BIOMECHANICS OF THE CEMENT INJECTION PROCESS IN VERTEBROPLASTY

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Introduction: Vertebroplasty is an emerging procedure to treat spinal fragility fractures related to osteoporosis. In this procedure, bone cement is injected under pressure through a cannula into a vertebral body. The in-situ polymerization of the cement augments and strengthens the weakened bone. Although vertebroplasty has been performed for over 15 years, very little is known about the biomechanics of the cement injection process. This study analyzes, experimentally and theoretically, the biomechanical forces (i.e. injection pressure) that underlie the cement injection process. We approach this question from a multi-disciplinary perspective that combines clinical, experimental and theoretical research.

Method: The following methods were used for this investigation:

1) THEORETICAL MODELING: The injection pressure, \( p \), is separated into two components: (a) delivery pressure – the pressure required to force the cement through a cannula (Hagen-Poiseille’s flow); and (b) infiltration pressure – the pressure required to force the cement to penetrate the cancellous bone (Darcy’s flow). This distinction is important because it separates and highlights the different pressure requirements that bone cements pose on the cement injection process. Mathematically, the pressure separation can be presented as:

\[
p\left(\frac{r_0^4}{2}\right) = \frac{Q^2}{\pi r^4 l} \cdot \left(\frac{1}{t^4} \cdot \frac{1}{l^4} \cdot \frac{1}{t^4} \right) + \frac{32}{l^4} \cdot \frac{Q^2}{\pi r^4} \text{ Delivery}
\]

where \( r \), is syringe radius, \( r_0 \) is cannula, \( \eta \) is cement viscosity (Krause), \( Q \) is cement flow rate, \( \kappa \) is bone permeability (Baroud, Nauman), \( r \) is radius of the expanding cement cloud in a vertebra, \( l \) is cannula length.

2) PARAMETER IDENTIFICATION: The parameters of the above pressure equation were identified in separate studies. (a) Bone permeability: the permeability of 52 cores that were harvested from 6 osteoporotic lumbar spines (age 66.7±9.6 years, BMD 0.51±0.24 g·cm\(^{-2}\)) was measured using a linear Darcian flow. Also, the morphology of the cores was quantified using a micro-CT. (b) Cement viscosity: viscosity, which is a key parameter in the pressure relation, versus time and shear rate was characterized in a rheometer (Baroud, 2003). (c) Clinical measurements: an injection device instrumented with a load and displacement transducer (Fig.2) was used to monitor in-vivo pressure and flow curves during actual vertebroplasties.

Results: Bone permeability was in the range of 1.9 – 9.7·10\(^{-6}\) m\(^2\), and bone porosity was in the range of 84 – 96%. Further, porosity predicts \( p<0.001 \) approximately 75% of permeability (Fig.2). The other important parameter for the pressure relation is the cement viscosity. It was identified as a function of shear rate and time (Baroud, 2003).

Fig. 1: Injection device (left) consisted of a delivery tool (into which a 5 mL syringe was placed) and a palm pilot. The tool was instrumented with a force and displacement transducer.

The clinical data showed that the cement was injected in strokes of 0.4 to 1.0 mL. Injection rate was in the range of 0.06-0.25 mL·sec\(^{-1}\). The injection pressure varied substantially because of the ongoing cement polymerization. The pressure was about 0.1 MPa (1 MPa=10 atm = 147 Psi = 7600 mmHg) at the start of the injection and it increased to more than 1.5 MPa towards the end of the procedure (Fig.3).

Discussion: Clinicians have employed various methods (e.g. altering the recommended liquid-to-powder ratio) to reduce the injection pressure. However, these methods pose additional risks.

A combination of clinical, experimental and theoretical method is used to analyze the cement injection with a particular focus on the injection pressure. The goal is to integrate our various findings in order to arrive at a broader understanding of the factors that affect cement injection and to eventually improve vertebroplasty so that its results are safe.

The most interesting findings of our experimental and theoretical models are that cement delivery requires most of the injection pressure, whereas cement infiltration requires very little of the injection pressure. The results of the model were confirmed in experimental tests on cadaveric vertebrae by a follow-up study and independently by Belkoff (2003). Therefore, it seems that the cannula geometry is a limitation for the cement delivery in vertebroplasty.

Conclusion: The results of the theoretical model – which incorporates components of independent experimental and clinical measurements on injection parameters – pinpoints the bottleneck in the cement injection process, and therefore, makes apparent targeted solutions, such as a redesigned cannula or a delivery device to control the cement flow.

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