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Improved ultrasound-based navigation for robotic drilling at the lateral skull base

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Abstract. Sensitive structures of the lateral skull base demand for robotic procedures a higher precision than provided by standard navigation systems relying on CT scans. Keystone of our multisensor approach to improve accuracy is the use of ultrasound for local navigation. In this study we compare two different ultrasound techniques to measure human skull bone in vitro: (A) the classic echo technique and (B) a combination of "coded excitation" and "matched filter" Technique B showed to be very useful by improving accuracy and practical penetration depth of the ultrasound. Sound velocity showed to be highly variable in the specimens. We therefore suggest sound velocity measurements during surgery. © 2004 Published by Elsevier B.V.

Keywords: Medical robotics; Navigation; Lateral skull base; Ultrasound

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1. Introduction

Robotic surgery at the lateral skull base demands a highly accurate navigation. Sensitive structures as the dura mater, the inner ear and the facial nerve must not be damaged [1]. Standard navigation systems rely on CT scans with an insufficient accuracy [2]. Our approach to increase accuracy is a multisensor-based local navigation which could be used as a stand-alone system or in combination with classic navigation based on CT or MRI. Sensors register force, torque and temperature, but keystone of the local navigation system is the use of ultrasound. We plan to use it in two ways: (1) At the beginning of the intervention to obtain a local, three-dimensional map for a preliminary planning of the drilling. For this the transducer is moved by the robot to scan the region of interest and its surroundings. (2) The accuracy of the map obtained is not sufficient for highly precise tasks. Tissue shift is of minor importance for osseous structures.

In former studies, we already investigated advantages and disadvantages of ultrasound transducer frequencies in acoustic properties of the human skull bone [3].

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The aim of this study was to determine if the combination of coded excitation and matched filter could improve accuracy and penetration depth of ultrasound measurements, and to evaluate the effects of contact and non-contact measurements.

2. Methods

Sixteen human skull bone specimen fixed in formaldehyde were prepared. The specimen derived from whole body donators, and this study was approved by the Board on Ethics of the Saarland, Saarbrücken (G). Thickness was measured mechanically (caliper rule, accuracy: 0.01 mm) and compared with the sonographic results. We used a one-dimensional ultrasound transmission system in water in the amplitude mode (A-mode) as shown in Fig. 1. We used a transducer (Panametrics , Ultran) with a frequency of 2.25 MHz and a sound wave form generator with D/A transformer 12 bit/100 MHz with a pulse repetition rate of up to 2 kHz. The receiver was open for 0.1–30 MHz bandwidth and a dynamic range of 100 dB. The measurements of the skull bone were performed in a non-contact mode with the transducers not touching the specimen when immersed in water at three distinct points for each specimen. As the surface of the skull bone in this region is not plane but slightly curved, the sound beam was always directed perpendicular to the specimen. The echo received was displayed graphically on a monitor as raw hf-data and after calculation of the cross-correlation. The examiner had to identify and to mark manually the entrance and exit echo. The thickness was calculated by the time difference of these two values and the mean sound velocity known from former experiments (2592 m/s). Two different sonographic wave forms were used: a simple pulse (“classic pulse” frequency 2.25 MHz, duration 0.4 μs) and a chirp (“coded excitation”, frequency 1–4 MHz, duration 2 μs). The echo of the latter was additionally processed by a filter enhancing the pattern of the chirp (combination of coded excitation and matched filter).

In a second step, the measurements were repeated with the coded excitation technique in a contact mode, the transducer being directly attached to the specimen.

3. Results

The use of cross-correlation calculations showed to be essential for the interpretation of results of “classic pulse” and “coded excitation” measurements. Often only

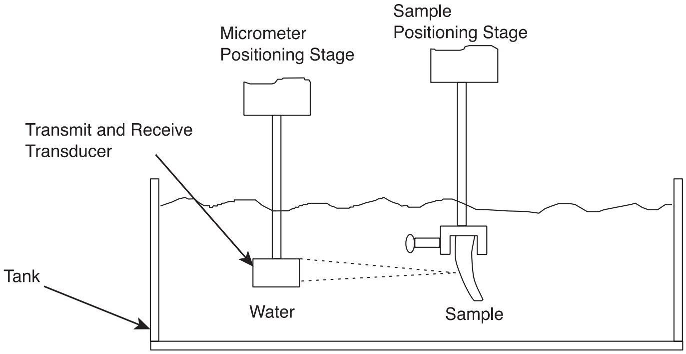

Fig. 1. Measurement of bone specimens of the lateral skull base in water.

this technique allowed to determine entrance and exit points from the noise of the echoes (Fig. 2). The "coded excitation" in combination with a matched filter reduced noise even more and sharpened the echo peaks (Fig. 3). By this attenuation did comprise data interpretation become less. Only 60% of echo patterns for the classical pulse method could be interpreted and included in statistics, while all data obtained by the coded excitation method allowed the clear detection of entrance and exit peaks.

In comparison to the mechanical measurement the calculated thickness of the bone for the classical pulse technique had a mean error of 18% (S.E.M. ± 5%) and for the coded excitation technique of 16% (S.E.M. ± 5%). Calculation of the mean sound velocity for human skull bone from this data shows a striking difference in comparison to our result from former experiments (2921vs. 2592 m/s).

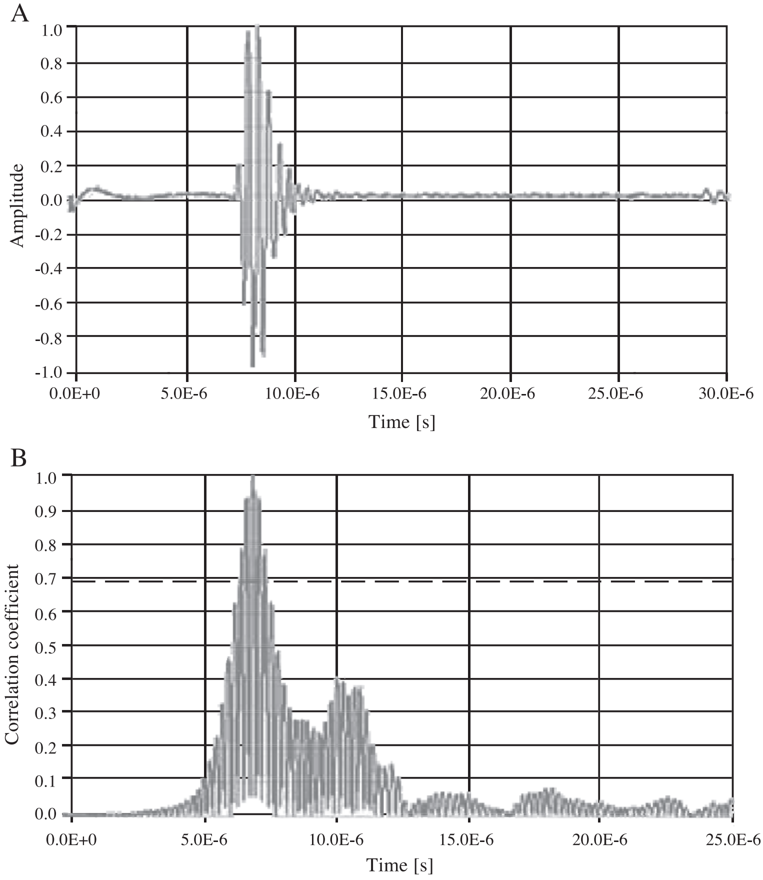

Fig. 2. Echo of a "classic pulse" measurement of a bone presented as raw data (A) and as correlation coefficient (B). The big first peak presents the reflection of the sound wave from water to the bone, the second peak the exit from bone to water.

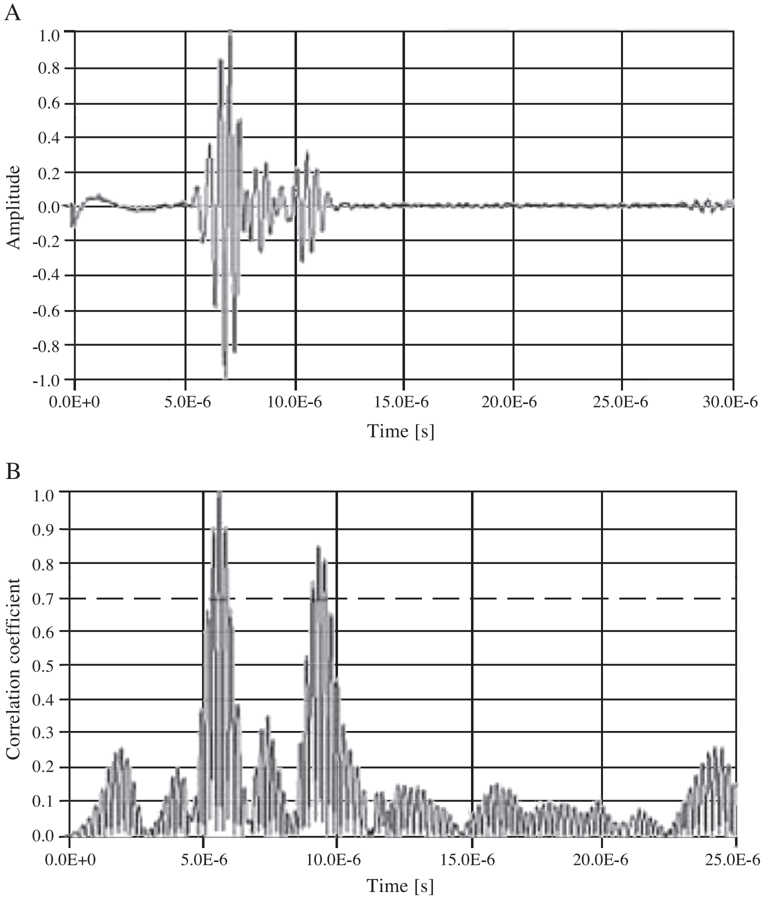

Fig. 3. Echo of a "coded excitation" measurement of a bone presented as raw data (A) and as correlation coefficient (B). Note that entrance peaks are similar to "classic pulse" technique but that exit peaks are a lot easier to identify.

By measuring bone thickness in a contact mode the mean error could be reduced for the coded excitation technique to 14% (S.E.M. ± 4 %). Calculated sound velocity for this technique was 2995 m/s.

4. Conclusion

Accuracy of ultrasound for navigation of the lateral skull base can be improved by the combination of coded excitation and matched filter in comparison to classic procedures. At the same time, this technique reduces the effects of attenuation by diminishing noise in the sound echo, enabling to measure thicker bones. Sound velocity is highly variable in human skull bone tissue and is technique-dependent. To increase accuracy, we propose to calculate the sound velocity during the operation by repeating measurements of one tissue spot after defined reduction of bone thickness.

Future work will include automated scanning by a robot, automated data interpretation and calculation of a three-dimensional map by a navigation system, transducer arrays, the use of other coded pulse signals to increase accuracy. Ultrasound offers multiple technical possibilities still not evaluated and is a promising complementary or alternative method to CT/MRT-based navigation even in bony tissue.

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References

[1] P.A. Federspil, et al., Development of the first forced-controlled robot for otoneurosurgery, Laryngoscope 113 (3) (2003 March) 465–471.

[2] A. Wagner, et al., Quantitative analysis of factors affecting intraoperative precision and stability of optoelectronic and electromagnetic tracking systems, Medical Physics 29 (5) (2002 May) 905–912.

[3] P.A. Federspil, et al., Ultrasound based navigation of robotic drilling at the lateral skull base, in: H.E. Lemke, K. Inamura, K. Diu, M.W. Vannier, A.G. Farman, J.H.C. Reiber (Eds.), CARS 2003—Computer Assisted Radiology and Surgery, Elsevier, 2003, p. 1358.