Use of computational fluid dynamics (CFD) to compare cement flow around distal centralizers in total hip replacement

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Introduction

Centralizing devices were introduced in order to achieve an optimal cement mantle and reproducible alignment of the stem during surgery (Goldberg et al., 1998; Morscher et al., 1995). While centralizers make a reproducible cement mantle thickness possible, there is a potential concern of changing the cement flow pattern. Inappropriate centralizer designs could possibly lead to cement delamination and/or entrapment of air (Noble et al., 1998; Berger et al., 1997; Smith et al., 1996). This investigation compared the cement flow pattern around a clinical successful centralizer which has been in clinical use for more than 10 years and a new centralizer design in regard to delamination and dead water areas using CFD.

Material & Methods

A three-dimensional CFD-model of the MS 30 hip stem size 10, the femoral canal (diameter 13 mm), the current MS 30 centralizer (#1) and the new centralizer design (#2) were used to perform CFD - simulations (Star CD software package) of the cement flow around the distal centralizers (Figure 1). As shown by Krause and coworkers (Krause et al., 1982) bone cement can be characterized as a non-Newtonian fluid. Bone cement rheology is influenced by the flow kinematics and the time after mixing (polymerization). As the dynamic viscosity $\eta$ increases with polymerization time, $\eta$ can be described as:

$$\eta = F(t) \cdot G(t)$$  \hspace{1cm} (1)

with a time dependent curing function $F(t)$ and a shear rate function $G(t)$. While $F(t)$ was taken from published literature for low viscosity bone cement (Zimmer LVC) (Lee and Turner, 1977), $G(t)$ was taken from an internal investigation. With $F(t)$ and $G(t)$ the dynamic viscosity can be written as:

$$\eta = 2.48 \cdot e^{t/95.24} \cdot \gamma^{0.48\cdot600\cdot1.05}$$  \hspace{1cm} (2)

Due to numerical constraints (time dependent change of flow kinematics and geometry during stem insertion) the CFD - simulation was modeled as follows:

1) the stem was positioned in the middle of the femoral canal in 90% of its final position,
2) the cement flow was introduced from distal to proximal with the stem fixed to its position,
3) neglecting the drag flow effect on the stem surface is reasonable (because the error is only 10%)
4) calculated stem insertion time was set as 10s, 20s and 30s leading to Reynolds – numbers $<<1$ (friction dominates inertia).

With these assumptions cement flow can be described as a series of snapshots. The final fluid mesh consisted of 340'000 elements for centralizer #1 and 380'000 for centralizer #2 respectively.
Results & Discussion

The current centralizer #1 with its more blunt form and the centralizer/stem transition zone which leaves a space between centralizer and stem showed areas with local flow patterns and dead water areas (blue colors in Figure 2) which could be critical in regard to delamination. In case of dead water areas any entrapped foreign body or air will stay in place. In contrast the slimmer centralizer #2 showed no signs of local flow patterns and overall significantly reduced areas of near zero velocity where air entrapment is likely to occur. For centralizer #2 the dead water area in front of the centralizer was reduced and the flow pattern and surface stress on the centralizer were more homogenous compared to #1.

Figure 1:  A) current centralizer in clinical use with pin to attach to the stem  
B) new centralizer design with three wings and possibility for stem subsidence within the centralizer  
C) CFD-model (dark blue: stem geometry, light blue: centralizer #1, red: cement)

Figure 2:  Representation of flow velocities in the cement mantle, on bottom lateral cortical wall  
red colors = high flow velocities, blue colors = low velocities  
left: cross sectional view through centralizer #1  
right: cross sectional view through centralizer #2
The CFD - simulation was able to show why entrapped air bubbles stay in the transition zone between centralizer #1 and stem as confirmed by in vitro experiments. Simplification of the CFD - simulation as presented here (cement flow around a fixed stem) were valid as long as the tip of the stem was not in its final position. The use of CFD - simulation has shown to be valuable for a better understanding of the factors influencing the flow pattern in the cement mantle and as completion of experimental cement flow studies.

References


