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Intraosseous monitoring and guiding by ultrasound: A feasibility study

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ABSTRACT

An efficient method for navigation within bone tissue boundaries is essential for performance of surgical procedures, e.g. without damaging of adjacent vulnerable organs. The application of sonographic measuring methods for this purpose promises to be effective in the ability to distinguish soft trabecular bone from dense cortical bone, owing to an order of magnitude difference in acoustic density between these structures. For this purpose, a specific method was developed that utilizes propagation of a 5 MHz ultrasonic wave through an aqueous milieu. Using this method a 0.2 mm resolution in measurements is achieved. This resolution is in an order of magnitude lower than is required for a clinical use. A three-stage experimental approach was adopted: measurements in a cubic "phantom" made of a transparent plastic material, in samples of fresh porcine femora, and in a clinical setting of drilling in the upper and lower jaw during dental implantation surgery in nine patients. Two patterns of the detected ultrasound wave reflections were found: low amplitude reflections from the aqueous surrounding and trabecular bone and highly reflected ultrasound waves from the cortical bone. We show that trabecular and cortical bones are distinguishable by real-time ultrasonic measurement. The distances of the drilled tracts, in the range of 58.0–122.0 mm for the "phantom" experiment, 22.6–35.5 mm for the ex vivo experiment and 10.0–11.5 mm in the clinical experiment, and residual distances to the opposite edge of the tested samples and organs, in the range of 21.0–82.0 mm for the "phantom" experiment, 3.8–11.36 mm for the ex vivo experiment and 2.1–6.9 mm in the clinical experiment, were measured by the presented sonographic method and compared statistically, using linear correlation and Bland Altman plot, to the mechanical and/or radiographic measurements in all three stages of the experiment. A correlation coefficient above 0.95 was considered an indication of high correlation, while a value of 0.75–0.94 was considered intermediate, and a value below 0.75 was considered poor.

A very high correlation ($p < 0.001$) and agreement between the sonographic and the "gold standard" measurements techniques, either mechanical or radiographic depending on the experimental setting, were found. Therefore the presented method of intraosseous sonographic measurements may provide an improved method for the monitoring of intraosseous drilling in respect of the currently used mechanical and/or radiographic clinical methods.

1. Introduction

An efficient method for monitoring and navigating bone tissue boundaries is essential for the safe and precise performance of surgical procedures involving extremities and the spine, and in maxillofacial surgery. For this purpose, the ability to distinguish soft trabecular bone from dense cortical bone is highly desirable. Currently, this distinction is based on surgical skills and recognition of the three-dimensional shape of the treated bone, with the aid of real-time fluoroscopy. Because this method can cause penetration of bony boundaries by metal hardware (Fig. 1), a more accurate method for the monitoring of intraosseous drilling that will avoid penetration of the outer bone boundaries is desirable. Recently, a new approach has been introduced for three-dimensional intraosseous navigation, based on radiological registration by plain X-ray imaging or by computerized tomography [1]. This method showed high navigation accuracy of most navigation systems aiming to at most 1 mm when targeting a single point and 1° when targeting a line or resection plane. When operator error is included, the accuracy of most systems is likely 2–4 mm for a targeted point and between 1° and 3° for a targeted trajectory [2]. However, despite the effectiveness of this navigation method, it usually requires sophisticated equipment and specially trained personnel who are not always available for broad clinical application. Therefore, a low cost and easily handled method for intraosseous surgical monitoring and guiding should offer an important additive value.

The use of ultrasonographic real-time measurement or imaging for this purpose may be effective if sufficient resolution between cortical and trabecular bone tissue can be achieved. We suggest

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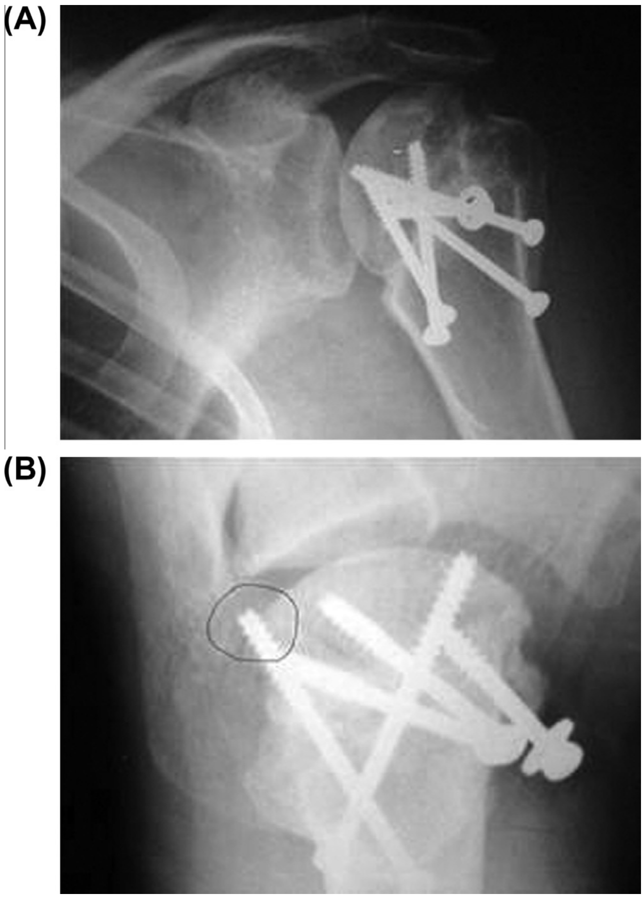

Fig. 1. (A) Radiograph of left shoulder (anterior–posterior view) following internal fixation of fracture at the surgical neck, fixed by metal screws. All the screw tips are seen inside the boundaries of the cortical, which is the outer dense bone boundary, and subchondral bone, a layer of dense bone tissue that is situated below and supports the cartilage cover of an articular surface of a head of humerus, i.e. long bone of arm. (B) Radiograph of the left shoulder of the same patient (axillary view). The tip of one of the screws (marked) is situated out of the boundary of the articular surface of the humeral head. This penetration of the fixating screw is obscured on the standard anterioposterior view shown in radiograph (A).

that this approach should be feasible as these tissue types are distinct in their microstructure and biomechanical characteristics. Cortical bone has a constant matrix density of 2 g/cm^3 with a maximum porosity of 5–10% [3]. Trabecular bone, which contains a significant proportion of open porous space filled with liquid bone marrow, has a lower density in the range of 0.2–0.7 g/cm^3 [3,4]. This relatively wide range of densities of the trabecular bone is due to variability in its porosity at different anatomical sites and its dependence on age and gender. The relative volume of the trabecular bone is about 10% of its total containment volume [3]. Therefore, the bone matrix density of the trabecular bone is an order of magnitude lower than in the cortical bone. In the cortical bone, the deposition of the matrix has a lamellar pattern that provides a dense microstructure. The trabecular bone microstructure behaves bio-mechanically as a solid open porous material owing to its high fluid content at around 90%. Therefore, given the difference in density between the compact cortical bone and the porous trabecular bone, the latter ought to allow for propagation of an ultrasound beam in contrast to the acoustic shielding of the former. This difference in acoustic density should provide effective contrast between the central trabecular bone and its cortical boundaries for measurements or imaging of the locations of these boundaries. In this report we describe a method for clear imaging separation between trabecular and cortical bone using sonographic scanning.

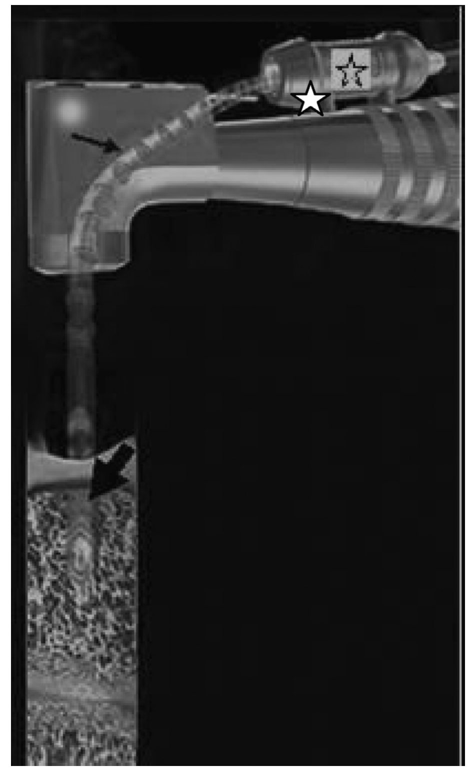

Fig. 2. A schematic representation of ultrasound measurement device. The ultrasonic waves from the ultrasonic transducer (☆) are propagated through a jet of water (thin arrow) into the drilled tract in bone (thick arrow) and reflected back via the same jet into the signal procession device (☆).

2. Methods

2.1. Ultrasound device components

Measurements are performed in the reflection mode by use of a single transducer in both transmit and receive. The method utilizes propagation of a 5 MHz ultrasonic wave through an aqueous milieu. This measuring system comprises a cell, an electronic unit and a display.

The cell comprises an ultrasound transducer (RI-4513-SCB, Piezo Technologies, Indianapolis IN, USA) installed in a suitable compartment and exposed to a fluid flow. This fluid is supplied to the cell from a pressurized reservoir via a flexible plastic tube (inner diameter: 4 mm; outer diameter: 6 mm; and length: 1.5 m). The flow output (the "free jet") is maintained as laminar. The transducer operates in pulsed mode in the range 3–8 MHz. We used frequency of 5 MHz, pulse duration is 5 ns. The frequency of the ultrasonic beam was defined empirically when the least attenuation with the higher resolution was observed. Using this method a 0.2 mm resolution in measurements is achieved. This resolution is in order of magnitude lower than is required for a clinical use.

The electronic unit consists of a transmitter sub-unit (JG-TR-05-01, JetGuide Ltd., Haifa, Israel, receiver sub-system (JG-REC-05-01, JetGuide Ltd., Haifa, Israel) and a signal processor sub-system (JG-DSP-05-01, JetGuide Ltd., Haifa, Israel). Since the same transducer is applied for transmitting and receiving the signals, a diplexer sub-system (JG-DIP-05-02, JetGuide Ltd., Haifa, Israel) was