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US detection of CB layer within a TB

J Halevy-Politch[1]*; A Craft[2]

[1]Technion I.I.T., Haifa 32000, Israel.

[2]Mi-Rei Associates, Haifa, Israel.

***Corresponding Author: J Halevy-Politch**
Technion I.I.T., Haifa 32000, Israel.
Tell: +972-4-834-2473;
Email: yapo@actcom.co.il

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Abstract

Background: A thin layer of Cortical Bone (CB) is located in a Trabecular Bone (TB), such as the wrapping around the Mandibular Canal (MC), located in the lower jaw. During an implantation surgery, this thin layer of CB, and the MC can be damaged - what should be prevented also by intraoperative monitoring.

Methods: Ultrasound (US) was applied in this study, enabling to obtain in Real-Time (RT) the distance/depth of the Front-Surface (FS) of a thin CB sample. This depth was measured from the entrance of the US to TB up to the FS of the thin CB.

Results: Small samples of thin CB were inserted at several depths of TB. The depths of the CB samples were measured by the developed US system and it was compared to a mechanical measurement. For most cases, an agreement within less than 2%, was obtained between these measurements.

Conclusion: It was demonstrated that the new US device provides depth information of thin CB sample located in a TB. These US measurements were performed with an accuracy that can prevent a damage to the thin CB during a surgery, or during other invasive treatments.

Keywords: Cortical Bone (CB); Detection; Implant; Trabeculae; Ultrasound (US).

Introduction

This investigation is looking for a detection method of a thin layer of dense material inside a softer one. By providing to such a detection system, also a Real-Time (RT) ability - an Intraoperative (IO) measuring solution is gained. Such cases, of layers with different densities, exist generally in nature; Here we will concentrate in the human body.

The deposition of the matrix has a lamellar pattern that provides the dense microstructure to the Cortical Bone (CB). The cancellous (Trabecular) Bone (TB) microstructure, due to its high fluid content (90%), behaves bio-mechanically as a solid open porous material [1]. The relationship between bone density and its modulus of elasticity is not linear [2], because it depends on the integrity of the trabecular mesh and on the chemical properties of the matrix that can be altered by age and systemic illness.

The mandible (as an example of an organ in the human body), consists of an outer layer of Cortical Bone (CT) (approximate thickness of ~1 mm). The alveolar process is occupied by the roots of the teeth with none or only a very small amount of trabecular bone in tooth bearing areas, while the central part of the mandibular body consists of Trabecular Bone (TB). The bone mass and bone activity in the TB vary with their function [3]. As the function is different in the three regions of the mandible, incisor, premolar and molar, and depending on the state of dentition, a variation in bone structure in the TB within a single mandible would be expected [4,5].

Detection of a thin CB located inside a volume of TB is the case that a surgeon is fronted during an implantation surgery, especially in the lower jaw. Here, there is located, from the anatomic point of view, the Mandibular Canal (MC), surrounded by a thin protecting layer of CB [6-8].

Meticulous treatment planning and increasingly sophisticated diagnostic tools, such as: Conventional X-ray, CT, MRI and various navigational software, are today, the gold standard in implantology [9].

The canal that opens at the mental foramen (mandibular canal), houses the inferior alveolar nerve and blood vessels; it begins at the posterior end of the body of the mandible and runs through the length of it, almost parallel to the lower border [10]. A knowledge of the position of the inferior dental (mandibular) canal in vertical as well as in buccolingual dimensions is of paramount importance during site preparation for implants, where Ultrasonic (US) measuring method was proposed and implemented during appropriate surgical studies [11-13], and similarly in brain and spinal cord, including vertebrae surgeries [14-16].

Material and methods

General

The attention is given here to the Ultrasound (US) reflections, by applying a single US transducer that Transmits (Tr) these signals and Receives (Rc) their echoes. The US propagates through the TB and while impinging the front surface of the CB (denser material), reflections are obtained. These are finally received by the US transducer followed by further amplification, filtering, data processing and finally displayed. The method for estimating the velocity (Speed of Sound = SOS) in TB [17], from transmission, attenuation and reflection processes in TB and pulse-echo measurements, was applied here. The monitoring system measures the time between the transmitted and received signals. For a more accurate measurement, the received US signals were coherently processed [18-21]. Thus, from an apriori knowledge of the SOS in the TB and in the saline solution, the depth of the CB layer was assessed.

The electronic parameters during the experimental measurements

Pulse Repetition Frequency (PRF) = 500 Hz;

The US frequency fUS = 5 MHz

The average was performed on 500 recorded signals.

The US parameters during the experimental measurements

Type of the US transducer: Panametrics, C310, f=5MHz

Transmission US modes: 1, 2 and 6 pulses per burst.

The mechanical parameters during the experimental measurements

Drilled depths in TB: 0, 2, 4 and 6 (mm).

CB within TB was fixed during the above drills.

The depth of CB was chosen to be different at every set of experiments.

Experiments were performed on several TB samples that were from a porcine Hip. A thin and small plate of CB was inserted in the TB at a depth 'A' from its upper surface. A bore of 2 mm (in diameter) was drilled in the TB. This was performed in several samples and in each one of them - at a different depth. Using this method, the upper surface of the CB sample was detected (as its attenuation is high, causing to a secondary reflection to be low) - as described schematically in Figure 1.

Note: All samples of CT and TB were obtained from a slaughter house.

The experimental sample

Figure 1: Describes the geometry of the measured sample that consists of B, with a thin and small plate of CB inserted in it.

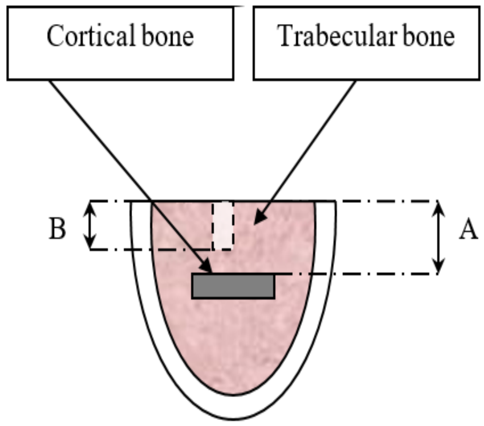

Figure 1: The geometrical set-up of the sample consisted of TB and a thin and small plate of CB inserted in it. The distance **'A'** was different in every set of experiments. Bores at depths **'B'** were drilled in each TB sample.

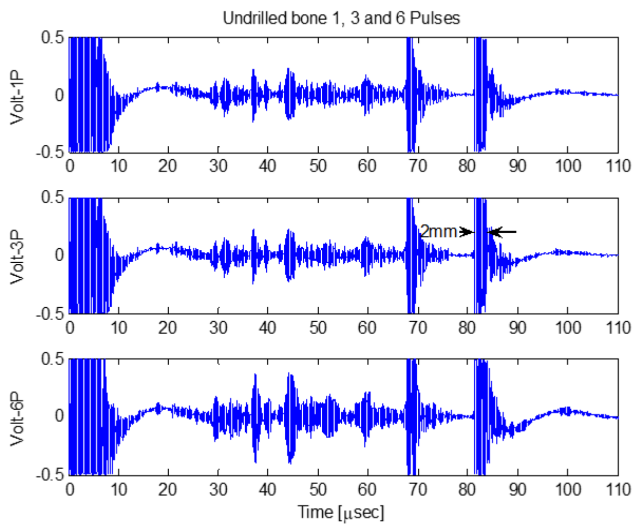

Figure 2: The reflected US signal from the TB sample, without a drilled bore, in which a thin CB sample was inserted. These measurements were performed at 5 MHz, applying 1, 3 and 6 pulses/burst.

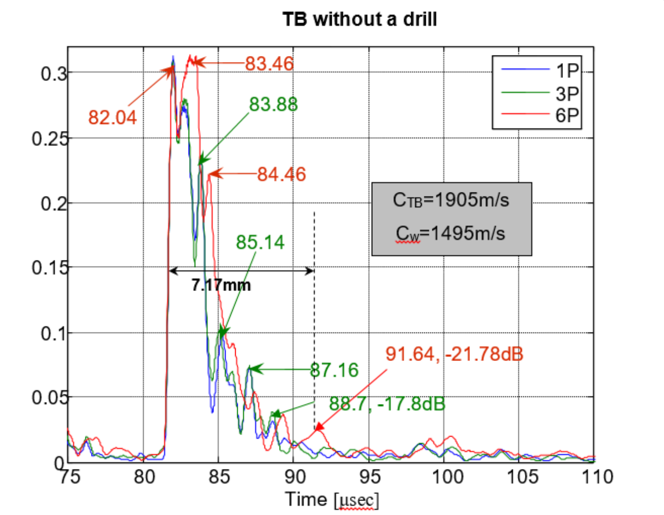

Figure 3: Zooming in time of the reflected US signals, as obtained from the CB sample, inserted in the TB, without a drilled bore in TB. These signals were received at 5 MHz, for 1, 3 and 6 pulses/burst, after coherent processing.

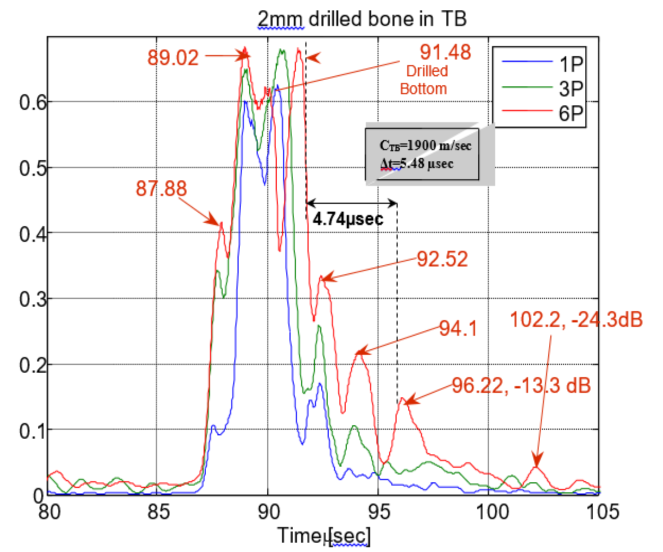

Figure 5: Measured reflections at fUS = 5 MHz, for 1, 3 and 6 pulses/burst. These reflections were obtained from the upper surface of the CB sample, inserted in the TB. The measurements were performed through a drilled bore in TB of 2 mm, filled with saline solution. The graph presents zooming with a coherent processing of the received signal.

Experiments and results

US detection of a thin CB in TB, without a drilled bore in TB

The presented reflections were obtained after coherent processing [18-21] of the detected signals.

The ordinate describes the attenuation [dB] relative to the first peak;

The abscissa describes the time [μsec].

The numbers in colors, describe the peak values, as obtained with time, for each transmission type (i.e., no. of pulses/burst).

Conclusion

Comparison of US to mechanical depth measurements

The depth of the CB (as described in Figure 1), was obtained from US reflections width, as 7.17 mm (as shown in Figure 3); When it was measured mechanically, the CB depth was found to be 7.21 mm. The difference between these measurements is 0.55%, thus enabling US depth measurements of this kind with good reliability.

The attenuation is relative to the first peak, which is in this case -21.78 dB, as shown in the graph of Figure 3, and it provides about 30 dB/cm. As the measurements were performed at 5 MHz, the attenuation can be expressed also, as 6 dB/MHz.

Drilled bore in TB, in depth of 2 mm

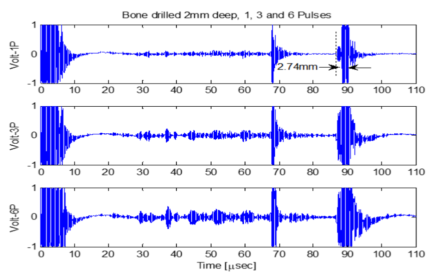

Figure 4: Reflected signals obtained from the front surface of the CB sample, as measured through a drilled bore in TB, of 2 mm in depth (the bore was filled with a saline solution). The US frequency was 5 MHz, in pulsed mode, with 1, 3 and 6 pulses/burst.

The ordinate describes the attenuation (decrease) in dB, relative to the first peak.

The abscissa presents the time [10-6 sec = μsec].

The red numbers describe the time (μsec) and the attenuation (dB) at a certain point.

Drilled bore - comparison measurements: The reflected signal, from the bottom of the drilled bore in TB, was obtained after 1.3 μsec, for a US velocity in saline solution as Cw = 1,495 m/sec. Thus, it provides a distance of 1.944 mm. The difference between mechanically and US measurement of this distance is 2.8%.

The Time of Flight (TOF) from the bottom of the drilled bore in TB to the upper surface of the CB sample (see Figure 1), was 5.48 μsec; For a measured velocity in TB of CTB = 1,900 m/sec, it provides a distance of 5.2 mm.

Accordingly, the total distance, from the entrance of the US signal into the drilled bore, to the upper surface of the CB, is 7.194 mm (US measurement). Mechanically, this distance was found as 7.21 mm. This provides a difference of 0.016 mm, or 0.22%.

Experiment where the TB bore was of 4 mm

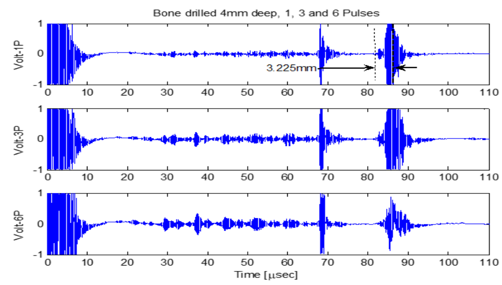

Figure 6: Reflected signals obtained from a CB, through a drilled bore in TB (depth of 4 mm, filled with saline solution). The US measuring frequency was 5 MHz, in pulsed mode, with 1, 3 and 6 pulses/burst.

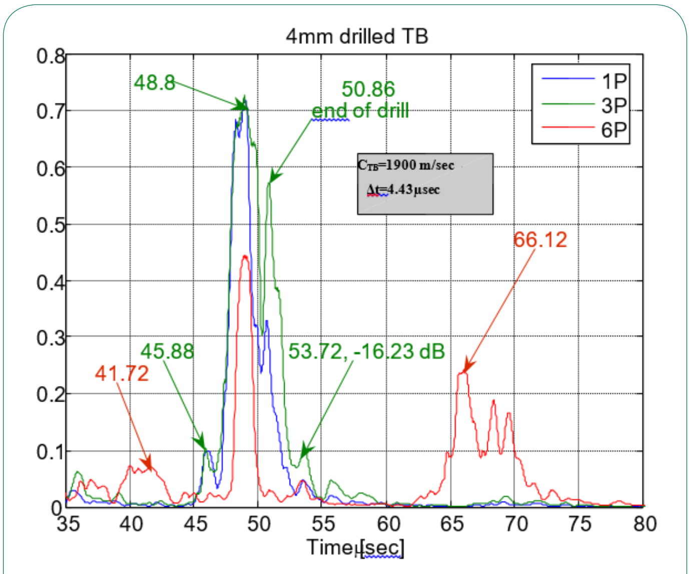

Figure 7: Measured US reflections at 5 MHz, for 1, 3 and 6 pulses/burst, obtained from the upper surface of a CB, inserted in the TB. The measurements were performed through a drilled bore of 4 mm in TB; filled with a saline solution. The graph presents a coherent processing of the received signal with zooming on the region of interest.

Total distance/depth, comparison of US with mechanical measurement: By taking the distance from the bottom of the drilled bore in TB to the upper surface of the CB as

$d_{TB} = 0.5 \cdot \Delta t \cdot C_{TB} = 0.5 \cdot 4.43 \cdot 10^{-6} \cdot 1.9 \cdot 10^3 = 4.2$ mm.

By adding the distance in the drilled bore (filled with a saline solution)

$d_w = 2.1 \cdot 10^{-6} \cdot 1.495 \cdot 10^3 = 3.13$ mm.

Thus, the total depth is

$d_{total} = 4.2 + 3.13 = 7.33$ mm.

Therefore, the difference related to the mechanical measurement is 0.12 mm, or in percentage 1.7%.

The ordinate describes the attenuation (decrease) [dB], relative to the first peak.

The abscissa is the time [μsec].

Red and Green numbers describe the time [μsec], while the Green describes also the relative attenuation (relative to the peak) at the measured point [dB].

Summary

In this work, we were interested to evaluate the reliability of US depth measurement of a thin CB sample that was inserted in the TB. Mechanical measurements were also applied, for comparison purposes.

The 'experimental sample' was designed and built in a way that will simulate the Mandibular Canal (MC) that is wrapped by a thin layer of a CB. There were prepared several 'experimental samples', where the CB was placed in different depths of the TB.

US measurements of the reflected signal were performed, where in all these experiments, the transmitted US frequency was 5 MHz, using a pulsed mode of 1, 3 and 6 pulses per burst.

The received signals by the US transducer, were fed through a calibrated pre-amplifier, to a coherent signal processing circuitry. From there it was fed to the input of the oscilloscope - and on its screen the time-response curves were obtained. On the mentioned screen, were also performed the attenuation and time difference measurements.

The mechanical measurements were obtained by means of a caliper (with a resolution of 10-2 mm) and by a calibrated drill (with graduations of 10-1 mm).

The US and the mechanical measurement were repeated 10 times at every condition, from where their mean value with the Standard Deviation (STD) were assessed.

Table 1: The reflected pulse widths (μsec) for 1, 3 and 6 pulses/burst, as a function of the drilled depth in TB (related to Figures 3, 5 and 7).

Table 1: Summarizes the reflected pulse-widths (μsec), relating to Figures 3, 5 and 7.

Depth of drilled bore in TB (mm)	Reflected pulse width, for 1 pulse/burst (μsec)	Reflected pulse width, for 3 pulses/burst (μsec)	Reflected pulse width, for 6 pulses/burst (μsec)
0	3.1	5.2	6.6
2	4.1	5.5	7.2
4	2.5	3.92	7.08

Without a drilled bore, the width of the main reflected pulse is similar to the transmitted one.

With 2 mm drilled bore, the widths and amplitudes of the reflected signals are similar; although the reflected pulse is wider as the no. of pulses/burst increases.

With 4 mm drilled bore: for 1 pulse/burst the reflection is in the center of the main reflected signal. It is wider for 3 pulses/burst and much more wider (with side-lobes) for 6pulses/burst.

Conclusion

By comparing the depth of the CB sample within the TB, by the US measurement versus the mechanical one, it was found that without a drilled bore in TB: they differ by 0.55%.

By comparing the depth of the drilled bore, between US and mechanical measurements, the difference was 2.8%. This difference was due to the accuracy of mechanical engraving on the drill, which was not better than 0.1 mm.

The total distance/depth, from the entrance to the drilled bore to the upper surface of the CB was 0.22% - for a drilled bore in TB of 2 mm.

The total distance/depth, by comparing US with mechanical measurements (for drilled bore of 4 mm) was 1.7%.

In conclusion, the differences between the obtained results with the US and the mechanical methods, was smaller than 3%.

According to the above conclusion, the US measuring method was applied during clinical experiments in real-time and intra-operatively - thus enabling to obtain better, faster and reliable surgical results [11-16]; Moreover, the patients were safer and also don't accumulate the x-ray radiation.

As for US measuring system, using a single pulse/burst, it provides a satisfying accuracy during the interpretation process; However, if higher energy is required, there exist the possibility to transmit 3 or more pulses per burst, but more attention is required during the interpretation process of the obtained signals, due to the difference in the temporal-coherence signal processing [19-22].

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