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On the use of polymer gels for assessing the total geometrical accuracy in clinical Gamma Knife radiosurgery applications

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Abstract. The nearly tissue equivalent MRI properties and the unique ability of registering 3D dose distributions of polymer gels were exploited to assess the total geometrical accuracy in clinical Gamma Knife applications, taking into account the combined effect of the unit's mechanical accuracy, dose delivery precision and the geometrical distortions inherent in MR images used for irradiation planning. Comparison between planned and experimental data suggests that the MR-related distortions due to susceptibility effects dominate the total clinical geometrical accuracy which was found within 1 mm. The dosimetric effect of the observed sub-millimetre uncertainties on single shot GK irradiation plans was assessed using the target percentage coverage criterion, and a considerable target dose underestimation was found.

1. Introduction

Gamma Knife (GK) stereotactic radiosurgery (SRS) is a well established treatment approach for the management of a wide variety of intracranial lesions. The efficiency of the technique is based on the high geometrical accuracy in target localization and the high precision in the delivery of a therapeutic radiation dose to the target, which facilitates restriction of the dose to surrounding critical structures. Besides the excellent mechanical accuracy of a GK unit (less than 0.5mm) [1], the total clinical accuracy of the technique may be relented due to the spatial distortion inherent in the magnetic resonance (MR) images used for target volume prescription [2].

This work presents an experimental procedure based on polymer gels used to assess the total geometrical accuracy in clinical GK applications taking into account every link in the GK treatment chain; from patient imaging and irradiation planning on clinical MR images, to patient positioning and GK dose delivery.

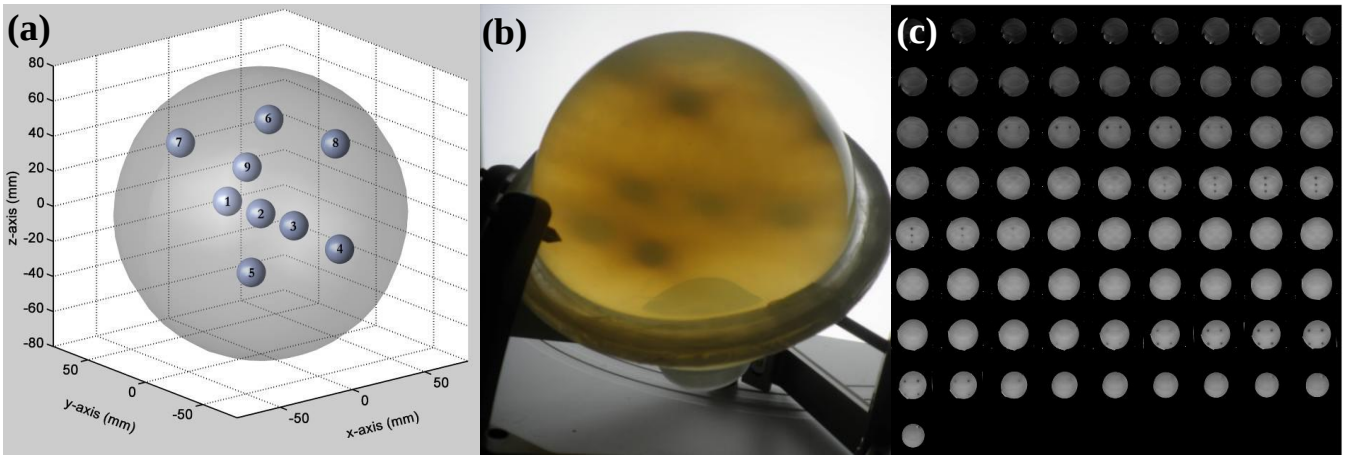

Figure 1. (a) A graphical representation of the GK irradiation plan. An identification number is assigned to each 8mm shot corresponding to its irradiation order. The origin of the coordinate system used was fixed to the planned coordinates of the second shot to facilitate presentation. **(b)** A photograph of the irradiated gel phantom mounted on the Leksell stereotactic frame. **(c)** Montage of the 73 axial T2-weighted MR images acquired from the irradiated gel phantom.

2. Materials and Methods

2.1. Polymer gel and experimental setup

The VIP gel formulation [3,4] (4% *N*,*N*-methylenebisacrylamide, 8% *N*-vinylpyrrolidone, 7.5% gelatin,, 0.0008% copper sulfate and 0.007% ascorbic acid diluted in hyperpure water with resistivity >18MΩ·cm [3,5]) was used for the purposes of this work. The VIP elemental composition, along with its mass density (d=1.031 g/cm^3), ensure its tissue-like properties regarding MR imaging. A spherical, 16 cm diameter PMMA flask filled with gel served as a head phantom and was used to accurately reproduce every link in the GK treatment chain.

2.2. Irradiation planning and delivery

Planning was performed on pre-irradiation CT images of the gel phantom, which are known to suffer from negligible geometrical distortion. The irradiation scheme involved the delivery of nine (9) single shots using the 8mm helmet collimator. The distribution of the shots within the phantom's volume was programmed so as to cover its major part and preclude any "cross-talking" between adjacent shots. A schematic representation of the irradiation plan is given in figure 1(a). Irradiation was delivered using a GK model 4C unit equipped with an automated positioning system (APS). A maximum dose of 25 Gy was programmed to be delivered at the planned center of each shot using the GammaPlan treatment planning system (TPS). This dose level lies safely within the linear dose-response region of the VIP gel formulation, while being much higher than the lower limit of dose detection (~2.5 Gy) [6]. A photograph of the irradiated gel phantom is presented in figure 1(b).

2.3. Magnetic Resonance Imaging

The irradiated gel phantom mounted on the Leksell stereotactic frame (with the localization box in-place) was MR-scanned at 1.5T 3 days post-irradiation using a protocol commonly employed for GK irradiation planning purposes. This involved a volume selective (3D), T2-weighted, turbo spin echo (TSE) pulse sequence (160 ms echo time, 2700 ms repetition time, 145.76 kHz per pixel receiver bandwidth). 73 axial (x-y plane) partitions were reconstructed with a voxel size of 0.4×0.4×1.5 mm^3. As seen in figure 1(c), the strong T2-weighting of the clinical MR sequence used results in adequate

image contrast for visualizing the radiation-induced polymerization. The set of the acquired MR images was subsequently used to construct a 3D matrix of MR signal intensities.

2.4. 3D data manipulation procedure

A custom-written algorithm [7], based on standard imaging routines, was used to accurately define the spatial coordinates of the center of mass for each of the GK single shot dose distributions registered to the gel by exploiting the symmetry that the corresponding MR signal intensity distributions present in space with respect to this point.

In the 3D MR signal intensity matrix of the irradiated gel phantom, the signal iso-intensity surfaces corresponding to a delivered shot were considered as solid bodies in space, and the spatial coordinates of the center of mass of each one were calculated. The coordinates of the center of mass of each shot were then determined as the average of the spatial coordinates resulting from 8 different iso-intensity surfaces for that shot, with the standard deviation in each dimension denoting the corresponding experimental uncertainty. The 8 intensity values of the iso-signal surfaces used to determine the center of mass coordinates of each shot were chosen so as to cover adequately the linear upslope and downslope parts of the "through-shot" signal profiles in all three dimensions. The above procedure was repeated for all 9 delivered shots. In order to preclude any systematic discrepancies stemming from the performance of this tool, the planned spatial coordinates of the 9 delivered shots were determined by applying the same algorithm to the 3D dose matrix of the irradiation plan which was DICOM exported from the GammaPlan TPS. The reference coordinate system used in this work for reporting planned and experimental results for the spatial coordinates of the delivered shots coincides with that utilized by the GammaPlan TPS for exporting DICOM RT dose data (see figure 1(a), but note that in this figure the origin of the coordinate system was fixed to the spatial coordinates of the second shot).

3. Results and Discussion

Figure 2 presents experimental results for the spatial coordinates of the center (CoC) of the 8th delivered shot (see figure 1(a)). As seen, the algorithm described in the previous section locates the shot's center of mass with sub-millimeter precision. Corresponding results were obtained for the rest 8 shots.

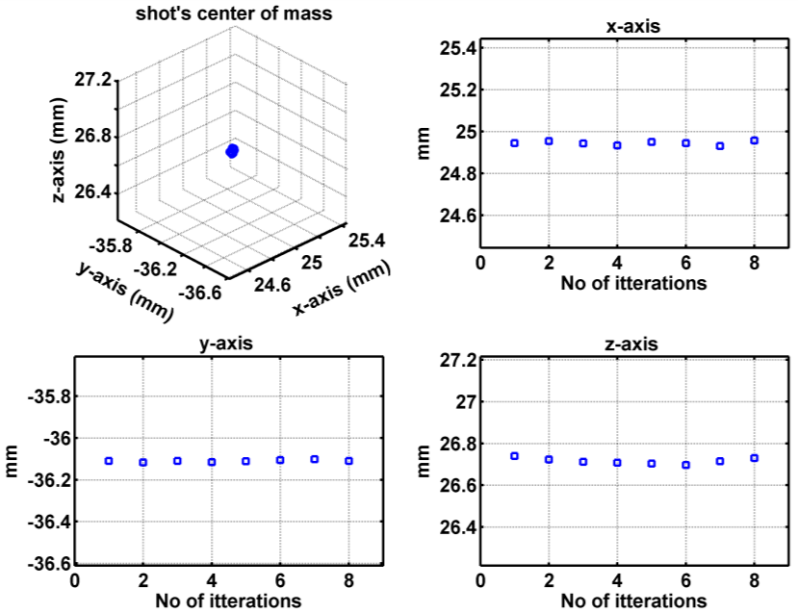

Figure 2. Polymer gel results for the center of mass coordinates of the 8th delivered shot. The x-axis label "No of iterations" corresponds to the number of the MR signal iso-intensity surfaces used.

Figure 3 presents results for the total geometrical accuracy of the GK unit and the specific clinical MR imaging protocol used in this work. For each shot, the experimentally defined CoC were subtracted from the corresponding planned values to determine the spatial components (denoted as dx, dy and dz) of the total displacement vector, which in turn were used to calculate its magnitude, dR. As clearly shown, the total displacement of each shot is dominated by its component along the x-axis dimension (a mean dx of 0.53 mm was calculated). It is also worth noting that the calculated dx values are all positive, implying that the experimentally determined shot centers are systematically shifted in x-axis (see

figure 1(a)), i.e., along the frequency encoding direction in MRI acquisition. These findings are in agreement with published results, according to which the difference in the magnetic susceptibility between the fiducial markers of the Leksell localization box and the polymer gel phantom results in a geometrical shift of the MR images along the frequency encoding direction. A theoretical calculation [8] based solely on susceptibility effects yielded an image shift of 0.3 mm for the specific MR imaging parameters used in this work. This finding, along with figure 3 data, indicates that the susceptibility-induced geometrical distortion is the dominant factor leading to geometrical inaccuracies for the clinical GK application studied. Overall however, the calculated dR values suggest that the total geometrical accuracy is well within 1mm.

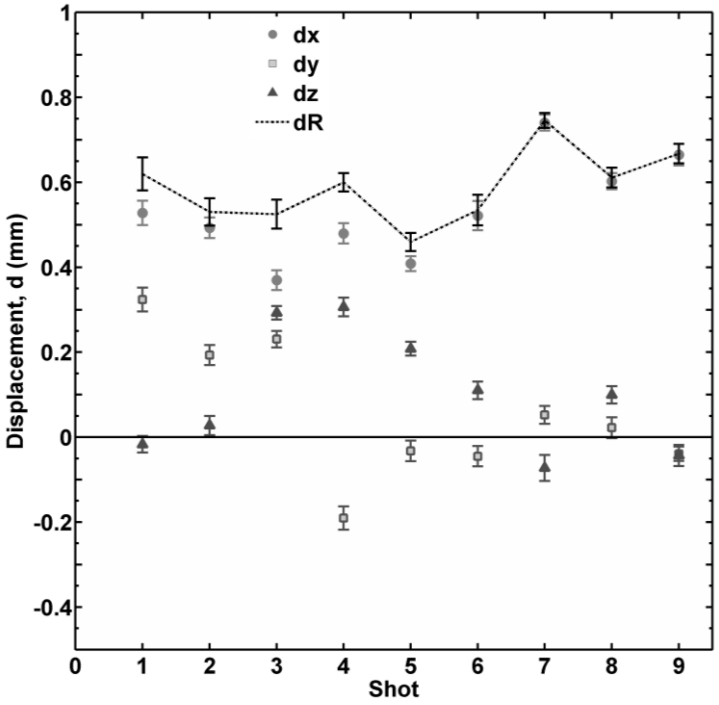

Figure 3. The total displacement, dR, calculated for each of the delivered shots along with its spatial components in each dimension (denoted with dx, dy and dz).

In an effort to assess the dosimetric effect that geometrical uncertainties of the order of the calculated dR values would induce to a clinical single shot GK application, a commonly used criterion for the evaluation of 3D irradiation plans was employed; that of percentage target coverage defined as the percentage of the target volume (TV) covered by a therapeutic iso-dose surface. Using the planned dose distribution data (see Sec. 2.2) in the GammaPlan TPS, a target volume was defined within each shot and the percentage target coverage by the 18 Gy iso-dose surface (i.e. 72% of the 25 Gy prescribed at the center of each shot) was calculated. The same calculation was then performed after "relocating" the shot in order to meet the experimentally determined spatial coordinates of its center. Results are summarized in table 1. As clearly shown, the sub-millimeter displacement found for each shot results in significant reduction in the target percentage coverage, implying that clinically the target receives a lower dose than that prescribed (with the difference being of the order of 10%).

Table 1. Percentage target coverage results calculated using the GammaPlan TPS for the planned and the experimentally defined coordinates of the center (CoC) of each shot.

Shot	Tumor Volume (TV) (in cm^3)	% coverage of TV by the 18 Gy iso-dose surface	
		Planned CoC	Experimental CoC
1	0.3414	95	87
2	0.3189	97	91
3	0.3218	96	89
4	0.3164	97	93
5	0.3148	97	93
6	0.3115	97	90
7	0.3254	97	93
8	0.3004	98	95
9	0.3176	97	92

This drastic effect stems from the steep dose gradient in all three dimensions of the GK single shot dose distributions, and is expected to soften when multiple shots are used to cover the target volume.

It should be noted that in the above analysis potential geometrical distortions in the CT images and diffusion of the polymer gel monomer, which could constitute sources of systematic uncertainties, were not taken into account since their effect in the total clinical geometrical accuracy was deemed negligible.

4. Conclusions

Results of this study show that the total geometrical accuracy in the specific clinical GK application examined is better than 1 mm. The susceptibility-induced geometrical distortion in the MR images constitutes the major contributor to accuracy degradation. Sub-millimeter geometrical uncertainties in single shot GK applications were found to have a significant effect in percentage target coverage.

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