On the role of polymer gels in the dosimetry of small photon fields used in radiotherapy

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Evangelos Pappas[1,2]

[1] Department of Medical Physics, Faculty of Medicine, University of Crete, 711 10 Stavrakia-Heraklion, Crete, Greece

[2] Medical Physics Department, Anticancer-Oncologic Hospital of Athens 'Saint Savvas', 171 Alexandras Ave., 115 22 Athens, Greece

email : epappas@edu.med.uoc.gr

1. Introduction

Small photon fields, having dimensions from 30 mm down to 3 mm, are increasingly used in modern radiotherapy techniques and especially in Stereotactic radiosurgery / radiotherapy (SRS / SRT) and in intensity modulated radiation therapy (IMRT - beam segments). These small photon fields are used in gamma-knife, X-knife, Cyberknife, helical Tomotherapy and general in LINAC - IMRT treatments using conventional or micro-MLCs.
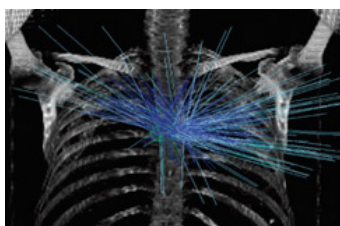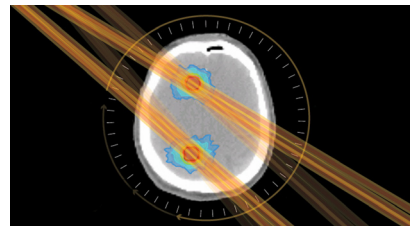

Figure 1. Cyberknife beams　　　　Gamma – knife beams　　　　Tomotherapy beams

The technological advances that allowed the use of such modern techniques for adequate encompassing of complex target volumes with the desired iso-dose surfaces were not followed by the corresponding necessary advances in dosimetry. The international dosimetry protocols (e.g. AAPM TG51, IAEA TRS 398) are mainly referred to photon field sizes from about 4 cm up to 40 cm.

The commissioning and periodic quality assurance of a radiotherapy system that utilizes small photon fields require accurate measurements of percentage depth doses (pdd), output factors and beam profiles. Large dosimetric errors during treatment and target-loss and/or Organs

At Risk over- or under-irradiation can often happen due to the increased uncertainty in measuring these parameters.

Small photon field dosimetry is very demanding due to:
 a) the high dose gradients that are present in narrow photon beams,
 b) the non-existence of lateral electronic equilibrium.

Moreover, the dosimeters used for such measurements should ideally exhibit certain characteristics:
 a) they should be tissue equivalent (and not perturb the radiation beam)
 b) they should *not* exhibit dose rate dependence of response (especially for profile measurements, since dose rate varies across the beam)
 c) they should *not* have directional dependence of response (especially for pdd and profile measurements, since the angular distribution of the electrons and scattered photons varies with distance from the beam central axis and with depth)
 d) they should *not* have energy dependence of response. (Usually dosimeters are calibrated at broad beams that exhibit a different (softer) photon spectrum compared to narrow beams)
 e) the spatial resolution should be high (in order to perform accurate measurements at high dose gradient regions – In narrow beams the dose gradient can be higher than 40% / mm)
 f) the sensitive volume of the dosimeter should be as small as possible in order to avoid volume averaging effects (that lead, for example, to penumbra broadening), but in the same time the detector sensitivity should be adequate for precise measurements (keep the statistical noise low)
 g) they should *not* perturb the radiation beam (and result to electron transport alterations)
 h) finally positioning (set-up) problems are always present (eg it is difficult to match the scanning path of the detectors' effective point of measurement with a direction that intersects the central axis of a narrow beam, when measuring profiles).

It is a fact that no single detector fulfills all the mentioned requirements. It has been proposed (Podgorsak *et al* 1999) that the use of a variety of detectors for small beam dosimetry is a good practice. In the literature have been presented small photon field dose characteristics measurements using air and liquid ionization chambers, radiographic and Gafchromic films, diamond detectors, plastic scintillators, TLDs, MOSFETs, radiophotoluminescence glass plates, polymer gels and silicon diodes (Buccilioni *et al* 2003, Westermark *et al* 2000, Robar and Clark 1999, Vach *et al* 2001, Martens *et al* 2000). The advantages and disadvantages of each dosimeter have been well reported.

The most important problems, among those listed above, present in almost all dosimetric systems used for narrow photon beam measurements are: a) dosimeter perturbation effects, b) volume averaging and c) positioning (set-up) errors (Das *et al* 2008, McKerracher and Twaites, 1999, 2006). It is believed that these problems can be addressed using polymer gel dosimetry which is a dosimetric method where the dosimeter and the phantom are identical and practically water equivalent, the spatial resolution of the measurements can be as low as sub-mm in three-dimensions and the derived data can be well manipulated for overcoming averaging and set-up errors (Pappas *et al* 2005, 2006).

A combination of narrow-beam data measurements performed using: a) conventional dosimeters and b) polymer gel dosimetry, can lead to a final trustable beam dataset that can be used safely as input in a Treatment Planning System and for quality assurance purposes.
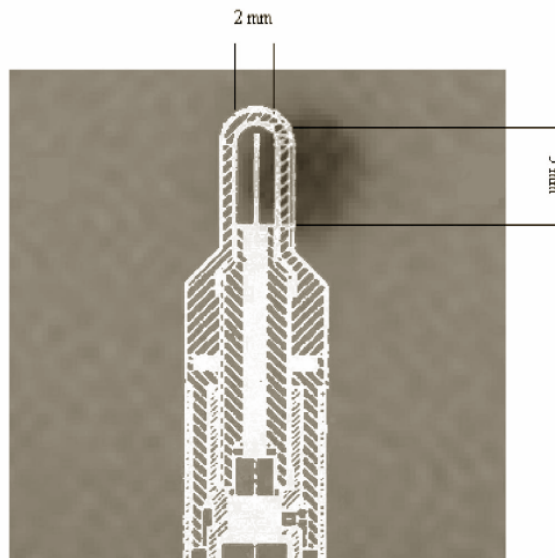
Figure 2. Positioning problems, volume averaging and electron transport alterations errors are the most important problems in small field dosimetry using conventional dosimeters. In this figure one can see a schematic representation of the longitudinal cross section of the PTW-PinPoint ion chamber, superimposed on a T2 map of an irradiated polymer gel with a 5 mm X-knife circular collimator (6 MV x-ray beam))

Below, are briefly presented: a) basic principles of polymer gel data manipulation methods for overcoming set-up and volume averaging errors and b) actual pdd, OF, and profile measurements of gamma-knife, X-knife and Cyberknife beams.

2. Manipulation of polymer gel data for overcoming positioning (set-up) and volume averaging problems

2.1 Overcoming set-up errors

The scanning path of the effective point of measurement of a conventional dosimeter, when for example one tries to measure the profile of a narrow beam, should cross the beam central axis. Figure 2 schematically shows that this is a difficult task. Small set-up errors can lead to erroneous results. Polymer gel dosimetry data can be well manipulated so that the central axis signal can be well defined, avoiding in this way positioning errors.
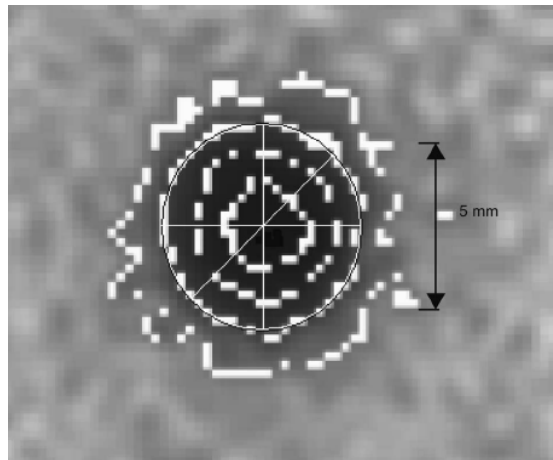
Figure 3. 0.25 mm resolution axial *T2*-map (perpendicular to the beams axis) of an irradiated polymer gel using a 5 mm circular collimator (6 MV x-rays). The four superimposed quasi-circular groups of white pixels correspond to four different random iso-*T2* values. The circle that fits one of them is also presented along with its center. All corresponding circle-centers lie within, or exist in the vicinity, of a unique pixel defined as the 'central pixel'. This pixel is presumed to belong to the beam's central axis

Within a *T2*-map (scanning level perpendicular to the beams central axis) of a polymer gel irradiated with a small circular photon field, a single pixel exists that corresponds to the beams' central axis (central pixel). This pixel can be determined by superimposing random iso-*T2* lines on the irradiated area of the *T2*-map, and subsequently by fitting corresponding circles as can be seen in the Figure 3. The calculated centers of these circles ideally lie within, or exist in the vicinity, of a unique pixel, hence, the central pixel. Accordingly, the important set-up errors present in small beam profile measurements can be eliminated.

2,2 Overcoming volume averaging errors

Volume averaging errors lead to beam penumbra broadening (that results to Organs At Risk over-irradiation) and to Output Factor underestimation (that results to higher delivered dose that that described). These volume averaging errors can be well estimated and eliminated by manipulating polymer gel data.

Estimating volume averaging errors in beam profiles measurements

By analyzing the *T2*-map of a 5 mm beam irradiated gel, the spin-spin relaxation rate *R2*-line profile that intercepts the *central pixel* (defined in the previous paragraph) can be converted to a % dose-line profile. As long as the delivered doses lie within the dose range where a linear dose – *R2* response exists, the background subtracted *R2* [$R2net=R2(D)-R2(0)$] can be normalized to the corresponding value of the central pixel. In this way, a beam profile that corresponds to a gel-detector size equal to the *T2*-map pixel size can be determined.

The same procedure can be followed if a square AxA mm^2 signal integration area is used for 'scanning' the *T2*-map along a linear direction that intercepts the central pixel (Figure 4). In Pappas *et al* (2006), 'A', was chosen to be 0.5, 1.5, 2.5, 3.5, 4.5, 5.5 and 7.5 mm respectively. Thus, the same *true* profile (*Pt*) can be measured using a variety of gel-detector sizes ('A'), each resulting in a corresponding *measured* profile (*Pm$_A$*).
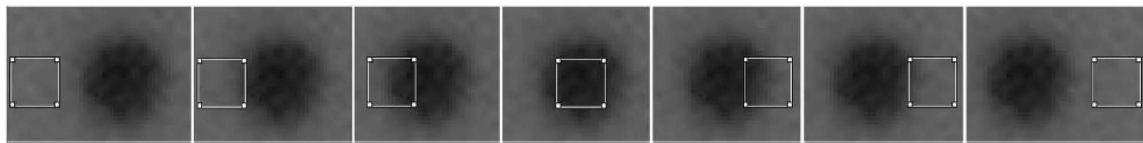
Figure 4. A square signal integration area AxA is superimposed on the *T2*-map of the irradiated polymer gel (A=3.5 mm in this figure). The same *T2*-map is presented sevenfold along with the same signal integration area at seven different positions along its 'scanning' path which crosses the 'central pixel'.
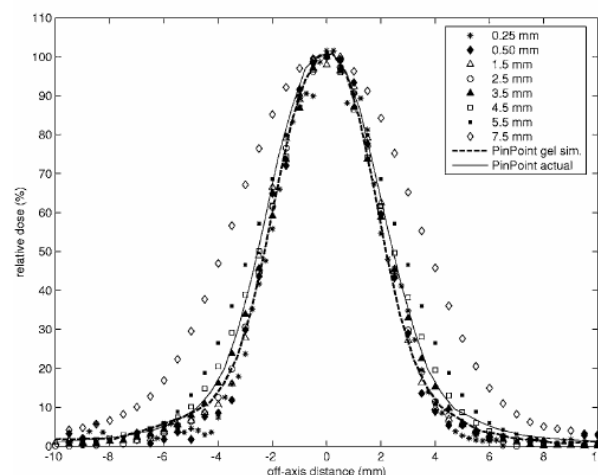

Figure 5. Beam profiles of the 5 mm diameter 6 MV stereotactic beam derived using polymer gel dosimetry with a variety of signal integration areas (or gel-detector sizes). In the same figure are also presented: a) actual corresponding PinPoint measurements and b) gel-derived measurements performed using a signal integration volume that approximates that of the PinPoint ion chamber

The knowledge of the dependence of the beam profile on the detector size used for measuring it, can lead to an accurate measurement of the true profile by extrapolating the measurements to zero detector size. In practice, a detector size equal to ~ 0.5 mm is adequate for not introducing volume averaging effects. By using an integration area equal to that of a known dosimeter, the volume averaging error introduced by this dosimeter can be estimated. Therefore a convolution kernel for this dosimeter can be extracted and then used for de-convolving actual dosimeter measurements and eliminating volume averaging errors. However, possible electron transport alterations will still affect the results. Since it is not the aim of this brief report to analyze deeper this issue, the reader is referred to Pappas *et al* (2006) for a more analytical presentation.

2.3 Estimating volume averaging errors in Output Factor measurements

By manipulating polymer gel data using a variety of signal integration areas one can also evaluate the volume effect to the Output Factor measurement. A small detector size (corresponding to a small integration area) results to relatively accurate but not very precise measurements. On the other hand, as the integration area is increasing (having the central pixel always at its center) the measurement becomes less accurate due to volume averaging. In Figure 6 are presented the OF measurements of a 5 mm diameter collimator (6 MV x-rays), performed using a variety of integration areas.
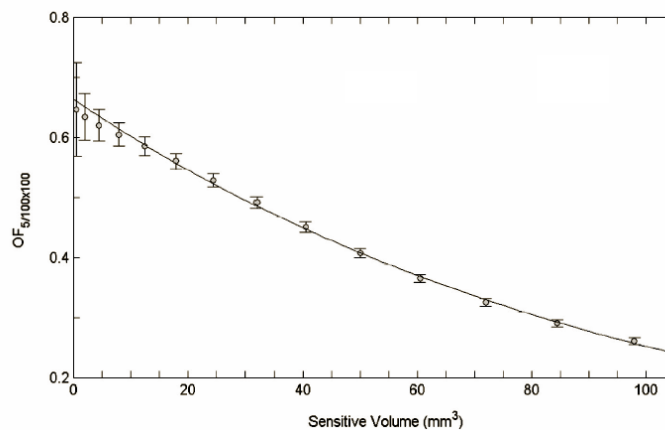
Figure 6. OF measurements of a 5 mm diameter X-knife collimator (6 MV x-rays), performed using a variety of integration areas using polymer gel data

In the case where high dose gradients exist in 3 dimensions, one can use the full 3D data set from polymer gel dosimetry. In figure 7 is presented the percentage of OF underestimation due to volume averaging for the 4 mm and 8 mm Gamma-knife helmets.
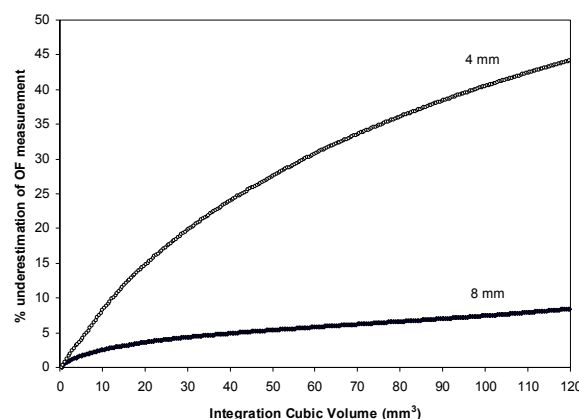

Figure 7. Percentage of OF underestimation due to volume averaging for the 4 mm and 8 mm Gamma-knife helmets

2.4 Pdds, profile and OF measurements

In the final section of this report are briefly presented pdd, profile and OF polymer gel derived measurements of small photon fields used in modern radiotherapy. Corresponding measurements performed using conventional detectors are also presented for comparison.

Pdds
The relatively low dose gradients along the central axis of a small field, makes the pdd measurements the less problematic among the small field data characteristics. In the figure below are presented polymer gel pdd measurements of the 5 and 10 mm diameter photon beams and corresponding conventional and PinPoint measurements.
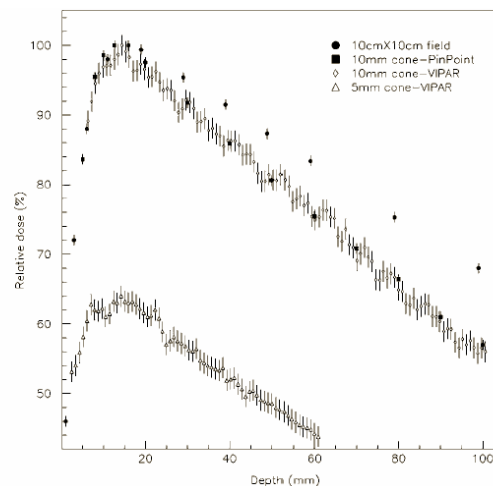
Figure 8. Pdd measurements of the 5 and 10 mm diameter photon beams (6 MV x-rays) performed using polymer gel dosimetry. PinPoint measurements for the 10 mm beam and for a 10 cm X 10 cm field are also presented

Profiles

By analyzing the *T2*-map of a narrow beam irradiated gel, the *R2*net profile along a line that intersects the central pixel, equals to the off-axis ratio of the irradiation area. The direction of the line can be arbitrary and profiles using a number of arbitrary lines can be averaged in order to reduce the statistical noise and derive a profile that characterizes the whole beam. However, in order to use *all* the available gel data for the measurement of a profile that characterizes a certain small field (and not just a number of random line profiles passing through the central pixel), the following process can be followed. A large number of circles centered at the irradiated area's *central pixel* can be used (three of them are presented in Figure 9 for a 30 mm collimator irradiated area). The average *R2*net value of the pixels that lie in the periphery of each separate circle (normalized to the central pixel R2net value) correspond to the off-axis ratio for a distance from the central axis equal to the circle radius. The normalization point in all cases can be the mean value that correspond to the central pixel and its eight surrounding pixels.
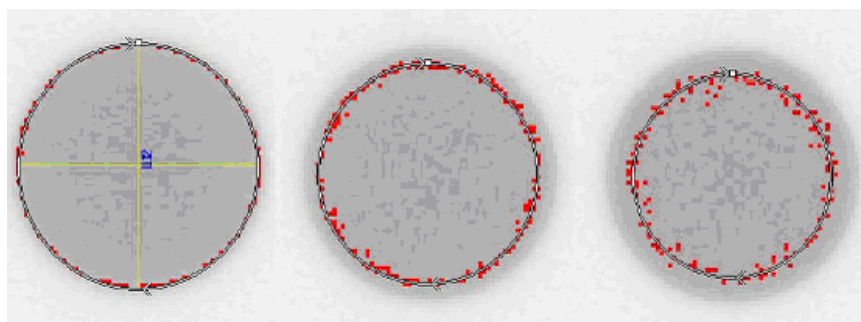

Figure 9. Three snapshots that correspond to three different random iso-*T2* pixels superimposed on the *T2*-map of the irradiated gel (30.0 mm irradiated area – magnified). The centers of the fitted circles lie within or adjacent to, a unique pixel: the central pixel. The mean value of the iso-*T2* pixels that lie on a fitted circle correspond to the *T2* value at a Off Axis Distance equal to the circles' radius.

Figures 10,11 and 12 present Cyberknife (5, 7.5 and 10 mm beams), gamma-knife (8 mm collimator helmet) and Novalis (7.5, 15 and 30 mm collimators) profile measurements performed

with polymer gel dosimetry. Corresponding measurements performed using diode detectors, PinPoint air ion chamber, films, diamond detector or diode array detector are also presented for reasons of comparison
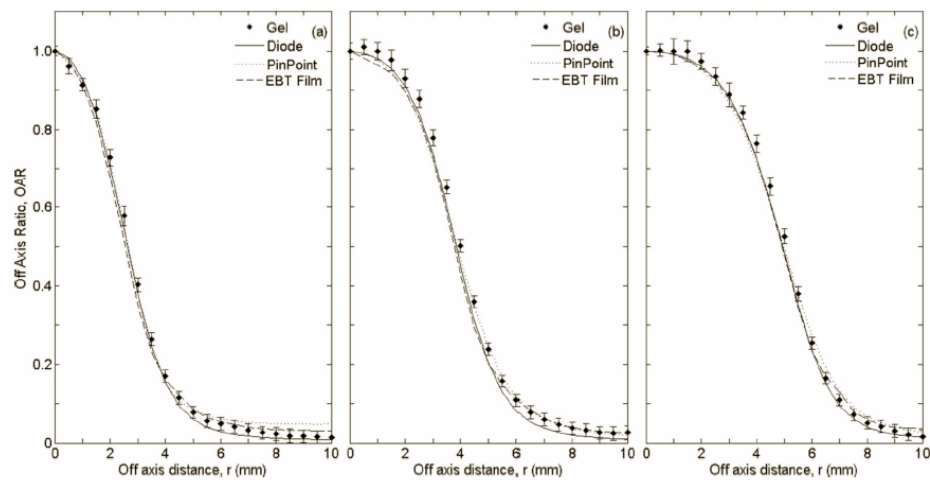

Figure 10. Polymer gel, diode, PinPoint and film measured Off Axis Measurements for the Cyberknife beams of 5, 7.5 and 10 mm diameter beams (from Pantelis *et al* 2008)
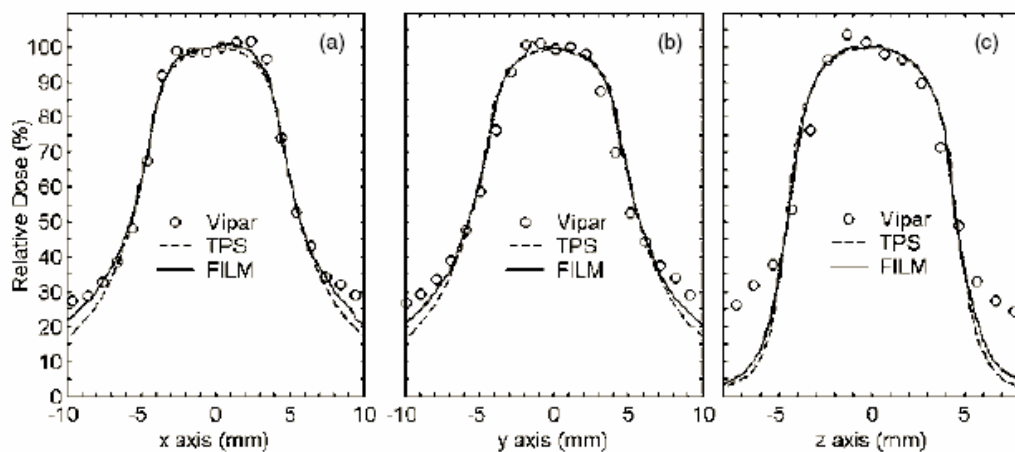

Figure 11. Gamma-knife 8 mm collimator helmet relative dose profiles. Corresponding Gammaplan calculations as well as radiochromic film measurements are also presented for comparison (from Karaiskos *et al* 2005)
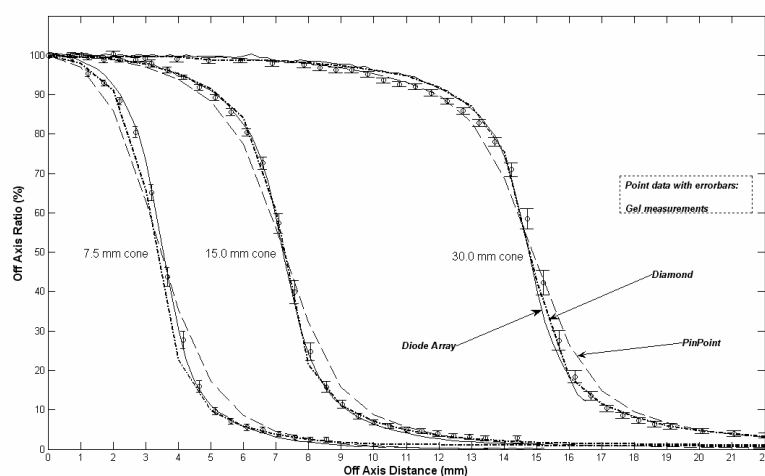
Figure 12. Beam profiles of 7.5, 15 and 30 mm Novalis beams. The solid line corresponds to the diode array (DOSI), dash-dot to diamond and dashed line to the PinPoint measurements respectively. Polymer gel data points are *not* connected with a line (Pappas *et al* 2008 in press)
Output Factors

Cyberknife output factors for the 5, 7.5 and 10 mm beams were measured equal to 0.702, 0.872 and 0.929 respectively, using polymer gel dosimetry.

X-knife (6 MV) output factor for the 5 mm beam was measured equal to 0.66, using polymer gel dosimetry.

Corresponding OF measurements using conventional detectors and Monte Carlo simulations are also available in the literature (Pantelis *et al* 2008, Pappas *et al* 2005).

3. Conclusions

Volume averaging problems, set-up errors and detector perturbation effects are the main problems present in small photon field dosimetry. Polymer gel dosimetry characteristics allow the elimination of these problems. Polymer gels can and should become a useful tool in clinical practice for small field data acquisition and periodic quality assurance in modern radiotherapy techniques where small photon fields are used.

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