Improved MAGIC gel for higher sensitivity and elemental tissue equivalent 3D dosimetry

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Purpose: Polymer-based gel dosimeter (MAGIC type) is a preferable phantom material for PET range verification of proton beam therapy. However, improvement in elemental tissue equivalency (specifically O/C ratio) is very desirable to ensure realistic time-activity measurements.
Methods: Glucose and urea was added to the original MAGIC formulation to adjust the O/C ratio. The dose responses of the new formulations were tested with MRI transverse relaxation rate (R2) measurements.
Results: The new ingredients improved not only the elemental composition but also the sensitivity of the MAGIC gel. The O/C ratios of our new gels agree with that of soft tissue within 1%. The slopes of dose response curves were 1.6–2.7 times larger with glucose. The melting point also increased by 5 °C. Further addition of urea resulted in a similar slope but with an increased intercept and a decreased melting point.
Conclusions: Our improved MAGIC gel formulations have higher sensitivity and better elemental tissue equivalency for 3D dosimetry applications involving nuclear reactions. © *2010 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3260844]

Key words: gel dosimeter, proton therapy, positron emission tomography

I. INTRODUCTION

Range verification is very important in high-precision proton (or other heavy ion) beam therapy. During proton therapy, small amounts of positron emitters, such as ^{11}C ($T_{1/2}=20.39$ min), ^{13}N ($T_{1/2}=9.965$ min), ^{15}O ($T_{1/2}=2.037$ min), and ^{38}K ($T_{1/2}=7.636$ min) are produced along the beam path via different channels of nuclear fragmentation reactions, most importantly (p, pn) reactions.[1–8] Positron emission tomography (PET) imaging of thus endogenously generated radionuclides (most importantly ^{11}C and ^{15}O) is the only practical approach for *in vivo* range verification of proton (or other heavy ion) beam therapy. To date, the most commonly used phantom materials for the PET monitoring of heavy ion (including proton) therapy include polymethyl methacrylate (PMMA),[1,4–6] polyethylene, and gelatinuous water (99% pure water).[9,10] However, the elemental compositions of those materials (specifically the O/C ratio) are very different from tissue composition, leading to different rates of $^{15}O/^{11}C$ productions in the phantom. Because of the large difference in ^{15}O and ^{11}C half lives, for PET imaging started during or immediately after proton therapy, the time-activity curves measured with these types of phantom materials are very different from expected tissue response. Another relevant but noncritical element is nitrogen, which will result in a small quantity of ^{13}N during proton irradiations (estimated initial yield <3% of total activity by Monte Carlo simulation studies[8]). In addition, dose distribution and actual proton range cannot be directly measured in such phantoms.

A polymer gel dosimeter is a preferable phantom material for this application. The three-dimensional (3D) dose distribution can be recorded in a gel phantom and imaged with magnetic resonance imaging (MRI),[11] therefore actual proton range can be measured directly and related to PET measured activity distal fall-off positions. Moreover, polymer gels have a better elemental tissue equivalency compared to other materials. Fong *et al.*[12] introduced the first normoxic gel formulation, the methacrylic and ascorbic acid in gelatin initiated by copper (MAGIC) gel. The O/C ratio of the MAGIC gel (10.68) is much closer to that of typical soft tissue (4.95) when compared with PMMA (0.53), but there is still a difference by a factor of 2, and further improvement is very desirable.

We have adjusted the elemental composition of MAGIC gel by adding a carbon-rich ingredient, glucose, and a nitrogen-rich ingredient, urea, to obtain an O/C ratio similar to soft tissue. The dose responses of the new formulations