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Original Contribution

ON ULTRASOUND IMAGING FOR GUIDED SCREW INSERTION IN SPINAL FUSION SURGERY

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Abstract—Spinal fusion surgery generally involves the insertion of screws in the pedicle, a three-dimensional (3-D) process that requires great skill if serious consequences are to be avoided. This article describes an image guidance technique based on generating B-mode images from within a small bore hole in the pedicle's trabecular bone. The purpose is to determine the viability and safety of the hole placement for subsequent insertion of the screw. Toward this end, this article endeavours to understand the factors that govern B-mode image quality. Specifically, the results of numerical simulations on the effects of transducer frequency and bone volume on image quality are presented along with demonstrations of B-mode image formation obtained *in vitro* on human pedicles using a 3.2 MHz probe. The results of the numerical simulations suggest that high frequency and high bone volume generally reduce the image quality. The *in vitro* experiments showed that the trabecular and cortical bone can be detected in the B-mode images. (E-mail: cobbold@ecf.utoronto.ca) © 2011 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasound imaging, Trabecular bone, Spinal fusion surgery.**

INTRODUCTION

Spinal fusion surgery is commonly indicated as part of the treatment process for a wide variety of ailments, including spinal tumours, spine trauma and degenerative disk disease. Many spinal fusion surgery procedures require the insertion of pedicle screws as part of the apparatus to immobilize (or fuse) the affected vertebrae, as illustrated in Figure 1. Insertion of the pedicle screws carries a significant risk of vascular or neurologic damage due to the proximity of the screws to important vessels and nerves. Specifically, accidental breaching of the cortical bone of the pedicle can lead to impingements on nearby blood vessels, the spinal cord or the nerve roots.

Before insertion of the screw, a bore hole is typically made using a cannulation probe to create a trajectory along the length of the pedicle, which would guide the subsequent insertion of the pedicle screw. Both the cannulation of the bore hole and the placement of the screw carry the risk of inadvertent damage to the soft tissue surrounding the vertebra. In either case, the cortical bone of the pedicle would be accidentally breached by the probe or screw. The goal of intraoperative image guidance is to prevent or detect potential breaching of the cortical bone and misalignment of the bore hole or pedicle screw before serious damage occurs.

Existing intraoperative image guidance systems for spinal fusion surgery include two-dimensional (2-D) and three-dimensional (3-D) fluoroscopy and infrared-based stereotactic guidance systems. Some of the difficulties and problems arising from the use of various surgical assist devices and imaging modalities have been previously summarized (Mujagić et al. 2008). Specifically, the use of ultrasound for intraoperative guidance in this field has been limited by the special problems caused by the high scattering and attenuation of trabecular and cortical bone. Despite these difficulties, recent studies have endeavoured to use ultrasound for spinal fusion surgery guidance. Kantelhardt et al. (2009a, 2009b) recently demonstrated intrapedicular imaging using a 20 MHz intravascular ultrasound probe catheter. The catheter is placed into the bore hole and used to obtain B-mode cross-sectional images from within the pedicle. Due to the high frequency, the reflection of the ultrasound

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beam from the inner wall of the trabecular bone is near total. This prevents the ultrasound beam from penetrating any significant distance into the trabecular bone, thereby preventing imaging of the cortical wall.

It should be noted that several patents have been granted for the use of ultrasound guidance in spinal fusion surgery. One of these (Goodwin 2005) describes an ultrasound method for detecting the difference between trabecular bone, cortical bone and soft tissue using the difference in acoustic impedance and echogenicity between the tissues. A second patent by Sproul (2004) describes how an ultrasound probe can be integrated into the cannulation probe. However, experimental data showcasing the application of these inventions has been lacking.

We have also been investigating the use of ultrasound imaging for this application. Earlier research focused on using through-transmission measurements to study the attenuation and speed of sound in trabecular bone (Mujagić et al. 2008). This research resulted in the fabrication of the 3.2 MHz prototype probe shown in Figure 2, which was designed for intrapedicular imaging. This same transducer was used in the current experimental investigations.

A major determinant of the ability to transmit ultrasound through trabecular bone is the bone volume. This is defined as the percentage of the trabecular bone occupied by trabeculae rather than by bone marrow. The bone volume varies greatly between individuals and depends on many factors, including age and incidence of bone diseases such as osteoporosis. The effect of bone volume on ultrasound propagation has been extensively studied. For example, both the attenuation of the ultrasound beam and the speed of sound have been shown to increase as bone volume increases (Bossy et al. 2007; Mano et al. 2007; Padilla et al. 2005; Anderson et al. 2008). Furthermore, trabecular bone has been shown to exhibit both positive and negative dispersion at different bone volumes (Anderson et al. 2008). Because attenuation and dispersion have an important influence on the image quality, obtaining a quantitative understanding of their behaviour as functions of frequency and bone volume is important. Such an understanding is especially significant in the development of an ultrasound probe system that can be used to successfully guide the placement of pedicle screws.

The purpose of this article is to illustrate the image quality that can be obtained with a prototype probe on *in vitro* human pedicles as well as to examine the effects of the bone volume of the trabecular bone and the frequency of the ultrasound transducer on image quality and accuracy. The presentation is divided into two parts. In the first is described a computer simulation model of trabecular and cortical bone imaging based on 3-D micro-CT measurements of a vertebra. Its purpose was to provide insight into the effect of increasing transducer frequency and bone volume on image quality, namely the visibility of the trabecular and cortical bone and the accuracy with which the position of the cortical bone interface could be estimated. The second part describes the results of *in vitro* experiments using a prototype 3.2 MHz ultrasound probe to form B-mode images from within human pedicles.

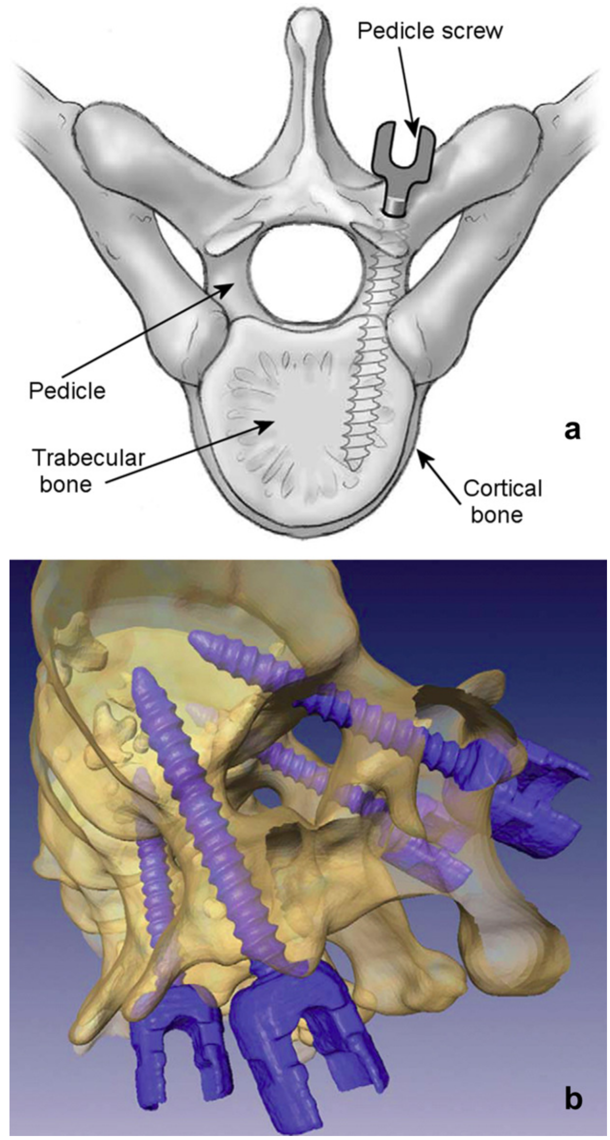

Fig. 1. Pedicle screw insertion. (a) The screw extends from the posterior arch through the pedicle and into the vertebral body. Modified version from Hartl et al. (2004), reproduced with permission from Elsevier. (b) Pedicle screws as visualized in the pedicles of L2 and L3 lumbar vertebrae. The right L2 screw is seen to violate the pedicle medially, while the other three screws are clearly shown to be entirely within the pedicle.