Simulation of ultrasound in the knee

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Abstract
A large body of evidence supports the use of low intensity pulsed ultrasound to augment bone healing and similar therapeutic benefits have been observed with damaged joint cartilage. It is an objective of this work to find paths of propagation of ultrasound in the knee and hence the optimal position for the ultrasound device. Determining the above in real tissues is complex and hard to achieve in practical terms; one solution is the use of computer modelling. A number of ultrasound simulation packages are available. In this work, Wave2000Pro (CyberLogic®, Inc) has been used to model ultrasound pulses with a frequency of 1.5 MHz in geometries similar in size and shape to knee. These simulations are two dimensional and require a number of assumptions to be made including linear propagation, homogeneity and isotropy of the materials under investigation. Simulations have been performed using Perspex shapes so that the software package could be validated in the laboratory. The outcome of these simulations matches measurements made in the laboratory with two different diameter needle hydrophones.

Introduction
Numerous studies have shown that the use of low intensity pulsed ultrasound augments bone healing [1, 2]. Research also supports the notion that similar therapeutic benefits may be achieved in damaged joint cartilage [3, 4].

This study is aimed at investigating the propagation of ultrasound in knees with a view to providing the optimal positioning of the ultrasound device for cartilage therapy. Measuring the intensity of ultrasound within the joint cavity of an intact knee poses a number of difficulties. The use of computer simulations provides a means of overcoming these difficulties, but the applicability of such simulations to the ‘real’ world is not well described. A ‘Perspex knee’ is used to compare experimental results with simulated results to help assess the suitability of computer modelling for this problem.

Method
For the computer simulations a number of commercial software packages were investigated. Consideration was given to the algorithms employed, material characteristics required, current and previous fields of application, ease of use and cost.

Computer simulations of ultrasound propagation were carried out using a commercial finite differences software package (Wave2000®Pro ver. 2.0, CyberLogic®, Inc., New York, USA) which allows the user to compute the full acoustic wave solution in an arbitrary two-dimensional object. With this software a heterogeneous medium is considered to be a collection of homogeneous linear isotropic regions characterised by constant values of density.
and elastic parameters. The algorithm imposes continuity of stresses and displacements across boundaries of any four homogeneous cells in the simulation model, each with material properties surrounding a cross-point [5, 6]. The specific acoustic equation that is solved in a Wave2000®Pro simulation is [7]:

\[ \rho \frac{\partial^2 w}{\partial t^2} = (\mu + \eta \frac{\partial}{\partial t}) \nabla^2 w + (\lambda + \mu + \xi \frac{\partial}{\partial t} + \eta \frac{\partial}{\partial t}) \nabla (\nabla \cdot w) \]

\( w \) = displacement at the point \((x,y)\). 
\( \rho \) = material density \((\text{kgm}^{-3})\). 
\( \eta \) = shear viscosity \((\text{Nsm}^{-2})\). 
\( \lambda \) = first Lamé constant \((\text{Nm}^{-2})\). 
\( \xi \) = bulk viscosity \((\text{Nsm}^{-2})\). 
\( \mu \) = second Lamé constant \((\text{Nm}^{-2})\). 
\( t \) = time \((\text{s})\).

Lamé constants \( \lambda \) and \( \mu \), the density and attenuation coefficient, must be known for each material in the simulation. However the Lamé constants can be calculated using the bulk longitudinal and transverse velocities or Young’s modulus and Poisson’s ratio. The simulations (see figure 1) used the material properties for Perspex and water (at 25°C) from the ‘libraries’ in Wave2000®Pro. The ultrasound was created by a ‘uniform’ 22mm diameter plane transducer producing a 1.5 MHz sine wave in a pulse of 12 cycles \((8 \mu\text{s})\) both in the simulations and the experiments. This length of pulse was chosen to keep the simulation time manageable while also reducing interference from reflections from the sides of the water tank in the experimental apparatus, though still providing a good approximation to a single frequency source.

The experimental set-up is shown in figure 2 and comprises of a 22mm plane circular transducer, two needle hydrophones (Precision Acoustics Ltd) and a Perspex ‘knee’ immersed in a water bath. Perspex was chosen because it is isotropic, easy to mill and the appropriate properties are documented within Wave2000®Pro. The Perspex knee consisted of a cylinder with a diameter of 40mm and a rectangular prism with a width of 40mm. These were positioned to create a ‘joint cavity’ with a minimum separation of 6mm. Three different transducer positions were used for the simulations and the experimental work (see figure 2). In position 2 the centre of the transducer is aligned with the centre of the ‘joint cavity’. In position 1 the transducer has been displaced -10mm in the direction of the y-axis; in position 3 the transducer has been displaced +10mm in the direction of the y-axis.

In the simulations, maximum pressure readings were taken using adjacent 0·2mm ‘uniform receivers’ positioned in a straight line at a distance of 40mm from the face of the transducer. Two simulations were performed for each transducer position; one with the Perspex in place and one without. In the water tank, a 1mm active element hydrophone and a 0·2mm active element hydrophone were both scanned in a horizontal plane at a distance of 40mm from the centre of the transducer face, taking readings at 0·2mm intervals. Each time the hydrophone was repositioned, an average peak to peak voltage for a minimum of 200 different pulses was taken from the oscilloscope. Initially this was performed with the Perspex in place and then with the Perspex removed. The simulated and the experimental results are normalised to the maximum of the corresponding results with the Perspex removed. This gives a normalised value which is related to pressure for both the simulations and the experimental results.
Figure 1: Simulation of the ultrasound field in the ‘Perspex knee’ with the transducer at position 2.

| Pulse Generator | Signal Generator | Amplifier |
|-----------------|------------------|-----------|
|                 |                  | Transducer |
|                 |                  | Perspex Knee |
|                 |                  | 40mm       |
|                 |                  | 20mm       |
|                 |                  | 6mm Joint Cavity |
|                 |                  | 40mm       |
| 1mm and 0.2mm needle hydrophones |

Frequency = 1.5 MHz
Pulse Length = 8µs
Drive Voltage = 9V pkpk

Figure 2. (a) The experimental set up used and (b) the three different transducer positions (not to scale).

Results
Plots of calculated and measured pressure are given in figure 3 to figure 8 for each transducer position: the points are joined to aid visualisation. Similar results are seen for both the simulations and the measurements. The simulations matched the 0.2mm active element...
hydrophone more closely than they matched the 1mm active element hydrophone. With the transducer at positions 1 and 2 an increase in the maximum ultrasound pressure is observed in the presence of Perspex. In position 3 no increase in pressure is seen when the Perspex is present.

**Figure 3.** Plots of normalised pressure with the transducer in position 1; Perspex removed.  
**Figure 4.** Plots of normalised pressure with the transducer in position 1; Perspex in place.
Figure 5. Plots of normalised pressure with the transducer in position 2; Perspex removed.

Figure 6. Plots of normalised pressure with the transducer in position 2; Perspex in place.

Figure 7. Plots of normalised pressure with the transducer in position 3; Perspex removed.

Figure 8. Plots of normalised pressure with the transducer in position 3; Perspex in place.
**Discussion**

The results indicate an increase in ultrasound pressure in the joint cavity when the Perspex is in situ with the transducer in positions 1 and 2. When the transducer is moved to position 3 no increase in pressure is observed. This suggests that the curved Perspex surface has a focusing effect on the ultrasound beam.

It is not surprising that there is closer agreement between the simulation and the 0.2mm active element hydrophone as the simulation used a 0.2mm ‘detector’. Simulations that use a 1.0mm detector are currently under way. The larger detector averages the ultrasound pressure over a larger area and may therefore miss some detail as it is scanned across the joint cavity.

**Conclusion**

Using Perspex and water, Wave2000®Pro can make useful predictions with simple geometries similar in shape and dimension to that of the knee. Whether this is replicated with the greater uncertainties introduced by the structure and physical properties of animal tissues is currently under investigation.

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**Acknowledgements**

This project is being made possible by an EPSRC Industrial CASE Award in partnership with Smith & Nephew.