A new approach to radiochromic three-dimensional dosimetry-polyurethane

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1. Introduction

Over the past 45 years, the ideal physical composition sought from a three dimensional dosimeter was that it should be a transparent plastic that is firm in structure, and tissue equivalent [1]. This paper describes such a dosimeter, which is composed primarily of the synthetic polymer polyurethane [2].

Polyurethanes are one of the most versatile man-made synthetic polymers [2]. They are used in medical devices, coatings, adhesives, sealants, and as elastomers used on floors and automotive interiors. The radiochromic components in the polyurethane formulation are radiochromic dyes and free radical initiators.

The performance parameters, diffusion of the image of the irradiated field over time, dose-response linearity, dependence of response on dose rate and dose energy, and the stability of the dosimeter have been evaluated and previously presented [3,4].

2. Materials and methods

2.1. Polyurethane formulation

The polymeric matrix is formed in two steps. In the first step, reacting an equivalent of commercially available polyol with two equivalents of a di-isocyanate forms a pre-polymer, referred to as “Part A”. The resulting “Part A” pre-polymer contains 1 to 15 % unreacted isocyanate and can be stored at room temperature for long periods of time. The second step consists of mixing the leuco dye, a free radical initiator, and a catalyst with “Part B” (a commercially available polyol) then blending with Part A in equal proportions, placing the blended material in the appropriate mold, and incubating at an optimal temperature under 60 psi to minimize out gassing. The reaction scheme is shown in the two step equation below.

\[
\begin{align*}
\text{Step 1} & \\
\text{HO-} & \text{R}_1\text{-OH (Polyol) } + 2 \text{OCN-} & \text{R}_2\text{-NCO (Diisocyanate)} \rightarrow \\
\text{OCN-} & \text{R}_2\text{-[} & \text{NH-} & \text{C(=O)}\text{-O-} & \text{R}_1\text{-O-C(=O)}\text{-NH-} & \text{R}_2\text{-]}_n\text{-NCO (prepolymer, PART A)}
\end{align*}
\]
Step 2
PART A + HO- R₃ - OH (PART B)+ leuco dye + free radical initiator + catalyst →
\[-\{(C(=O)-NH-R₂-NH-C(=O)-O-R₁-O-C(=O)-NH-R₂)ₙ-NH-C(=O)-O-R₃-O\}₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋₋…..
Figure 2. Visible spectrum (500-800 nm, left – right) of the image on the left shows leuco malachite green (bottom line) and malachite green (top line, max 633 nm). Image on the right, benzamine - 4,4′,4”-methylidynetris leuco form (bottom line) and oxidized form (top line) with maximum at 623 nm.

The polyurethanes used in these studies have an elemental composition of C at 61%, H at 9%, N at 10%, and O at 20% to give an electron density of \( Z_{\text{eff}} = 6.6 \) with a mass density of 1050 kg m\(^{-3}\). Depending on the weight percent of the halocarbon added to the polyurethane as free radical initiators the \( Z_{\text{eff}} \) can be increased by 1-2. There are two additional characteristics of polyurethanes, which make them ideal for a radiochromic based dosimetry. First, polyurethanes can be fashioned into an optically clear three dimensional solid. Second, polyurethanes can be polymerized at a relatively low temperature (<80°C), which minimizes undesired thermal oxidation reactions, which increase the background of radiochromic dosimeters. An example of two irradiated dosimeters (5 Gy) containing leuco malachite green is shown below.

Figure 3. Images taken from the top of tapered 1 Kg cylinders. On the left, the cylinder was irradiated with a 4 inch square field and on the right with a 3 inch square field.

Below is an image of a reconstructed slice of an irradiated dosimeter created after laser OCT scanning. The dosimeter was first irradiated with a square field followed by irradiation using a lead stencil with the dosimeter name, Presage™.
Figure 4. Reconstructed slice of an irradiated dosimeter created after laser OCT scanning.

References

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