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5aBAa8. Computational simulations of time of flight and attenuation of first arriving signal from healing process of diaphyseal femur fractures.

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Quantitative Ultrasound (QUS) has been proposed to evaluate structural conditions from bone tissue in a non-invasive way. These techniques are based on the fact that the ultrasound propagation depends directly of tissues structures, so, they carry information about them. Based on these arguments, the aim of this work was to estimate the time-of-flight (TOF) and attenuation of the first arriving signal (FAS) using computational simulations (Wave2000® CyberLogic, inc., NY, EUA) in an axial transmission model in different kinds of fracture, during the healing process. In this work we used QUS techniques to analyze the fracture healing process. The FAS has been chosen because it does not suffer interference of other waves since it is the first signal to arrive at the receiver. TOF increases immediately after bone fracture. When bone tissue starts to consolidate, TOF decreases and stabilizes with the same value of the intact bone. Attenuation is bigger in oblique and spiculate fracture than transversal ones for the same stage which suggests that attenuation is sensitive to the kind of fracture. Other studies are being conducted to clarify this point.

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INTRODUCTION

In the last years, quantitative ultrasound (QUS) measurements of bone tissue have been attracting the interest of researchers\(^1\). These interests are mainly due to its low cost, portability and absence of ionizing radiation\(^1\). QUS techniques were first proposed to diagnose osteoporosis\(^2\). In recent years, these techniques have shown the possibility to discriminate fracture, as well as the healing stages\(^2,3,4,5\). Among the most common QUS parameters found in literature to evaluate the fracture healing status are the time-of-flight (TOF) and the attenuation of the ultrasonic wave\(^1,2\). In general, waves are sensitive to the medium structures, and during the fracture healing process the bone structure is in constant changing, so these quantitative parameters are expected to change in response to the tissue structural variation.

Time of flight can be defined as the time between the emission and reception of an ultrasonic wave. It is a function of wave speed and therefore directly related to medium properties. The signal attenuation can be defined as the amplitude fall between two distinct propagation positions. It is also dependent on medium characteristics (classically, attenuation is the result of wave absorption and scattering). Another kind of amplitude drop that can be understood as attenuation is due to impedance difference (reflection). The medium impedance is a function of speed and density, two variables that change during the bone healing. It is a convenient definition when studying bone fracture.

The first arriving signal (FAS) is the signal that arrives at the receiver in first place. It carries on information about tissue condition and it does not suffer interference of any other wave. This signal has a relationship with the cortical thickness, and for purpose of this work, this signal is the lateral wave\(^6\). When a spherical wavefront reaches a fluid-solid interface, it is partially reflected and refracted. During this process, the point that connects these two wavefronts makes an angle \(\theta\) with the axis normal to the surface. When this angle reaches the critical one, according to the well known Snell’s Law, a phenomenon closely related to total reflection takes place and the theory predicts the existence of a linear wavefront that connects the refracted and reflected wavefronts. This wave is called lateral wave or head wave\(^6,7,8\).

The objective of this work is to estimate the time of flight (TOF) and attenuation of the first arriving signal (FAS) on different kinds of bone condition using axial transmission axial models with numerical simulations.

MATERIALS AND METHODS

General setup

All fracture-healing geometries were modeled with the commercial software Wave2000\(^6\) (Cyberlogic, New York, NY), using an axial transmission setup. This software solves the wave equation (equation 1) in two dimensions based on a time domain finite difference method.

\[
\rho \frac{\partial^2 w}{\partial t^2} = \left[ \mu + \eta \frac{\partial}{\partial t} \right] \nabla^2 w + \left[ \lambda + \mu + \varphi \frac{\partial}{\partial t} + \frac{\eta}{3} \frac{\partial}{\partial t} \right] \nabla (\nabla \cdot w),
\]

where \(\rho\) is material density, \(w\) is the displacement vector, \(\lambda\) and \(\mu\) are the first and second Lame constants respectively; \(\eta\) and \(\varphi\) are shear and bulk viscosity, respectively.

A rectangle with 180 x 50 mm was used to simulate the region containing the fracture geometries (Figure 1) that are formed by a bone plate (all stages), bone callus (3-7 stages) and water to mimic soft tissue (all stages). The point source and receivers with width of 3 mm were positioned 15 mm above the cortical bone plate, with a 52 mm of separation between the source and first receiver. The source was adjusted to emit a sine modulated Gaussian pulse with duration of 3 \(\mu s\) and center frequency of 1 MHz. The receivers were spaced 1 mm from each other, and were set to produce an output equal to the pressure average at their faces. The grid size and time step were 0.2 mm and 0.00436 \(\mu s\).
The three following fracture geometries were studied in this work: transverse, oblique (30° degrees) and spiculate. Seven healing stages, proposed by Gheduzzi et al., were modeled for each fracture geometry. In the first stage (Figure 2a), a plate with 180 x 10 mm was used to simulate the intact bone, and water to simulate the surrounding soft tissues. In the second stage (Figure 2b), the bone is broken apart, represented by two plates and a 2-mm gap between them (transverse fracture). The inflammation process starts, with blood represented by water. In the third stage (Figure 2c), two Gaussians were used to model the hard and soft callus with 40 and 2 mm of width, respectively, and a 6-mm height. The fourth stage (Figure 2d) represents the initial reabsorption of soft callus by the hard callus. In the fifth stage (figure 2e), the complete reabsorption occurs, including the soft callus in gap. In the sixth stage (Figure 2f) the complete formation of bone takes place, and the last stage (Figure 2g) represents the callus remodeling, modeled by a Gaussian with 20-mm width and 3-mm peak. Figure 2h and 2l represent the second stage of oblique and spiculate fractures, respectively.

**Signal Processing**

A routine algorithm was implemented in Matlab® (MathWorks Inc., Natick MA) programming environment to detect FAS amplitude and time-of-flight. The first peak was used as the reference point (Figure 3). The software uses the derivative concept to find the first signal peak and returns its amplitude and time coordinates.
FIGURE 3. Example of signal received in numerical simulations. The criterion used to obtain the attenuation and TOF curves is the first peak.

Material Properties

The properties of the materials used in the numerical model are depicted in Table 1.

TABLE 1. Material properties: Density ($\rho$), Young modulus ($E$) and Poisson ratio ($\sigma$), respectively. Longitudinal ($V_L$) and shear ($V_T$) speed of ultrasound were calculated by the software. All values were taken from reference 3, except for water.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (kg m$^{-3}$)</th>
<th>$E$ (GPa)</th>
<th>$\sigma$</th>
<th>$V_L$</th>
<th>$V_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Callus</td>
<td>1600</td>
<td>5</td>
<td>0.3</td>
<td>2050</td>
<td>1095</td>
</tr>
<tr>
<td>Cartilage</td>
<td>1050</td>
<td>2.45</td>
<td>0.3</td>
<td>1775</td>
<td>946</td>
</tr>
<tr>
<td>Cortical Bone</td>
<td>1850</td>
<td>16.45</td>
<td>0.37</td>
<td>4000</td>
<td>1800</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>Library</td>
<td>Library</td>
<td>1500</td>
<td>0</td>
</tr>
</tbody>
</table>

*Library of the Wave2000

RESULTS

In Figure 4 there is an example of the propagation pattern for the transverse fracture in three different propagation times in the numerical model.

FIGURE 4. Example of wave propagation pattern in three time instants for the transverse fracture case. (a) Lateral wave before reaching the fracture. (b) Lateral wave after leaving bone callus. (c) Lateral wave at the end of the path.
Time of Flight

Figure 5, 6 and 7 show the time-of-flight curves for the three fracture geometries in all stages. Table 2 shows the TOF value for stages 1 to 7.

FIGURE 5. Time of flight for the seven transversal fracture-healing stages.

FIGURE 6. Time of flight for the seven oblique fracture healing stages.

FIGURE 7. Time of flight for the seven spiculate fracture healing stages.
TABLE 2. TOF values for the three fracture geometries.

<table>
<thead>
<tr>
<th>Stage</th>
<th>TOF-Transverse (µs)</th>
<th>TOF-Oblique (µs)</th>
<th>TOF-Spiculate (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1, 6 and 7</td>
<td>62.59</td>
<td>62.59</td>
<td>62.59</td>
</tr>
<tr>
<td>Stage 2</td>
<td>63.43</td>
<td>63.30</td>
<td>63.64</td>
</tr>
<tr>
<td>Stage 3</td>
<td>63.16</td>
<td>63.12</td>
<td>63.38</td>
</tr>
<tr>
<td>Stage 4</td>
<td>63.21</td>
<td>62.99</td>
<td>63.38</td>
</tr>
<tr>
<td>Stage 5</td>
<td>63.03</td>
<td>62.99</td>
<td>63.21</td>
</tr>
</tbody>
</table>

Figure 8, 9 and 10 show the attenuation curves for the three fracture geometries in all stages.

**Attenuation**

![Attenuation - Transversal Fractures](image1)

**FIGURE 8.** Attenuation for the seven transversal fracture healing stages.

![Attenuation - Oblique Fracture](image2)

**FIGURE 9.** Attenuation for the seven oblique fracture healing stages.
FIGURE 10. Attenuation for the seven spiculate fracture healing stages.

<table>
<thead>
<tr>
<th>Stage</th>
<th>AMP-Transverse</th>
<th>AMP-Oblique</th>
<th>AMP-Spiculate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1, 6 and 7</td>
<td>0.0111</td>
<td>0.0103</td>
<td>0.0107</td>
</tr>
<tr>
<td>Stage 2</td>
<td>0.0058</td>
<td>0.0053</td>
<td>0.0052</td>
</tr>
<tr>
<td>Stage 3</td>
<td>0.0064</td>
<td>0.0062</td>
<td>0.0070</td>
</tr>
<tr>
<td>Stage 4</td>
<td>0.0065</td>
<td>0.0059</td>
<td>0.0071</td>
</tr>
<tr>
<td>Stage 5</td>
<td>0.0088</td>
<td>0.0085</td>
<td>0.0092</td>
</tr>
</tbody>
</table>

TABLE 3. Amplitude values for the three fracture geometries.

DISCUSSION

This work is intended to evaluate the attenuation and time-of-flight of different fractures geometries for several fracture healing stages with numerical simulations.

The healing stages one (intact bone), six (bone consolidation) and seven (callus remodeling) of the three fractures geometries have equal results for TOF and attenuation, because they are independent of the fracture kind.

Time of Flight

For all fracture geometries in the second stage the fracture takes place (broken bone). As consequence of that discontinuity, TOF increases and reaches its highest value as the biological material in between the fracture gap is seen by the wave as soft tissue (US speed lower than in bone). From stages three to five, the cartilage is gradually replaced by the hard callus, which produces a TOF decay. In the stages six and seven, bone is completely consolidated and TOF recovers the first stage value (intact bone). It is interesting to note that the difference between stages six and seven is the callus form, but the time-of-flight is the same. This result points to an independence between TOF and callus geometry, and further carefully investigated is needed.

In Table 2 are the TOF values for the last receiver. It was concluded that the oblique fracture always has the shortest time of flight. The transverse TOF is bigger than spiculate. These results have shown the possibility to use TOF to discriminate different kind of fractures, as well different stages of fracture healing process.

Attenuation

The attenuation curve shows differences between stages for each of the fractures geometries. The inflexion minimum point in stage two is the smallest (smallest attenuation value). When bone starts to consolidate, in stages three, four and five, this point tends to go up. Table 3 shows that the amplitudes in the second stage (last receiver) show that oblique and spiculate fractures have bigger attenuation than transverse ones. When callus formation occurs, this pattern does not appear anymore. In stages three, four and five, spiculate fracture has bigger amplitude than transverse and oblique, and oblique has larger attenuation than transverse fractures.
Study Limitation and Future Expectations

These numerical models do not take into account noise and attenuation by absorption (attenuation values for each healing stage are not available yet), that will affect experiments, therefore, additional processing treatment has to be done when dealing with experimental data (e.g., noise filtering, attenuation compensation). Another aspect to be taken care of for experimental results is the instrumentation accuracy and precision since TOF values are very small. Experimental test need to be done to confirm this results, however, these simulation analyses of TOF and attenuation together, may give some directions to future exploration. They may be used in future to assist doctors to discriminate fracture types and stages of fracture healing.

ACKNOWLEDGMENTS

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REFERENCES