INTRODUCTION: Spinal metastases are a common and serious manifestation of breast cancer. These lesions can cause pain and vertebral collapse and, due to the proximity of the spinal cord and nerves, can lead to serious neurological complications. For patients with an actual or impending vertebral collapse (indicated by spinal instability or intractable pain), conventional treatment often occurs in two phases—a surgical procedure in which bone cement (polymethylmethacrylate, PMMA) is injected into the vertebral body to stabilize the bone (e.g., kyphoplasty or vertebroplasty), followed by external beam radiation therapy (EBRT) to control tumor growth. The effectiveness of using EBRT for treating spinal metastases is limited by radiation to the spinal cord, which limits the dose that can be safely delivered to metastases within the vertebral body. Additionally, EBRT is fractionated into 10 separate treatment sessions to minimize the effects of spinal cord radiation exposure, making it inconvenient for the patient.

As a novel treatment approach, we propose to combine kyphoplasty or vertebroplasty with radiotherapy by mixing a radionuclide with the injected cement. A single procedure using this radioactive bone cement would provide structural reinforcement to the bone while simultaneously irradiating the tumor from within (i.e. vertebral brachytherapy). This study evaluated the feasibility of using radioactive bone cement to deliver therapeutic radiation to the vertebral body without undue risk to the spinal cord.

METHODS: A T-12 human cadaveric vertebra was obtained from a 69-year-old female donor and CT scanned (GE Discovery VCT PET/CT, calcium hydroxyapatite phantom, standard reconstruction, 0.625-mm pixels, 1.25-mm slices, 80 kVp, 280 mAs). In-house software was used to transform the CT scan data into a Monte Carlo N-Particle (MCNP) radiation transport model consisting of a three-dimensional rectangular lattice of 0.625 mm × 0.625 mm × 1.25 mm voxels (Figure 1). Thirty bone materials were represented in the model, with both trabecular and cortical bone represented by a spectrum of complementary volume fractions of solid cortical bone and yellow bone marrow, ranging from 100% yellow bone marrow to 100% solid cortical bone. Each MCNPX voxel of bone was assigned a material based on the quantitative CT (QCT) density of its constituent CT voxels, with QCT density used to calculate the total density and volume fractions of the constituent bone and marrow within that voxel. The atomic composition of each bone material was calculated according to its relative bone and marrow volume fractions, with the atomic composition of each part given by Kramer et al. All soft tissue in the model, including the spinal cord, muscle, and fat, was represented by a single material, with density and atomic composition given by Kramer et al.

A 1.19 cm-diameter × 1.13 cm-height cylindrical volume of Spineplex® bone cement (Stryker, Kalamazoo, MI), with a radioisotope uniformly distributed within all bone cement voxels, was simulated within the model (Figure 1). Two candidate radioisotopes were studied: $^{32}$P (14.3 day half-life) and $^{89}$Sr (50.5 day half-life), each previously FDA-approved for intravenous treatment of bone metastases, and with complete energy spectrums from Medical Internal Radiation Dose data. A pulse-height energy tally (*F8) was used to calculate the energy (MeV) deposited in each voxel of the model, per source particle.

Thirty million particle histories were simulated (MCNPX v.2.5.0, Los Alamos National Laboratory, LANL) to characterize the dose distribution within the vertebral body. The results were linearly scaled to an arbitrary distance from the cement boundary, and the activity required to deliver this dose distribution was calculated.

RESULTS: The dose distributions for both radioisotopes showed similar characteristics, demonstrating axisymmetric distributions about the cement implant and rapidly decreasing dose with increasing radial distance from the cement. Initial activities of 0.94 mCi and 0.51 mCi for $^{32}$P and $^{89}$Sr, respectively, would deliver over 300 Gy to bone within 1.6 mm of the cement implant and over 80 Gy to bone within 2.8 mm, while keeping the dose at 3.4 mm under 45 Gy (Figure 2).

DISCUSSION: The predicted dose distribution shows that a therapeutic radiation dose would be delivered to all bone within ~3 mm of the cement volume without undue risk to tissue beyond 3.4 mm (such as the spinal cord), indicating preliminary feasibility of this technique. A subsequent study will involve validation of the CT scan-based radiation transport models. Once validated, the models can be used for future development of the technology, directed at achieving an optimal therapeutic result by refining the choice of radioisotope(s), amount of activity, and geographic distribution of the cement. We will also study the sensitivity of the radiation dose distribution to variations in bone size, density, and tumor types, differences in bone cement formulations, and other factors associated with a potential clinical application.

With further development, this technology may yield a clinically feasible procedure that would eliminate the need for 10 radiation therapy sessions, making it convenient for the patient. This procedure would also deliver a higher dose to the bone metastases and a lower dose to the spinal cord and other normal tissues than conventional EBRT, potentially improving the clinical outcome.


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