Designing phantom for head-and-neck treatment verification: feasibility tests with bone and bone equivalent material incorporated into polymer gel

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Abstract. This work presents different approaches to manufacture of polyacrylamide gel (PAG) with bone inhomogeneity in an attempt to construct an authentic phantom for verification of head-and-neck irradiation specially for quantifying the absorbed dose in the spine. A special phantom was designed which includes air tube simulating thorax and accommodates model of spinal canal. Several methods of bone implantation into PAG were tested. The results indicate that proper mechanical surface cleaning of the bones eliminates the detrimental effects of chemicals used for bone conservation, while sufficient nitrogen flushing during the manufacture procedure effectively lowers the amount of oxygen present in the bone pores.

1. Introduction

In the last decade, polymer gels proved to be a very useful tool for three-dimensional visualization and measurement of absorbed dose distribution in a variety of medical applications – stereotactic radiosurgery (SRS) [1], intensity modulated radiotherapy (IMRT) [2], brachytherapy [3] or breathing adapted radiotherapy (BART) [4]. Most gel authors sought to model the real world situation using appropriate shapes and dimensions of gel phantoms (e.g. pelvic phantom for prostate IMRT verification, etc...); however, the flexibility of gel dosimeters enables to manufacture even more authentic phantoms, incorporating different kinds of inhomogeneities either of natural origin, simulating bones [5, 6] and cavities [6, 7], or artificial implants and clips [8]. These kinds of heterogeneous phantoms along with a convenient three-dimensional read-out method provide the only experimental way to quantify the absorbed dose with sufficient spatial resolution in regions of
electronic disequilibrium [5]. The manufacture of heterogeneous phantoms is more complicated than pure gel phantoms since the implanted heterogeneity must be chemically stable and oxygen free (if normoxic gel is not used) to eliminate fatal errors in measurement results interpretation [5]. Moreover, when magnetic resonance imaging (MRI) is used to read-out the response of the irradiated gel, a special requirement is imposed on the MRI compatibility of the implanted heterogeneity [8] and the gel container.

This work aims to investigate the possibility of implanting real bone samples and bone substitutes into a gel sample. Attention is paid to the head-and-neck treatment verification as this location presents a complex site with irregular surface and different heterogeneous organs (e.g. spinal cord, vertebrae, larynx, etc.). A dedicated glass phantom was designed to simulate the shape of the head-and-neck region. It can accommodate vertebrae (real or bone-like material) and thus simulate the spinal canal filled with the radiosensitive gel.

The following text summarizes practical experience and complications encountered when implanting real bones into a polymer gel.

2. Materials and Methods

2.1. Head-and-neck phantom design
A glass hollow bust-shaped container was designed with maximum wall thickness four millimeters. The container fits into a polystyrene bed, which contains contrast markers (tubes with copper sulphate solution or copper wires) to facilitate co-registration between different sets of transversal image data. The phantom can be supplied with vertebrae or its substitutes (Figure 1).

During the first MRI scanning session the phantom was tested for artifacts. A real set of neck vertebrae was positioned inside the container, which was filled with gelatine to fix the bones in one position (Figure 2).

An alternative bone equivalent material [9] (relative electron density to water 1.514, mass density 1.609 g/cm³, used for electron density/HU calibration in radiotherapy planning) was also tested for MRI compatibility, but shaped bone substitutes are not available yet.

2.2. Gel composition and preparation
The composition of a polyacrylamide gel (PAG) used in this work is given in Table 1. The gel preparation followed a well-established procedure using a perspex nitrogen filled glove box [10]. All gel containers were washed with distilled water prior to filling to avoid gel contamination.

2.3. Implanting bone samples into gels
To investigate the chemical influence of a bone on the gel dosimeter (no previous information was available on the chemicals used to conserve the bone samples) a small piece of bone (the same batch as the vertebrae) was implanted in a glass flask filled with PAG during the standard manufacture procedure (in the nitrogen flushed perspex box). This sample wasn’t irradiated due to vast polymerization which occurred within few hours from preparation.

During the second test, three samples of bones were used. Two out of the three were mechanically cleaned and washed with distilled water. The third piece was additionally cleaned with acetone and then washed with distilled water as well. The bone samples were immersed in a nitrogen atmosphere (approximately 1 hour) to flush oxygen from its pores prior to the positioning into the glass containers.

2.4. Gel irradiation
The PAG samples (the second test) with implanted bones were homogenously irradiated with a Gammacell 220 unit (MDS Nordion, Canada) with the dose rate of 7.75 Gy/h five days from the
manufacture procedure (stored in refrigerator). Two samples with bones, one cleaned mechanically and the one cleaned with acetone received 11.5 Gy. The remaining sample (mechanically cleaned) was left unirradiated as a reference.

2.5. MRI scanning protocol and data processing

The three PAG samples (the second test) were scanned 12 hours from irradiation. The same MRI scanning sequence was used for the PAG samples and the H&N phantom: 2D T2 weighted multiple spin echo sequence (16 echoes), with equidistant TE 22.5 ms, TR 2000 ms. Number of signal averaging, slice orientation, pixel size and slice thickness varied and are indicated alongside of each particular figure. The scanning was performed using Siemens Magnetom Expert (Siemens, Germany) 1T scanner in the head coil and the T2 map was reconstructed using the scanner’s manufacturer software (Numaris) since no significant difference was observed in comparison with least-squares fit of echo images performed aside; the first echo was excluded.

T2 maps and profiles were further processed in Matlab 6.5 (The Mathworks, USA) equipped with the Image Processing Toolbox.

3. Results and discussion

Phantom imaging revealed that no significant artifacts are present in the images. The major complication could be caused by susceptibility effects close to the phantom walls, which would be more pronounced, if stronger magnetic field was used. Glass wall also presents the major drawback from the point of view of designing an authentic phantom.

In the first experiment, with the bone implant without any surface cleaning, the polymerization process was noticeable within few hours after gel preparation around the bone implant apparently induced by unknown chemicals from the bone (the sample was not irradiated).

Results of the second experiment with bones cleaned mechanically and with acetone are summarized in Figure 3. It shows the R2 map with the three bone samples and corresponding R2 profile.

In the second experiment, the first container with mechanically cleaned bone (11.5 Gy) shows reduction of response around the bone most probably caused by remaining oxygen in its pores. The acetone-cleaned sample exhibits stronger reduction in R2 probably due to traces of acetone. The last sample (mechanically cleaned, unirradiated) shows that polymerization takes place only on the surface of the implanted bone, which implies that the mechanical surface cleaning reduced the effect of unknown chemicals (compared to the first trial with bone implanted without any additional manipulation).

The results indicate that the way of reducing oxygen levels in bone pores by sufficient nitrogen flushing can be successful when it is performed for longer time interval. PAG compositions enriched with tetrakis(hydroxymethyl)phosphonium chloride (THPC) were not tested due to its reduced sensitivity compared to the standard PAG. A different way how to overcome complications with real bone implants could be to coat them in some chemically resistant substance or to use bone substitutes with similar parameters as a real bone (electron density and mass density) in order to model similar interaction processes of radiation [5, 6, 7].

4. Conclusions

Further research in bone equivalent materials and real bone implants is ongoing.

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