

Brachytherapy polymer gel dosimetry with xCT

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Background: Polymer gels are an emerging new class of dosimeters which are being applied to the challenges of modern radiotherapy modalities. Research on gel dosimetry involves several scientific domains, one of which is the imaging techniques with which dose data is extracted from the dosimeters. In the current work, we present our preliminary results of investigating capability of X-ray CT for extracting brachytherapy dose distributions from a normoxic gel dosimeter. **Materials and Methods:** A normoxic radiosensitive polymer gel was fabricated under normal atmospheric conditions and poured into three phantoms. Using Cs¹³⁷ brachytherapy sources, the phantoms were irradiated with different dose distributions with a LDR Selectron remote after-loader. To improve SNR, 25 images were obtained of each slice for image averaging and an averaged background image of an un-irradiated gel phantom was then subtracted for artifact removal. To further improve the accuracy, a self-consistent normalized method was used for calibration of the dosimeters based on an assumption of a linear dose response between zero and maximum dose regions in the gel. **Results:** Although results reveal very similar CT-number gradients to that of brachytherapy dose distributions, but the method does not fulfill brachytherapy dosimetry requirements. This might be due to the high prescribed doses in this study which in turn results in a large change in the CT numbers. This change in the CT numbers of the images can not be considered to have a linear relationship with dose which was the basic assumption of our calibration method, so the results are just qualitatively comparable. **Conclusion:** In this study, the results of using X-ray CT for brachytherapy polymer gel dosimetry is promising but not still satisfying. Improving a proper calibration method for correlating CT numbers to dose will be significantly helpful for performing measurements with CT. The main limitation for CT is still a low signal to noise ratio especially in lower dose areas. Iran. J. Radiat. Res., 2005; 3 (3): 101-108

Keywords: Polymer gel dosimetry, normoxic, brachytherapy, MAGICA, X-ray CT.

INTRODUCTION

The perplexity of assessing the final complex delivered dose in modern

radiotherapy modalities has raised a substantial need and motivation toward finding a comprehensive dosimetry method which should have the capability of accurate multi-dimensional dose verification and quality assurance (QA) of the whole treatment⁽¹⁾. Up to now, gel dosimetry systems are the only true 3-D dosimeters⁽²⁾. No other conventional dosimeter is capable of fulfilling the requirements of a comprehensive 3D measurement of a dose distribution with sharp gradients and irregular shape⁽¹⁾.

The laborious manufacturing process of conventional polymer gels has been significantly simplified by the introduction of new generation of polymer gels that can be fabricated under normal atmospheric conditions⁽³⁾, for which they are called normoxic.

Conventionally magnetic resonance imaging (MRI) has more widely been used for gel readout^(4, 5). Although "reading" a gel dosimeter with MRI requires specialized expertise and many factors should be taken into consideration, due to excellent spatial and dose resolution of MRI-based dose maps and its more availability in clinics compared to other alternatives, it is still the method of choice in most of the gel dosimetry experiments. Other than optical and spectroscopic methods, X-ray computed tomography has more recently been tried for extracting dose distribution data from gel dosimeters utilizing the radiation induced changes in physical density of the gels⁽⁶⁾. Image averaging methods for reducing noise, background subtraction for eliminating artifacts and image post-processing has been

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used to improve the quality of CT gel dosimetry results ^(6, 7, 8) but due to the stochastic nature of X-rays and low density changes in an irradiated gel, the obtained resolution is still not satisfying. Yet it has been reported that CT gel dosimetry is capable of achieving better results and can be improved to the levels very close to MRI ⁽⁷⁾. To our knowledge, there is still no published quantification on the abilities of X-ray computed tomography for brachytherapy gel dosimetry read-out.

Due to the fact that a major advantage of gel dosimetry lies on its ability to reveal steep dose gradients along which conventional dosimeters could not so easily be used, and considering the simplicity, more availability and other advantages of CT gel imaging over MRI ⁽⁵⁾, it seemed necessary to investigate CT capabilities (also incapacities) of brachytherapy dose measurements. Such a practical quantification will itself be necessary for designing any future expedient measures to be taken to improve the gel response in brachytherapy applications when scanned with CT.

In this paper, the feasibility of implementing X-ray CT for brachytherapy gel dosimetry was studied. Different dose distributions were planned by Cesium-137 brachytherapy sources of a Selectron remote after-loader and irradiations were performed by a gynecological applicator inserted into a specific gel phantom. The changes in CT number have been compared with the treatment planning data.

MATERIALS AND METHODS

The phantoms and gel preparation.

"MAGIC", which stands for "Methacrylic and Ascorbic acid in Gelatin Initiated by Copper", was the first normoxic polymer gel proposed by Fong *et al.* in 2001 ⁽³⁾. In a previous study, a small amount of agarose had been added to the recipe proposed by Fong *et al.* for MAGIC gel to strengthen its base matrix and to form a stiffer gel which is more resistant against environmental changes ⁽⁹⁾. The new gel was also found to have a broader dose range compared to that

of MAGIC ⁽¹⁰⁾. This gel was named MAGICA with the last "A" standing for agarose. The preparation of the gel followed the same steps as reported for MAGIC ⁽³⁾ except in that 0.5% (w/w) of agarose was dissolved in hot water and added to the gelatin solution when both solutions reached 48°C. Four similar Perspex walled phantoms with the dimensions of 19×13×2 cm were constructed and filled together with the same gel. Three of the phantoms had a tight cap in which a Perspex tube with a 3 mm wall thickness was fixed for the gynecological applicator (the cylinder) to be inserted inside the gel. The forth phantom was used for background subtraction. 15 plastic test tubes were also filled with the same gel for a preliminary evaluation of the gel response to radiation.

Treatment planning and irradiation

A tele-therapy Cobalt-60 machine (Theratron 780- AECL) was used to irradiate the test tubes laterally when they were horizontally fixed inside a water tank at the depth of 5cm with a source-to-surface distance (SSD) of 80 cm. One tube was left un-irradiated while the others were irradiated to doses of 2.5, 5, 7.5, 10, 15, 20,..., 60 Gy. Front and rear surfaces of the tubes were marked by adhesive stickers and the test tubes were irradiated with their front side facing up to the beam. This marking was later used for positioning the imaging slice at the middle of the test tubes between the front and rear surfaces where the gel was exactly at the depth of 5 cm during irradiation.

The original gel dosimeters were irradiated as follows: The first phantom was irradiated with a single Cs source for 27.96 hours. The second irradiation was performed with all 36 cesium sources of the Selectron after-loading machine, loaded into the applicator in a manner to form a quasi-cylindrical (sausage shape) dose distribution. The irradiation duration was 2.95 hours. The third phantom was irradiated for 4.37 hours with a more complex dose distribution. Eleven active pellets were arranged in positions 1, 2, 3, 4, 5, 6, 7 and 21, 22, 23, 24 to yield a dose distribution as the shape of an "8" digit. To provide full scatter conditions, all phantoms were placed in a cubic water tank during

irradiation.

The choice of the prescribed doses was a compromise between saturation limits in one hand and on the other hand, not giving too low a dose, where the density changes do not provide sufficient contrast in CT images. Gel dosimeters were irradiated 2 days after gel fabrication.

The Nucletron Selectron after-loader was equipped with a PLATO Treatment Planning System (TPS) which was used for prescribing dose to the gel-dosimeters and comparing the gel measurements with, as gold standard.

CT imaging

Scanning was performed by a Siemens Somatom Plus-s, single slice, rotate-rotate machine of the third generation. Images were obtained in a plane in the middle and across the longitudinal cross section of the phantoms. All phantoms were scanned together 4 days after irradiation. 25 images were obtained from each dosimeter and from the un-irradiated gel. The following CT image acquisition parameters were chosen with due attention to recommendations by Hilts *et al.*⁽⁷⁾: tube voltage 137 kV, tube current 440 mA, exposure time 1 s, slice thickness 5 mm with standard reconstruction algorithm. To ensure the identical positioning of the dosimeters for background subtraction and image processing, they were aligned and tied up together with adhesive strips.

Data Post-processing

CT images were transferred in DICOM format to a personal computer for further image processing. Image averaging and background subtraction were performed using modified MATLABTM software developed in-house for image averaging and subtraction. Hilts and co-workers (2004) proposed the use of image processing techniques to reduce noise in CT gel images⁽⁸⁾. Accordingly, an ADAPTIVE filter with a 3×3 pixel mask size was also applied on the final polymer gel dosimeters image, presuming the noise in the images to be Gaussian distributed.

Dose derivation

As regions of the same dose in the

dosimeters were found not to have the same CT numbers, a self calibrating normalized method was used for more accurate calibration. The following equation as proposed by Cardenas *et al.*⁽¹¹⁾ was used for each dosimeter:

$$(nN_{CT})_i = \left(\frac{(N_{CT})_i - (N_{CT})_{min}}{(N_{CT})_{max} - (N_{CT})_{min}} \right) \times 100 \quad (\text{eq.1})$$

where $(N_{CT})_i$ is the CT number averaged over a small region of interest of 3×3 pixels and nN_{CT} is the normalized N_{CT} in percentage for that ROI. Note that the subtraction of $(N_{CT})_{min}$ from $(N_{CT})_i$ and $(N_{CT})_{max}$ is performed automatically by background subtraction in CT image processing for artifact removal. If there is a linear relationship between N_{CT} and Dose (D), that is $N_{CT} = aD + b$, then the above equation will easily yield the normalized dose, nD , as described by Cardenas *et al.* in reference no 11. $(N_{CT})_{max}$ was chosen from the pixels 4mm distance from the Perspex tube walls to avoid any possible polymerization inhibitions or residual artifacts near the Perspex tube.

To compare these normalized doses (relative values) with absolute values of the planning anticipations, nN_{CT} was scaled up by being multiplied at the actual dose of the point of maximum N_{CT} from treatment planning. The results of CT measurements and TPS are then plotted together in one diagram in the following section.

RESULTS

Figure 1 shows the HU and associated uncertainty as a function of absorbed dose up to 60 Gy for the test tubes. The data is extracted after image averaging and applying the adaptive filter. CT number of each test tube is the average number over identical regions of interest inside the test tubes and the error bars show the standard deviations in the ROIs. The response shows a slight polynomial behavior and fits quite well to a polynomial function ($R^2=0.9908$) as illustrated in figure 1. Yet, a linear fit is also possible with good fitness ($R^2=0.9635$). Linear regression of data for the HU-dose

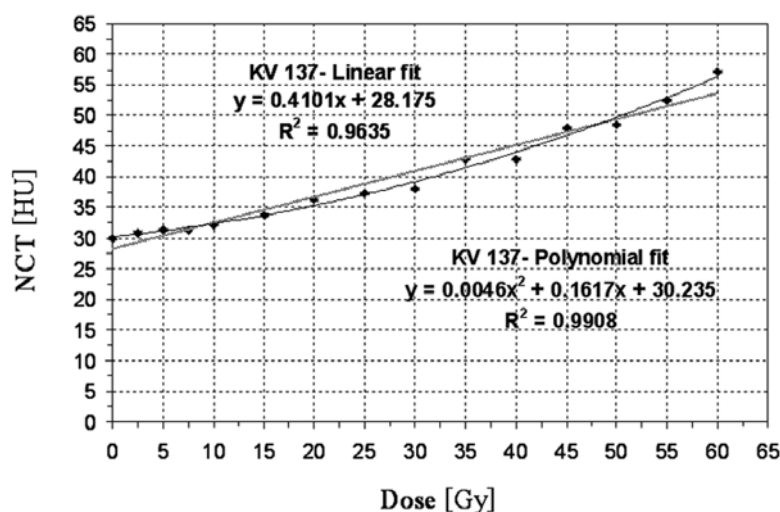


Figure 1. The HU and associated uncertainty as a function of absorbed dose up to 60 Gy for a single slice in the same position averaged from 25 acquired images of the test tubes.

sensitivity curve up to 60 Gy was 0.41 HU.Gy⁻¹. The absorbed dose range up to 60Gy did not show any saturation effects.

Figures 2-4 show the HU changes with distance in the three dosimeters. Profiles were plotted by averaging three pixel rows in the final processed CT image. For the dosimeter irradiated with a Cesium point source, the position of the profile is selected at the source level, perpendicular to the Perspex tube at a distance 45mm superior to the bottom of the dosimeter. The position of the second profile is 90mm superior to the bottom of the dosimeter which was irradiated with a linear array of 36 Cesium sources.

This is approximately the middle of the applicator, where the dose distribution has a more uniform shape. As the dose distribution in the third dosimeter was more complex, 3 profiles were plotted at three levels, 57 mm, 83 mm and 104 mm superior to the bottom of the dosimeter associating to the "belly", "neck" and "head" of the "8-shape" dose distribution. A schematic view of the position of these profiles is given inside each graph at the top left corner.

In figure 5, the PLATO TPS data is compared with the gel measurements in the first dosimeter. Figure 6 shows the second dosimeter and figures 7 and 8 are the results

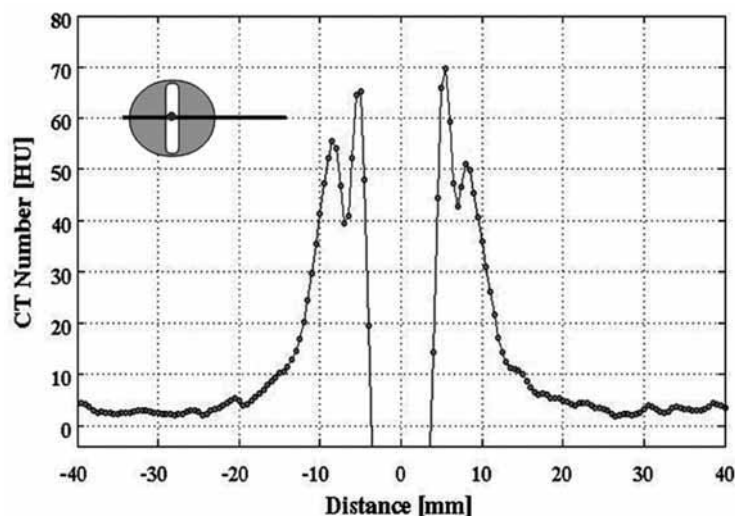


Figure 2. Profile of N_{CT} versus distance for the dosimeter irradiated with a Cs^{137} single point source. The polymerization inhibition is seen as a valley in high dose region near the Perspex tube. The position of the profile is schematically illustrated at the top left corner.

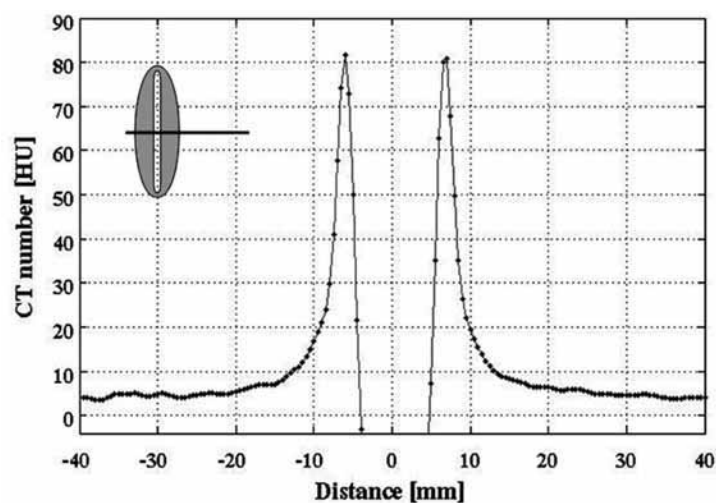


Figure 3. Profile of N_{CT} versus distance for the dosimeter irradiated with a linear array of 36 Cs sources. The position of the profile is schematically illustrated at the top left corner.

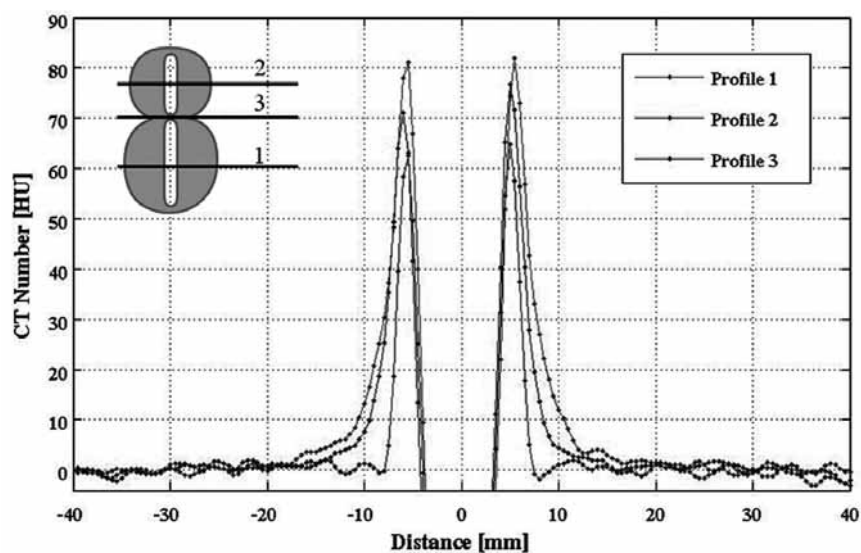


Figure 4. Three Profiles of N_{CT} versus distance for the dosimeter irradiated with an "8-shape" dose distribution. The position of the profiles is schematically illustrated at the top left corner.

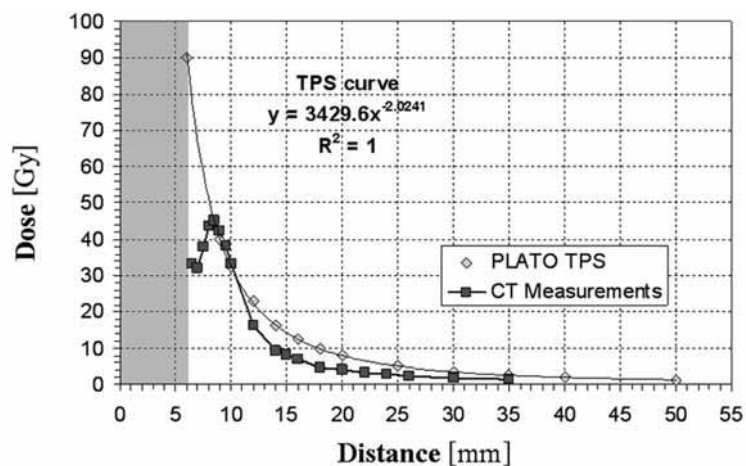


Figure 5. Comparison of the CT measurements with dose calculations by PLATO Treatment Planning System in the first dosimeter, irradiated by a single Cesium source for 27.96 Hours. The gray bar shows the presence of the Perspex tube.

of profiles 1 and 2 in figure 4. Data along profile 3 was too noisy to be plotted in a dose comparison diagram.

DISCUSSION

In figure 2, a polymerization inhibition is observed in the first neighboring 2mm distance of the Perspex tube; which is also reflected in figure 5. Profile 3 on figure 4 also shows polymerization inhibition in the vicinity of the Perspex tube. These inhibitions could be seen by bare eye in the original dosimeters. The Self-absorption effect of the applicator, dose rate effects or oxygen permeability of the Perspex tube may

be responsible for this, but finding the actual cause of the observed inhibition effects, needs more investigations.

In figures 5-8 the diamonds represent PLATO TPS and the squares represent the gel measurements. The curve of gel measurements crosses the TPS curve at the point of normalization. Areas closer to the Perspex tube (which its presence is represented by a gray bar in the first 6 mm of the diagrams of figures 5-8, show higher values than our gold standard (TPS) and areas farther, show dose underestimation.

In figure 1, the maximum change in CT numbers is 27HUs for a maximum dose of 60Gy. The changes in CT numbers in figures 2-4 are on average 70HUs. It should be noted

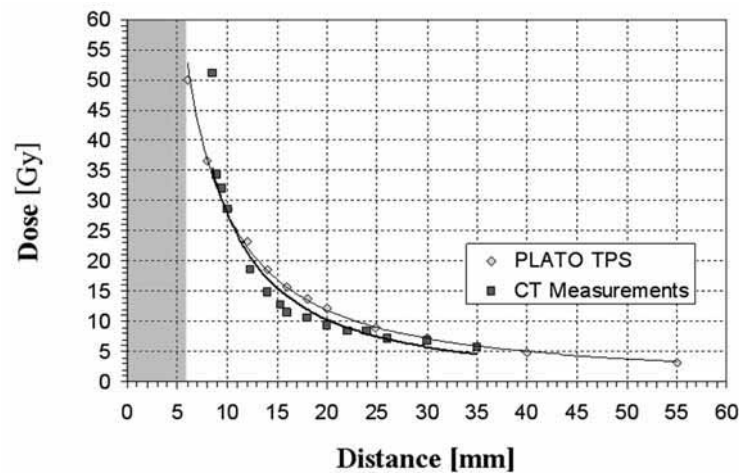


Figure 6. Comparison of the CT measurements with dose calculations by PLATO Treatment Planning System in the second dosimeter, irradiated by a 36 Cesium sources for 2.96 Hours. The gray bar shows the presence of the Perspex tube.

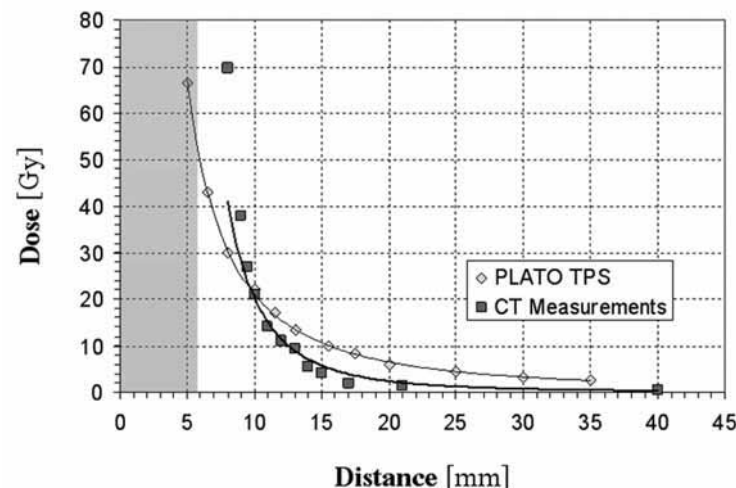


Figure 7. Attributed doses in profile 2 of figure 4 in comparison with the PLATO TPS calculations. The gray bar in the first 6 mm illustrates the presence of the Perspex tube.

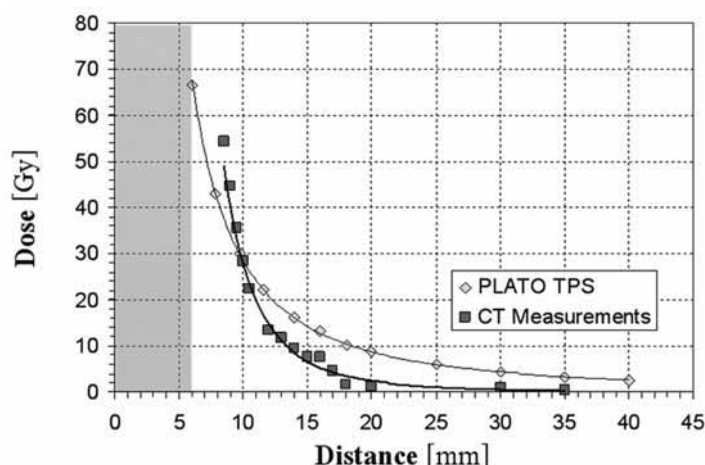


Figure 8. Attributed doses in profile 1 of figure 4 in comparison with the PLATO TPS calculations. The gray bar in the first 6 mm illustrates the presence of the Perspex tube.

that the gel has previously been scanned with MRI and no significant energy dependent was observed⁽¹⁰⁾. This discrepancy should be justified. Although the presence of the Perspex tube inside the gel, its effect on the reconstructed CT image, and the artifacts near the walls of the Perspex tube may partly be considered responsible for this discrepancy, but it seems that the major problem lies in the calibration method used for correlating CT numbers to brachytherapy dose distributions.

In equation 1 we presumed a linear response between areas of zero and maximal dose in the gel, and performed a relative calibration. The discrepancies in lower and upper areas of the normalization point show that this presumption does not provide adequate accuracy. The assumption of linearity in CT dose response is really not valid over the large dose range we were considering.

No published data was found on any previous assessment of brachytherapy dose distributions with CT gel dosimetry. In the only similar work, Audet *et al.* have implemented CT for verification of a stereotactic dose volume⁽¹²⁾. They used a relative dose calibration by dividing the CT images by the maximum ΔN_{CT} . To compare measured and planned relative dose information, they then attributed measured dose image pixel values to relative dose ranges and reported consistency with 50% and 80% isodose lines of their planning

system. They have reported a same problem in deriving lower doses as was experienced in this study, for example in profile 3 of figure 4. The lower dose gradient at this profile combined with the low signal to noise ratio causes the pixel values to be irrelevant to the actual dose. In other words dose errors in low dose gradients translate into inherently poorer spatial definition of a particular relative dose value and distance to agreement measurements no longer pertain⁽¹²⁾.

CONCLUSION

The major problem of implementing X-ray CT for brachytherapy gel dosimetry seems to lie in calibration of the dosimeters. There are two counter-acting factors; the first is that in lower doses the signal to noise ratio is poor and thus the obtainable information from the gel is limited. The second is that in high doses the change in CT numbers does not follow a linear relationship with dose. In this very experiment, we did not observe similar CT numbers for identical doses in our external test tubes (that were irradiated with known doses) and the original dosimeters.

We believe that these results can be significantly improved if a proper calibration method could be developed and a modern CT scanner is commissioned for optimal performance.

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