Published in final edited form as:

Ultrasonics. 2011 April ; 51(3): 253–257. doi:10.1016/j.ultras.2010.10.008.

Proof of Concept: In Vitro Measurement of Correlation between Radiodensity and Ultrasound Echo Response of Ovine Vertebral Bodies

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Abstract

An acoustic guidance method for pedicle screw placement during spine fixation surgery was recently investigated, with a view toward preventing complications such as injury to the spinal cord, thecal sac, and spinal nerve roots due to screw misplacement. The method relies upon the change in the ultrasound amplitude reflected at different sites—from the outer posterior cortex, through the pedicle, and toward the distal ventral cortex. The amplitude change was empirically observed through in vitro measurement of ultrasound amplitude at the different sites by inserting a 2.5-MHz single element transducer into a vertebral body through insertion pathway created by an advancing screw. This paper provides a theoretical and experimental rationale behind these empirical findings and distance-dependent correlation coefficients between amplitude and bone mineral density within the vertebral body, which approached 97%.

Keywords

Acoustic devices; Pedicle screw; Spine fixation surgery; Ultrasound guidance

INTRODUCTION

Major complications can occur in pedicle screw fixation surgery when a screw is misdirected within the pedicle or advanced too far. These complications include injury to the spinal cord or to the spinal nerve roots [1], [2]. Recently, we proposed a guidance method that could be used to reduce the incidence of these complications [3]. The method exploited the empirical finding that ultrasound amplitude changed at successive measurement sites along the insertion pathway of an ultrasound transducer—from the outer posterior cortex, through the pedicle, and toward the distal ventral cortex of the vertebral body. From in-vitro

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experiments with ovine vertebral bodies, it was shown that the initial measurement of ultrasound backscatter amplitude reflected at the outer posterior cortex was the highest among the values measured at inside of vertebral body. As a 2.5-MHz single element transducer was advanced into the interior marrow, the amplitudes tended to be decreased from the highest one by a factor of 3 at least. As the transducer tip site approached the distal ventral marrow-cortex interface, the ultrasound amplitude was increased again. The ratio of ultrasound amplitude measured at the interior marrow to that at the marrow-cortex interface was larger than 2.25. Knowing these high-to-low-to-high changes in ultrasound amplitude along the screw insertion pathway makes it possible to anticipate the approach of the ventral cortex. From the experiments with 10 vertebral bodies, the approach of the marrow-cortex interface within 1.5-cm distance could be detected when three consecutive increases in ultrasound amplitude, measured at 5 mm increments, occurred. This can serve as a criterion to alert the surgeon to stop any further advancement of the screw, and thereby prevent a distal perforation of the ventral cortex.

In this paper, a theoretical and experimental rationale behind these empirical findings is presented. It will be shown that the amplitude change along the insertion pathway of an ultrasound transducer is closely related to bone mineral density within the vertebral body. This will be verified by in vitro measurement of distance-dependent correlation coefficients between radiodensity and ultrasound amplitude of ovine vertebral bodies

THEORY

The anterior and center areas of vertebral body exhibit a trabecular structure, i.e., cancellous bone that has a spongy network of very thin bone layers mixed with soft tissue and blood. In the transition from marrow to cortex (i.e., the marrow-cortex interface), the spongy network of thin bone layers becomes much denser and the bony structure becomes more regular in shape [4]. Therefore, cancellous bone has different acoustic properties — the sound speed and the attenuation coefficient — compared with general bone. For example, while the sound speed in skull bone is generally about 3360 m/s [5], the speed in cancellous bone ranges from 1500 to 2000 m/s depending on the anatomic orientations of cancellous bone and on the employed estimation methods (i.e., phase-speed or transit-time measurements) [6]. This can be explained by the fact that cancellous bone is a composite material consisting of bone mineral and blood in its interstices. This is the reason why its overall elastic properties such as density are considerably different from skull bone. In particular, a change in density, ρ , proportionally affects the acoustic impedance ($\text{kg/m}^2\text{-sec}$, or Rayl) of cancellous bone expressed as $Z=\rho c$ where c is the sound speed. From measurement data of the sound speeds and acoustic impedances in blood and skull bone [5], the density values can be estimated: 1039 Kg/m^3 in the case of blood and 1786 Kg/m^3 in skull bone. As a result, when cancellous bone contains a higher amount of blood in its holes, the overall density becomes lower, as does the associated acoustic impedance.

Once an ultrasound wave encounters an interface between two media with different acoustic impedances, the part of energy carried by the original wave is reflected at the interface and the rest penetrates it. The magnitude of the reflected wave is determined by difference between the acoustic impedances of two media [4]. The pressure reflection coefficient indicating what amount of pressure, p_R , is reflected as a percentage of the original pressure, p_I , is expressed as

$$R = \frac{p_R}{p_I} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \quad (1)$$

where the incident angle is zero degree, Z_1 is acoustic impedance of a medium in which ultrasound is propagating before meeting the interface of another medium with acoustic impedance Z_2 .

If ultrasound is transmitted into a vertebral body immersed in water, Z_1 is the acoustic impedance of water, 1.48 MRayl and Z_2 is the acoustic impedance of the vertebral body; Z_2 is proportionally related to the fractional density of bone mineral in the vertebral body. The value for Z_2 may vary with a change in the measurement spot, which can be the location of an ultrasound transducer advanced into a progressively deepened hole created inside the vertebral body. The values would be expected to be close to the acoustic impedance of blood, 1.61 MRayl, when an ultrasound transducer reaches to the central marrow of vertebral body. At the more distal ventral marrow-cortex interface, on the other hand, the impedance may be similar to that of dense bone such as skull bone (acoustic impedance of 6 MRayl [5]).

Consequently, the pressure reflection coefficient expressed in (1) changes along with different acoustic impedances, Z_2 , of vertebral body that is directly associated with the fractional density of bone mineral. From this, we conclude that if a measurement spot is composed of a relatively larger amount of blood than bone mineral, the acoustic impedance will be lower; moreover, ultrasound reflected from the spot will have a lower amplitude level than that from dense bone. In general, at each depth within vertebral body, we would expect the backscatter amplitude levels to be significantly correlated with bone mineral densities.

METHODS

To experimentally verify the hypothesis, two ovine lumbar vertebral bodies were used because these are anatomically similar to the human spine in the lumbar region. The vertebral bodies were scanned by a 3-D micro-computerized axial tomography (CAT) at the University of Southern California Molecular Imaging Center, Los Angeles, USA. The 3-D micro-CAT scan reconstruction was performed at 100- μ m resolution with a cone beam reconstruction array in 750 acquisition steps. Total reconstruction voxels were 768×768×512 (voxel size of 0.105036 mm). Micro-CAT bone radiodensity measurements were made in Hounsfield Units (units of X-ray attenuation) with the following scale: air, -1,000; water, 0; compact bone, +1,000. Six regions of interest (ROIs) were selected sequentially along the drilled pathway. At the ROIs, the ultrasound backscatter amplitude and the mean micro-CAT scan bone mineral density were measured. Fig. 1 shows a representative 3-D micro-CAT image with the six divided areas along the insertion pathway.

Acoustic measurement was conducted in a water bath as shown in Fig. 2. To measure ultrasound amplitude at each depth within the vertebral body, an initial hole in the cortex was created with the drill shaft angled 45 degrees (relative to the anterior-posterior plane) toward the ventral (anterior) cortex and the cylindrical cavity was deepened with a flat-bottom drill (Irwin Industrial, Inc., Wilmington, OH, USA) until the depth was about 6 mm. Particulate bony debris were intermittently removed as needed after each step. In the experiment, a 2.5-MHz focused single element transducer (E1400; Valpey Fisher Corp., Hopkinton, MA, USA) was used to acquire echo signals from the interface between water and cancellous structure inside the vertebral body. Since typical pedicle screws have a diameter ranging 5 to 8 mm, an ultrasound transducer should be comparable in diameter to the pedicle screws. Note that in practice, a transducer should have a diameter less than that of typical pedicle screws (which will be explained later). In addition, because the proposed method is based on acoustical measurement of the fractional density of bone mineral that is regarded as a lumped acoustic mass, it is desirable that transmitted beams are focused on a

measurement site and the focal area is large. This means that a measurement transducer should be focused and its operating frequency should be as low as possible. From these reasons, we chose the 2.5-MHz focused single element transducer with 3.8 mm-diameter face recessed 1 mm within the casing and a focal length of 6.35 mm, which is commercially available.

Since the focal length of this transducer was 6.35 mm and the aperture was recessed by 1 mm from the end of casing, it was easy to position the focal area around a measurement site if the transducer was advanced by 5 mm. For this, we marked on the casing of the transducer at 5 mm increments. Therefore, the transducer could be manually advanced into the deepened cavity in 5 mm increments and excited to generate ultrasound by using a pulser/receiver analyzer (5900 PR; Panametrics Inc., Waltham, MA, USA). Subsequently, echo signal reflected from a water-cancellous structure interface was recorded through a digital oscilloscope (LC534; LeCroy Corp., Chestnut Ridge, NY, USA). On receiving, a high-pass filter with a cutoff frequency of 1 kHz and a low-pass filter with a cutoff frequency of 20 MHz were used for the purpose of noise suppression. Before recording, echo signals were amplified by 40 dB through a built-in preamplifier inside the pulser/receiver analyzer. After the first measurement, the cylindrical cavity was deepened again by 5 mm and the same procedure for acoustic measurement was followed. The process of deepening the cavity in 5 mm increments followed by a corresponding acoustic measurement was performed until the advancement of the flat-bottom drill reached at the distal ventral marrow-cortex interface.

EXPERIMENTAL RESULTS

Measured radiodensity values of each ROI indicated in Fig. 1 are summarized in Table I. As seen from Table I, radiodensity was the highest in the ROI 1 where the dense outer posterior cortex was included. The value decreased in the less-dense marrow and increased as the transducer approached the distal ventral cortex. This trend is similar to the changes of levels of reflected ultrasound acquired at the successive measurements as shown in Fig. 3. The first measurement was performed after the flat-bottom drill created an insertion pathway in the sample by a depth of 6 mm. In the measurement, the focal depth of the transducer was placed just beyond the interface between water and cancellous structure and only one echo signal from the interface was received. After acquiring the echo, the flat-bottom drill deepened the hole by 5 mm and subsequently the pulse-echo measurement was carried out again. Note that since the distance between the transducer and the measurement site was always same in each measurement, the echo appeared on the oscilloscope after the same time of flight, i.e., about 8 μ s. The measurement results were composited into a single figure (i.e., Fig. 3) after normalized with their maximum magnitude by taking into account of the depths of the measurement sites.

A correlation coefficient between the radiodensity values and ultrasound amplitudes was calculated using MATLAB (MathWorks Inc., Natick, MA, USA). For this, the peak level of ultrasound amplitude at each waveform in Fig. 3 was measured. In the case of radiodensity values, the value of the ROI 1 was discarded because not only did it contain the dense outer posterior cortex, but also acoustic measurement was started at the depth of about 6 mm from the outer posterior cortex. Therefore, six values of ultrasound amplitude and five values of radiodensity were available to compute a correlation coefficient. Since the computation of a correlation coefficient requires the same number of samples, the samples were interpolated and the results were normalized with their maximum values as shown in Figs. 4 and 5. The correlation coefficient of the sample 1 was 0.97 and that for the sample 2 was 0.92. This agreed well with our hypothesis that the levels of amplitude measured at each depth of the vertebral body should be significantly correlated with bone mineral densities at the each depth. In fact, this result is reasonable because the relative change of bone mineral densities

(dashed line in Fig. 4) is closely associated with the relative change of acoustic amplitude (solid line in Fig. 4) along depth as explained in the Theory section. In other words, the lowest bone mineral density among measurement values means that cancellous bone contains the highest amount of blood and thus the acoustic impedance of the composite material consisting of the bone mineral and the blood comes close to that of water. From Eq. (1), therefore, the ultrasound amplitude reflected from the measurement site should be the lowest.

DISCUSSION AND CONCLUSIONS

The measured close relationship between the levels of ultrasound amplitude and the bone mineral density inside vertebral body is consistent and most encouraging. It lends support to the prospect of developing an ultrasound transducer-based approach for monitoring the screw position, particularly when the marrow-cortex interface is being approached. Such an approach may be a useful tool in preventing complications such as injury to the spinal cord, thecal sac, and spinal nerve roots due to screw misplacement during pedicle screw fixation surgery.

In fact, there was an attempt to utilize A-mode ultrasound signals for the purpose of pedicle screw guidance [6]. In the feasibility study of this method, an aluminum reflector (i.e., a strong reflector) was placed in the opposite side of a transducer used to transmit and receive ultrasound. By doing so, a high amplitude echo was obtained from the interface between water and cancellous bone as well as the aluminum reflector and cancellous bone, compared to that inside cancellous bone. If the sound speed inside cancellous bone is known, therefore, its thickness can be calculated from the A-mode signal. However, this method has two weaknesses in the clinical use. First, it may be hard to obtain echo signals from the distal ventral cortex in practical situation. Although a flat aluminum reflector was used in the in-vitro experiments to model a boundary between cancellous bone and cortical bone, in practice, ultrasound transmitted from a transducer can hardly reach to the distal ventral cortex. This is because the transmitted ultrasound is mostly reflected from the outer posterior cortex. In addition, the distal ventral cortex is not as much flat as the aluminum reflector, which possibly causes ultrasound reaching the distal ventral cortex to be scattered. The second weakness is that this method requires the accurate sound speed of cancellous bone to estimate its thickness with A-mode signals obtained. However, the sound speed varies with specimens. Since it is difficult to measure the sound speed of cancellous bone in vivo, the thickness may be inaccurate in practice.

On the other hand, the proposed method relies upon the change in the ultrasound amplitude reflected from an interface between water (or blood) and cancellous bone (or distal ventral cortex). This is possible because the amplitude of echo signals can be measured at each depth of pedicle screw advancement. After advancing a pedicle screw by a certain depth such as 5 mm, ultrasound amplitude reflected from the interface between water and cancellous bone can be measured. When at every advancing step the measurement is carried out, we can obtain the change in the ultrasound amplitude reflected from the each measurement site. Since ultrasound amplitude becomes higher as the measurement site approaches toward the distal ventral cortex compared to the center of cancellous bone, the amplitude change can be used for the purpose of pedicle screw guidance.

In the conventional pedicle fixation surgery, the pedicle is cannulated by either a power dental burr or an awl and then the largest possible pedicle screw is inserted into the hole on the pedicle [7]. Therefore, if a cannulated screw to accommodate an ultrasound measurement transducer is available, the proposed method can be viable. As a first step, for instance, an initial hole is created by a power dental burr as same as the conventional

method, of which depth is about 6 mm. The cannulated screw, in which an ultrasound transducer is tucked as shown in Fig. 6, is inserted into the hole and the pulse-echo measurement is performed. After the measurement, the transducer is drawn out and the power dental burr is inserted into the cannulated screw to deepen the hole by a certain depth, e.g., 5 mm. This drilling and pulse-echo measurement procedure is repeated until either the amplitude of the measured echo signal becomes about 2.25 times larger than the smallest value or three consecutive increases in ultrasound amplitude is observed when the measurement is performed at 5 mm increments [3]. In fact, the decision criterion was made from the experiments with ovine vertebral bodies. For the practical application of the proposed method, the criterion should be confirmed by in-vitro experiments with the human vertebral bodies.

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Fig. 1.
Representative 3-D micro-CAT image indicating the six divided areas for bone mineral density measurement.

Fig. 2.
Experimental arrangement to measure ultrasound reflected from the interface between water and cancellous bone.

Fig. 3.

Reflected ultrasound acquired at successive measurements in 5-mm distance increments each time that the flat-bottom drill created a progressively deeper insertion pathway in the sample. The ultrasound was measured at each measurement spot and individually recorded. The measurement results were composited into a single figure.

Fig. 4. Normalized magnitude of measured ultrasound amplitudes and radiodensity values along the insertion pathway in the sample 1.

Fig. 5. Normalized magnitude of measured ultrasound amplitudes and radiodensity values along the insertion pathway in the sample 2.

Fig. 6. Conceptual sketch of the A-mode ultrasound guidance; a cannulated screw accommodating an ultrasound measurement transducer is used to perform the drilling and pulse-echo measurement procedure.

Table 1

Radiodensity values (Hounsfield Units, HU) in each region of interest (ROI) measured by the Micro-CAT.

	ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6
Sample 1	325.4	162.0	124.4	181.0	178.2	255.9
Sample 2	252.2	85.8	70.6	102.2	112.6	196.2