Ultrasonic measurement of the thickness of human articular cartilage \textit{in situ}

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Abstract

\textit{Objective.} The objective of the present study was to explore the possibility of using the ultrasonic pulse–echo technique for the non-invasive measurement of cartilage thickness \textit{in situ} during a joint arthroscopic examination. The accuracy of the ultrasonic measurement was assessed \textit{in vitro} against that of an established needling technique which is destructive.

\textit{Methods.} The velocity of sound in articular cartilage was measured in an \textit{in vitro} study of one set of ipsilateral human ankle and hip joints at 69 test sites. Its variability was determined.

\textit{Results.} The velocity of sound in human articular cartilage measured \textit{in situ} varied widely (1419–2428 m/s; mean: 1892 m/s; s.d. 183 m/s) and therefore the error in the thickness of cartilage obtained from ultrasonic measurement based upon a constant velocity of sound could be as large as 33.6\% (mean 7.38\%; s.d. 6.25\%).

\textit{Conclusions.} The ultrasonic pulse–echo technique is not accurate for the measurement of the thickness of cartilage \textit{in situ}. An alternative (albeit minimally invasive) would be the needling technique. This requires the development of a specialized probe.

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\textbf{KEY WORDS:} Cartilage, Ultrasound, Thickness.
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Materials and methods

Cadaveric ankle and hip joints were obtained from the right leg of a female donor aged 80 yr. The weight and height of the donor were 64 kg and 1.70 m, respectively. No osteoarthritic changes were observed in the articular surfaces of both joints. Cartilage was in a pristine condition when examined with the Indian ink technique [4].

A mesh was drawn on the articular surface using a soft, felt-tipped pen dipped in haematoxylin. Measurements were made at the centre of each rectangular grid. In total, 69 test sites were measured (17 on the ankle tibial surface, 12 on the ankle talar surface, 27 on the femoral head surface and 13 on the acetabular cup surface). Two sets of measurements were made at each test site: (a) the time interval for the ultrasound wave to travel through the cartilage layer using the non-destructive pulse–echo technique; and (b) the thickness of the cartilage using the needling technique developed in our laboratory [2]. During the tests, cartilage specimens were immersed in physiological saline solution to avoid dehydration.

A Panametric pulser/receiver dual piezoelectric transducer (Model M316, focal length 0.75 inch, frequency 20 mHz, aperture 0.125 inch) was used in this study. It was excited by a pulse signal generated by an associated electronic circuit to send an ultrasonic wave, with the saline solution as the couplant, towards the specimen. The transducer was pointed perpendicularly to the articular surface. When the wave front hit the articular surface of the cartilage layer and, subsequently, the cartilage/bone interface, two echoes were generated and received by the transducer. From the echoes, the time period for the sound wave to travel through the thickness of the cartilage layer was obtained. The measurement accuracy of the technique was determined using carbon steel gauge blocks and ultra-high-molecular-weight-polyethylene (UHMWPE) discs. Simple linear regression analysis showed that the thickness was linearly correlated with the time interval for the ultrasonic wave to travel through the thickness of the specimen \( r = 0.99986 \) and \( r = 0.99995 \) for the UHMWPE and steel calibration specimens, respectively. Furthermore, the coefficients of variation in the velocity of sound were found to be 0.44 and 0.58% for the UHMWPE and steel specimens, respectively. This would result in similar percentages of errors in the thickness measurement with this technique.

The needling technique for the measurement of the cartilage thickness can be described briefly as follows (see also Fig. 1). The joint specimen was held rigidly in a holder and a sharp needle was pushed vertically into the cartilage layer under a constant load. A sensitive piezoelectric load cell detected the load signal and identified the instances for the needle to contact the articular surface and the cartilage/bone interface. A linear variable differential displacement transducer (LVDT) was simultaneously used to measure continuously the position of the needle and hence, identified the distance for the needle to have travelled between the instances of surface and bone contacts. This distance was the thickness of the cartilage at the specific test site [2]. The measurement accuracy of this technique was determined using silicone rubber specimens adhered on to aluminium plates. The coefficient of variation in the thickness was found to be 1.2% [2]. Once these measurements had been completed, the velocity of sound travelling through the cartilage layer at each test site was calculated from the thickness value measured using the needling technique and the sound travelling period.

Results and discussion

The ranges, mean and standard deviation values of the velocity of sound measured are listed in Table 1. The coefficient of variation in the velocity of sound in cartilage is about 9.7%, which is an order of magnitude higher than that in the steel and polyethylene calibration specimens.

The velocity of sound in cartilage thus exhibits large regional variations. Therefore, it would not be appropriate to use the ultrasonic technique for the measurement of cartilage thickness, since this latter is derived as the product of the velocity and the travel time of the ultrasound signal through the cartilage layer. To assume an average value for the velocity would thus result in considerable errors in thickness measurements. It would also render meaningless any attempt at longitudinal monitoring of cartilage loss over a period of time during the disease process, since the difference in cartilage thickness measured on two successive occasions may be

![Fig. 1. Load and displacement signals for the determination of cartilage thickness during a needling test.](image)
much smaller than the inherent error in the thickness measurement (ca. 33%).

On the other hand, because of this wide variation of velocity of sound in cartilage which we have found in this preliminary investigation, a potential useful application of the ultrasonic measurement technique could be found in monitoring the mechanical properties of cartilage. This can be achieved if the thickness of cartilage can be measured by other means such as the quantitative MRI technique [1], which is non-invasive, or by the needling technique, which may be minimally invasive. This latter technique, however, would require the development of a special probe for use in the operating theatre.

The following conclusions can be reached from this preliminary study.

1. The velocity of sound in human articular cartilage measured in situ varied widely (1419–2428 m/s) with its mean and standard deviation being 1892 m/s and 183 m/s, respectively.

2. The percentage error in the ultrasonic measurement of cartilage thickness, based upon the average velocity of sound of 1892 m/s, could be as high as 33.6% (mean 7.4%; s.d. 6.3%).

3. The ultrasonic technique is not sufficiently accurate for the measurement of the thickness of cartilage in situ.

4. A possible alternative may be the needling technique which is somewhat invasive, but minimally so. However, an instrument should be specifically designed for this purpose.

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References