FINITE ELEMENT MODELLING OF THERMAL DAMAGE TO TISSUE BY CURING BONE CEMENT IN VERTEBROPLASTY

Andrew M New

School of Engineering Sciences
University of Southampton
Southampton SO17 1BJ
United Kingdom

INTRODUCTION

Vertebroplasty is a surgical technique in which a collapsed or collapsing vertebra is injected with bone cement in order to stabilize the vertebra and/or prevent further collapse. Vertebral collapse most commonly occurs in osteoporotic vertebral bodies and may lead to loss of height or other spinal deformity, pain and occasionally neurological complications. The principal aim of the vertebroplasty procedure is pain relief, although an alternative technique which also uses bone cement, kyphoplasty, also aims to reverse deformity. The main advantages of vertebroplasty are that it can be carried out by injection of the cement into the vertebra through the skin, which is less traumatic for the patient than alternative treatments which may involve open surgery, and that it can be performed as an outpatient procedure which results in low cost. Early reports suggest that the technique is successful, most studies reporting pain relief in 67-100% of patients, although length of follow-up is currently relatively short [1].

Although the cement clearly plays a structural role, the effects of the cement curing process are not fully understood. It has been proposed that heat generation during cement polymerization may destroy pain receptors within the vertebral body, contributing to the pain relieving effect of the procedure. On the other hand, some surgeons have expressed concern that excessive heat generation may lead to damage to the spinal cord or nerve roots as they exit the vertebral column.

The aims of this study, therefore, were to implement a finite element (FE) model of the cement curing process and to use the model to assess temperature histories of tissue surrounding a bolus of cement curing within a vertebral body.

METHODS AND MATERIALS

The cement curing reaction was modeled using a kinetic equation to relate the instantaneous local volumetric heat generation rate in the cement, S, to the local degree of polymerization of the cement, α and the local temperature T via the polynomial function R(T) as shown in equation 1 [2].

$$S = R(T)\alpha(1-\alpha) \qquad (1)$$

The curing model was incorporated into a FE model using the procedure illustrated in Figure 1.

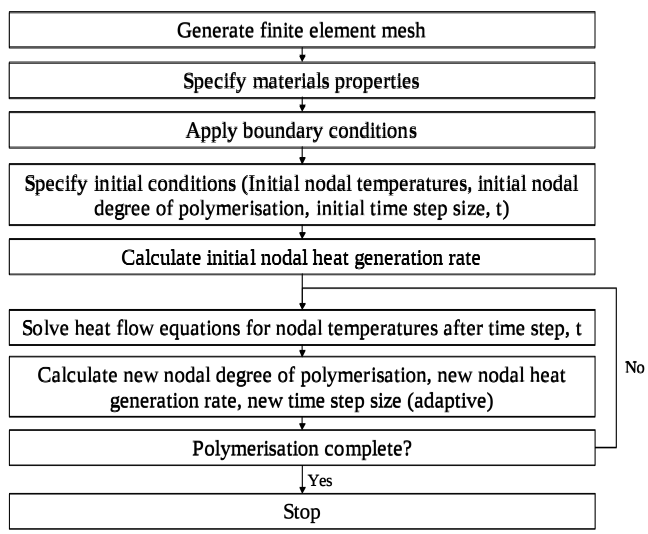

Figure 1: Incorporation of the kinetic equation into a FE model

Following the method of Revie et al. [3], a “necrosis index” was calculated as the solution progressed to evaluate the effects of the heat generation in the cement on the surrounding tissue. For each element at each time step in the analysis, a necrosis index increment was calculated by dividing the time step size by the time to thermal damage at temperature T, where T is the average temperature in the element over the time step. The time to thermal damage at temperature T was calculated using a function fitted to the data of Moritz and

Henriques [4]. In order to avoid problems with extrapolating beyond the range of temperatures for which Moritz and Henriques provide data, temperatures above 65°C were assumed to cause a necrosis index increment of 1 for the time step, and temperatures below 44°C a necrosis index increment of 0. Finally, the necrosis index increments were summed to calculate the necrosis index, with values greater than 1 indicative of thermal necrosis of the tissue.

The FE meshes used in the present study were adapted from that developed by Smit et al [5] and made available on the website of the International Society of Biomechanics [6]. The mesh used for the results presented here is shown in Figure 2. The middle vertebra contains a bolus of cement occupying a volume of approximately 5cm³.

The thermal properties and curing kinetics of Surgical Simplex cement were taken from Baliga et al. [2], and the thermal properties of tissues from Huiskes [7] and Duck [8]. Initial temperatures of 23°C and 37°C were specified for the cement and tissues respectively.

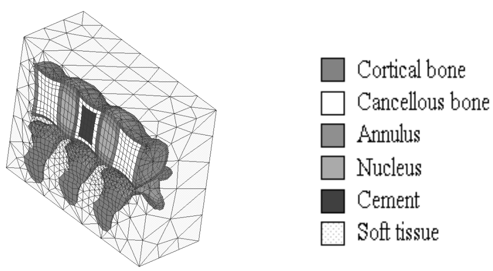

Figure 2: Typical FE mesh.

RESULTS

Figure 3 shows the temperature histories of 3 nodes in the FE model. Initially, the temperature of the cement slowly increases due to absorption of heat from the surrounding tissue. As the polymerization reaction begins to accelerate at around 6 minutes, the temperature in the cement begins to rise rapidly, reaching a peak of 117°C at the center of the cement mass at around 7 minutes. Temperatures on the surface of the cement increase slightly more slowly, reaching a peak of 90°C also at around 7 minutes. Temperatures on the surface of the bone close to the spinal cord rise much more slowly and reach a peak of around 43°C approximately 1.5 minutes after the peak in the cement temperature.

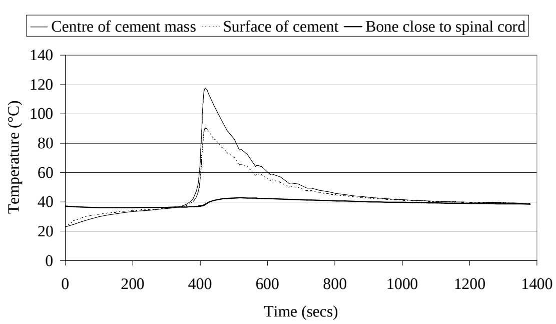

Figure 3: Temperature histories of selected nodes.

Figure 4 shows a contour plot of the necrosis index in the tissue surrounding the cement after the polymerization is complete. The zone of thermal necrosis extends approximately 6mm around the bolus of cement in all directions.

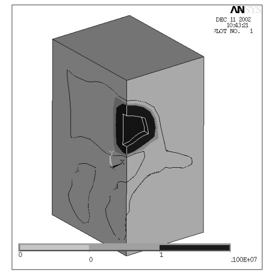

Figure 4: Necrosis index after completion of polymerization - section plane through center of middle vertebral body.

DISCUSSION

Although temperatures at the center of the cement were high, temperatures on the surface of the bone near the spinal cord remained within safe limits, with no thermal necrosis predicted in this region. The predicted necrotic zone extended through most of the cancellous bone surrounding the cement and into the cortical bone forming the outer layer of the vertebral body. This would seem to indicate that regions where cells would be expected to be destroyed lie within the vertebral body.

An experimental study [9] showed much lower peak temperatures within the cement (peaks of around 70°C). This may have been due to the use of smaller quantities or different distributions of cement within the vertebral body, both of which would be expected to alter the rate of cure of the cement and hence the local temperature histories.

Further work will include investigating the effects of different cement types and using more realistic geometries to better represent the shape of collapsed vertebrae.

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