (van Geems et al 1995). A CT slice is a true map of that transverse section of the body.

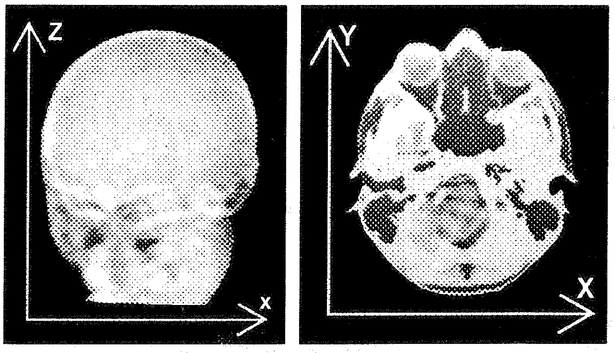

Figure 2: An AP surview (left) and a slice (right) in the XY plane at eye level.

The positioning of CT slices is planned with the aid of CT surviews (Figure 2), which are somewhat analogous to X-rays. The geometric property of X-rays - the central projection in which all rays pass through the perspective centre - only partly applies to CT surviews. The CT scan beam projects outward from it's focus in a single fixed plane, parallel to the XY plane (Figure 1). By moving the bed in the direction of the Z axis, through the fixed scanning plane, the CT surview is built up. Thus central projection geometry applies only to the horizontal axis of the surview, whereas the vertical / z axis is linearly mapped.

Using modified photogrammetric techniques, the AP and LAT surviews can be used to determine 3D coordinates (van Geems et. al., 1995). A two dimensional control, mounted on the CT bed, is included in the scan of the surviews. The CT laser "pointer" / beam, which lies in the XY plane of the CT scanner, is used to align the two dimensional control, so that all control points fall within the same XY plane. Thus only a single slice, through the plane containing the control points, is required to image all the control points. By utilising the control point coordinates from both the surviews and the slice, parameters for the surviews can be determined using a two dimensional projective transformation algorithm (a two dimensional DLT).

The two dimensional projective transformation algorithm for a particular surview is:

$$x_i = h_{11}X_i + h_{12}Y_i + h_{13} - h_{21}x_iX_i - h_{22}x_iY_i \qquad (1)$$

where the h elements are the parameters pertaining to that surview, X_i, Y_i are the slice coordinates of the control point i, and x_i is the surview coordinate on the horizontal axis of that surview of control point i. A minimum of five control points is required to solve for the parameters of any given surview. As the Z axis is linearly mapped, only a constant needs to be added to make the Z axis of the CT surview system coincident with the Z axis of the CT slice system. All coordinates determined in the CT surview system must be transformed into the CT slice system, and not some arbitrary 3D system, as any intracranial targets, such as a lesion centre, can only be coordinated in the CT slice system.

As modern CT scanners are not restricted to only scanning an AP and LAT surview, but can scan from any position on the 360 degree circle, oblique surviews can be used to obtain an overdetermined solution of 3D "slice" coordinates.

4. MULTIPLE SURVIEWS OF A PHANTOM HEAD

Multiple surviews of a phantom head, with four external reference markers and a ball bearing, within the mask, defining a "lesion centre" , were scanned with the CT control mounted at the head of the CT bed (Figure 3).

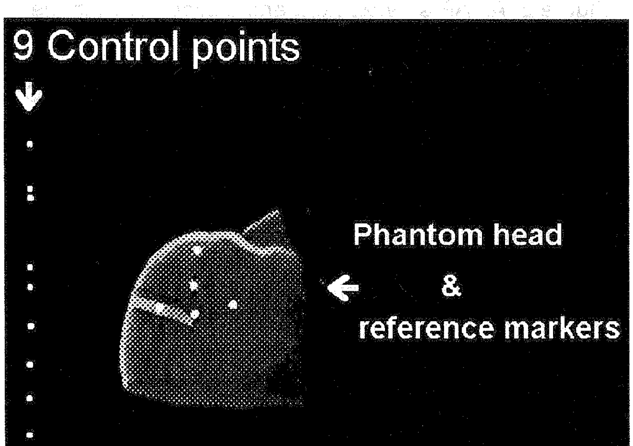

Figure 3: A LAT surview of the phantom head, with four external reference markers and one marker defining the "lesion centre". (The surview images in this paper have been enhanced for presentation purposes.)

Only four external reference markers were used to simulate the four targets required for the Cape Pointer. An AP and LAT surview, and three oblique surviews at 340, 30, 50 degrees were scanned (Figures 3 & 4). An AP surview is scanned from posterior to anterior (Figure 1) - at 90 degrees on the CT gantry; a LAT surview is scanned from right to left (Figure1) - at 0 / 360 degrees on the CT gantry. 6 slices were scanned, one in the XY plane containing the control points, and five in the XY planes containing the external reference markers.

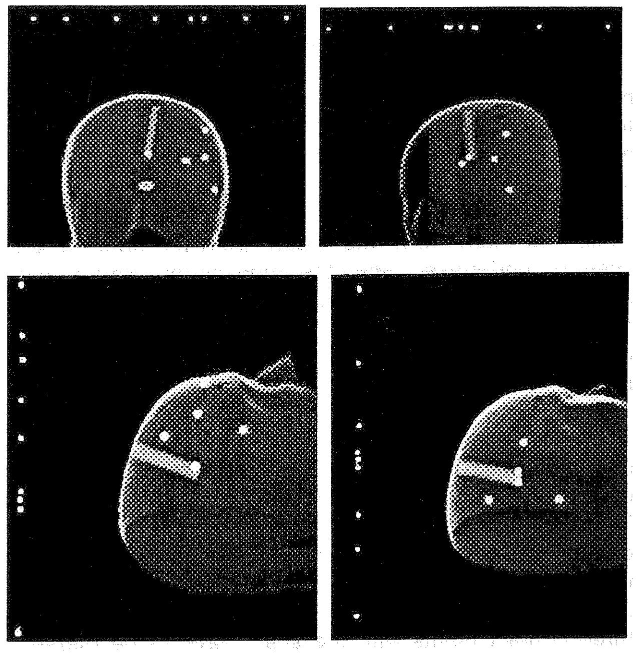

Figure 4: Surviews, from top left to bottom right are: AP surview, oblique surviews at 50, 340 and 30 degrees.

All control points, and the five phantom markers, were measured on the surviews and slices. All surview parameters were calculated from the digitised data. The accuracy of the transformation was assessed using all of the control points (9 control points in total), with a standard deviation of residual errors of 0.6mm and 0.4mm in X and Y respectively. (As there is a linear relationship between the Z axis of the slice system and the vertical axis of the surview system, it was not included in the accuracy assessment.)

"Slice" coordinates were calculated using the surview parameters and the digitised surview data pertaining to the five markers. The standard deviation of the residual errors, comparing calculated "slice" coordinates to the actual slice coordinates, was 0.4mm, 0.2mm and 0.5mm in X, Y and Z respectively. These deviations are within the measuring resolution of the CT scanner.

All reference markers were measured in the reflex metrograph (Scott, 1981), which has a measuring resolution of 0.1mm. The markers were measured four times and the mean data set adopted as error free. Standard deviations of the residual errors from comparing data sets were:

metrograph to calculated "slice" coordinates - 0.6mm, 0.7mm, 0.2mm in X, Y, Z respectively

metrograph to measured "slice" coordinates - 0.8mm, 0.8mm, 0.6mm in X, Y, Z respectively

These results showed that multiple surviews can be used to determine 3D coordinates and maintain the accuracy that is achieved by using the conventional method of CT coordination.

4.1 Verifying CT measuring accuracy using an IP8 Matrox card

All CT scan images were transferred to a PC with a Matrox IP8 image processing card and remeasured. This was to utilise the software written for the IP8 to find target centres to subpixel accuracy using a centre of gravity algorithm. Due to the transfer protocol, the image size was reduced from 1024x1024 to 512x512. CT scanners operate in Hounsfield numbers, which are equivalent to grey scales, and normally range from -1000 (air, black) to 1000 (bone, white), with water as zero. The particular scanner at the UCT Radiotherapy Department has a range of -2048 to 2048. As the IP8 card only has a grey scale range of 256, grey scales had to be reduced accordingly. Due to these factors, the IP8 only served to verify the results already obtained, but did not improve the overall accuracy obtained from the multiple surviews.

4.2 Multiple surviews versus AP & LAT surviews using the Phantom scans

To ascertain what the accuracy difference is between using multiple surviews versus AP & LAT surviews to calculate CT "slice" coordinates, the AP & LAT surviews of the Phantom head were used. Comparing calculated "slice" and measured slice coordinates, there was no change in the overall accuracy. Only when comparing metrograph to measured "slice" coordinates, was a slight degradation in accuracy discernible on one of the axes, the Y axis. Standard deviations of the residual errors were:

metrograph to measured "slice" coordinates -
0.6mm, 1.0mm, 0.3mm in X, Y, Z respectively

5. MULTIPLE SURVIEWS OF A CRANIUM

To be able to simulate the patient situation more closely, the phantom head was replaced by a cranium / skull. Bone and the metal ball bearings, used as external reference markers, yield very high Hounsfield numbers and therefore show up white on CT images. By using a skull, the effect of the bone on the visibility of external reference markers could be tested.

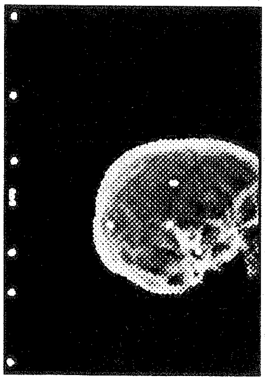

Figure 5: An oblique surview of the skull scanned at 30 degrees on the CT gantry.

Six CT surviews of a skull, to which four external reference markers were attached, were scanned. The six surviews included an AP and LAT surview, and four oblique surviews scanned at 340, 30, 60 and 120 degrees on the CT gantry. The CT control was again mounted at the head of the CT bed. Five slices were also scanned. Control points and skull markers were digitised on the surviews and slices. Two oblique surviews, the oblique surviews at 30 and 60 degrees, are illustrated in Figures 5 and 6.

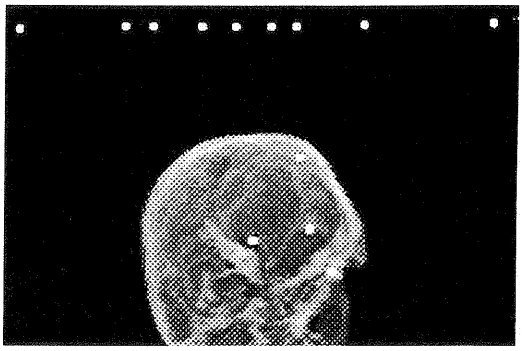

Figure 6: An oblique surview of the skull scanned at 60 degrees on the CT gantry.

Surview parameters were calculated and the standard deviation of residual errors from the two dimensional projective transformation calculated, with 0.8mm and 0.3mm in X and Y respectively.

Once the data reduction had been completed, calculated "slice" and measured slice coordinates were compared, resulting in a standard deviation of residual errors of 0.4mm, 0.7mm and 0.4mm in X, Y and Z respectively.

The skull markers were measured four times in the reflex metrograph and the mean data set adopted as error free. Standard deviations of the residual errors from comparing data sets were:

metrograph to calculated "slice" coordinates -
0.4mm, 1.0mm, 0.2mm in X, Y, Z respectively
metrograph to measured "slice" coordinates -
0.2mm, 1.0mm, 0.2mm in X, Y, Z respectively

The results, when compared with the metrograph, were slightly worse than the overall accuracy normally expected from the CT scanner, i.e. 1.5mm. This could be due to the fact that on certain surviews, where a target appears to image on the edge of the skull, (where the CT scan beam has to pass through a large amount of bone) the definition of such target is not always good, making the correct placement of the CT's digitising cursor difficult.

5.1 Multiple surviews versus AP & LAT surviews using the scans of the cranium

The comparison of the data, obtained from the multiple surviews to that obtained from the AP & LAT surviews, resulted in the following standard deviations of residual errors:

calculated "slice" to measured slice coordinates
0.6mm, 0.7mm, 0.7mm in X, Y, Z respectively
metrograph to calculated "slice" coordinates -
0.6mm, 1.6mm, 0.4mm in X, Y, Z respectively
metrograph to measured "slice" coordinates -

0.1mm, 1.0mm, 0.3mm in X, Y, Z respectively

The standard deviations overall were only slightly higher than those obtained from the multiple surviews, with the exception of the standard deviation in Y between metrograph to calculated "slice" coordinates.

6. DISCUSSION

The lengthy statistical tests, though tedious, are necessary to ascertain whether using multiple surviews for 3D coordinate determination is feasible. It is important that every precaution be taken, especially when such a vital organ as the brain is involved. When developing any medical technique it is necessary to not only determine the overall accuracy of a system, but to determine the accuracy of such a system in an actual mock up of the procedure, in which it will eventually be used.

The accuracy that can be obtained to coordinate external reference markers using multiple surviews, is within the accuracy that can normally be attained by the CT slice system, i.e. an overall expected accuracy of 1.5mm. When comparing the results to those obtained from the coordinate determination of the AP and LAT surviews, no significant improvement in accuracy was gained. Multiple surviews however allow for redundant observations, and therefore can be utilised for blunder detection. This is not possible when using only the AP and LAT surviews or slices for 3D coordinate determination of external reference markers.

To scan four external reference markers in the CT slice system, a surview, to plan the slice placement, and four slices are required. Due to the minimum slice thickness of 2mm, the CT laser beam is often used to line up the slices to ensure that the marker will lie in the centre of the 2mm slice. To coordinate the same four markers using multiple surviews - for example an AP, a LAT, and one oblique - requires fewer scans and no lining up procedures, and therefore a reduction in scanning time. It also provides a check for any blunders.

Tests performed on the CT scanner at the UCT Radiotherapy Department show that surview parameters remain static over very long periods of time, and thus it may only be necessary to calibrate a CT scanner after each service. A single point could be attached to the CT bed and coordinated using a single slice and multiple surviews prior to a patient scan being undertaken. This would ensure that the CT scanner has not undergone any changes since it was last calibrated.

As there is some image degradation of markers falling close to the edge of the skull, due to the amount of bone the CT beam has to intersect, it would be advisable to run further trials before adopting the procedure where patients are concerned. By attaching some external markers to a live subject, and scanning multiple surviews of the subject's head, the effect of bone, as well as intracranial tissue, on the image quality of the markers can be ascertained.

Uisng multiple surviews is a fairly simple procedure. The 2D control can be built in any hospital workshop and, as it is coordinated in the CT slice system, no special measuring equipment is required to coordinate the control. The software, to calculate surview parameters and the 3D "slice" coordinates, is relatively simple and can be written by someone with reasonable computing and mathematics experience. These factors make it a technique that is relatively simple to adopt for use with a CT scanner. Tests should still be carried out to ensure that the technique has been correctly implemented.

7. CONCLUSION

Modern CT scanners, that can scan oblique surviews from any position on the 360 degree circle of the CT gantry, can use multiple surviews to obtain 3D coordinates of external reference markers, using a two dimensional projective transformation algorithm.

The accuracy of such a 3D coordinate determination falls within the measuring resolution of the CT scanner, i.e. of 1.5mm for the CT scanner at UCT's Radiotherapy Department. Coordinate determination using multiple surviews provides an overdetermined solution. Although the overdetermined solution does not improve the overall accuracy, in comparison to the coordinate determination using only an AP and LAT surview, it does however provide a very important check for blunders without increasing the overall scanning time.

Before multiple surviews are adopted to coordinate external reference markers, it would be advisable to run further trials using a live subject.

In conclusion all the work carried out for this paper was conducted on the CT scanner at the UCT Radiotherapy Department. Before using multiple surviews, in conjunction with a two dimensional projective algorithm, it is imperative that the necessary trials be undertaken before adopting the technique to be used with another CT scanner.

8. REFERENCES

References from Journals:

Adams, L.P., van Geems, B.A., Jaros, G.G., Peters, J., Wynchank, S., 1995. Stereophotogrammetric-controlled pointing device for neurosurgical use. Med. & Biol. Eng. & Comput., 1995, 33, 212-217.

Levin, C.J., Hough, J., Adams, L.P., Boonzaier, D., Rüther, H., Wynchank, S., 1993. Determining locations of intracerebral lesions for proton therapy. Phys. Med. Biol., 38:1393-1401.

Scott, P.J., 1981. The reflex plotters: measurement without photographs. Photogrammetric Record Vol.X:435-446

References from Other Literature:

van Geems, B.A., Adams, L.P., Hough, J., 1995. The use of a two dimensional projective transformation to solve for the parameters for the anterior-posterior and lateral surviews of a CT scan. IAPRS, 30(5W1):366-371.