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High-resolution magnetic resonance flow imaging in a model of porous bone–implant interface

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Abstract

Purpose: To evaluate the application of high-resolution MRI methodology for characterizing the fluid velocity field and evaluate fluid shear field within a simplified in vitro model of a bone–implant interface.

Materials and Methods: The study used a specific micromotion canine bone implant that has been used for over a decade in the experimental evaluation of anatomical, biomaterial, mechanical and surgical factors influencing the quality of the implant interface.

To allow its implementation in an MR coil, a nonmagnetic model of the micromotion implant was fabricated. The model consisted of a cylinder of polymethylmethacrylate (PMMA) representing the implant, located within an annular controlled gap into a block of coralline-derived bulk porous hydroxyapatite (HA; Interpore Cross International, Irvine, CA, USA). The assembly was potted in a polycarbonate shell and connected to a gravity-feed flow system consisting of a water fluid reservoir and peristaltic pump. Cross-sectional fluid velocity images through the principal axis of the implant were generated using a phase-encoding MR imaging technique; axial fluid flow was derived, and fluid shear was evaluated using a Newtonian fluid model.

Results: Due to the nonuniform gap of the actual experimental construct, a highly nonuniform flow through the annular gap and a secondary flow through the porous HA block were observed. Axial velocity magnitudes in the range 0.04 to 14 mm/s were measured, and the flow velocities within the annular gap and the surrounding bone differed by nearly two orders of magnitude. Image analysis showed that 95% of total flow passed through the annular gap and 5% was transported through the porous HA block. Fluid shear was computed within the porous structure and the annular gap, and they differed by one order of magnitude.

Conclusion: We demonstrated that high-resolution MR flow imaging has the resolution to measure fluid transport processes noninvasively through a nonmagnetic model bone implant. Gap fluid flow and fluid flow into the permeable skeleton (HA block) were quantified, and these data allowed the noninvasive determination of fluid shear. These promising results are encouraging for applications in biological tissue, artificial bone substitutes, tissue engineering and clinically relevant studies concerning implant fixation.

Keywords: High-resolution MRI; Porous media; Biomaterial; Peri-implant flow imaging; Implant fixation

1. Introduction

Although the statistics on primary implant replacement are encouraging, an increase in revision operations has occurred [1], with up to 20% of all hip replacement operations being revision. This is due to increasing life span of patients with joint replacements, an increasing number of implanted joints and younger ages at index operation. Revision surgeries have poorer functional outcomes, higher failure rates (5–60%) and higher morbidity [2]. Prevention of loosening and improvement of revision surgeries remain one challenge in modern joint replacement.

Conditions influencing bone growth in the vicinity of implants (and their fixation) include the surgical technique [3] and coupled mechanical and biochemical factors [4–6].

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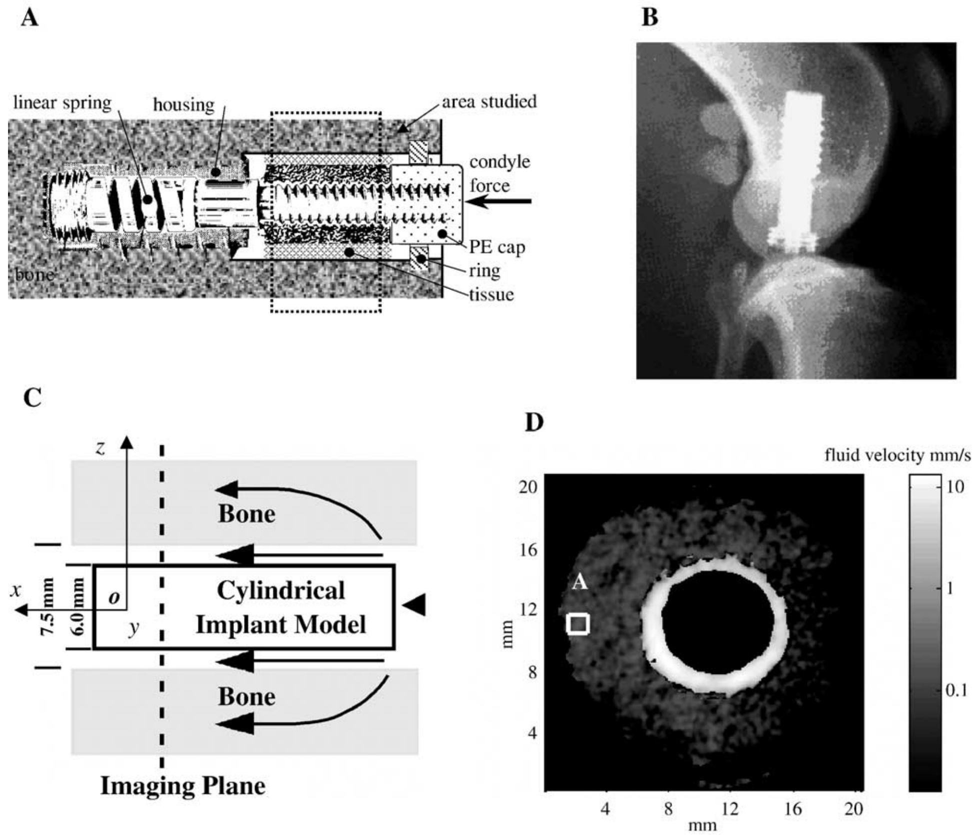

Fig. 1. (A) Micromotion implant, (B) in vivo implantation, (C) in vitro implant model (schematic), (D) image of MR flow velocity v (mm/s).

Successful uncemented artificial joint replacement is dependent on the stimulation of bone formation around the implant in the immediate postoperative period [7] since successful cell migration, proliferation and differentiation are needed to establish the bony matrix.

Among the numerous factors influencing bone growth in the early postoperative period, fluid flow is of particular interest. Pressure, fluid flow and fluid viscosity have an influence on cell transportation and differentiation [8]. Osteoblasts and chondrocytes are also known to be responsive to fluid flow [9], and locally applied pressure has been associated with focal osteolysis [10]. Additionally, fluid flow in the peri-implant space can assist in drawing mobile cells to the surface by increasing their circulation, consistent with the concept of the effective joint space for nonbiological materials [11]. Wear particles driven by fluid flow may contribute to elevated pressure by their role in increasing the tissue inflammatory response with local fluid accumulation and for their potential to block (plug) circulation in the surrounding permeable trabeculae.

Bone porosity and permeability will also influence the mechanical conditions in the peri-implant space (and thereby modulate the biological activity there) [12]. Furthermore, porosity and permeability will influence transport phenomena, and intertrabecular permeability is critical for vascularization [12]. It is expected that permeability will also constitute a relevant design parameter for successful development of artificial bone substitutes [13]. Therefore, there is a need to develop a means to quantify localized effects of substrate permeability on peri-implant and intratrabecular fluid flow parameters.

We concentrate on a loaded micromotion canine bone implant that has been developed as a tool to identify and rank the ability of various mechanisms to promote or deter interfacial bone growth [14]. The implant and its in vivo location in the dog knee are presented in Fig. 1A and B, respectively. Briefly, the model permits controlled axial motion (stable implant: 0 μm; unstable implant: 500 μm) of a cylindrical (6.0 mm od) implant within a larger diameter hole (7.5 mm od) in the surrounding bone. The implant moves as a result of loading of the piston.

The literature review highlights that fluid flow and implant fixation are highly correlated, but the real-time investigation of in vivo phenomena is still complex. Histological investigations in the micromotion canine implant suggested that formation of interfacial bone could coincide with regions of reduced fluid shear within the annular gap of the implant [15].

Our specific objective was to develop high-resolution MRI methodology for characterizing the fluid velocity field and shear field within a simplified in vitro model of the micromotion bone implant. This methodology can also be applied to improve the knowledge of transport phenomena in porous artificial bone substitutes. Ultimately, we intend to