MODELLING THE ACOUSTIC TRANSMISSION OF BIOLOGICAL TISSUE AT LOW FREQUENCIES

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1 INTRODUCTION

The structures of the human body emit a variety of acoustic and electrical signals – mechanical vibrations, noises and electrical current – as they perform their intended functions. Much of clinical medicine is concerned with understanding and interpreting these signals. In particular, when there is a medical problem, clinicians attempt to make a diagnosis based on an interpretation of the non-normalcy of these signals.

Palpation is one clinical method used where the patient´s body is touched by hand to examine the size, consistency, texture, location, and tenderness of the underlying organ or body part[1,2]. With regard to the abdominal region, the examiner uses palpation to identify pathogens and to diagnose irregularities in the condition of abdominal organs by applying his/her hands on the abdominal wall. There is a question regarding the reliability and accuracy of palpation as a diagnostic technique and misdiagnosis has lead to a significant number of unnecessary or inappropriate procedures[3]. Angtuaco *et al.*[4] reported that abdominal palpation did not itself influence gastrointestinal sounds. However the analysis for this study was carried out using band pass filtering between 100 to 1000Hz, which is above typical physiological frequencies of the abdomen[5]. Other research[6] shows that a significant amount of bowel activity appeared in the lower range (i.e. below 100 Hz). Bullock-Saxton *et al.*[3] reported on the unreliability of palpation. Lee (in Bullock-Saxton *et al*.[3]) concluded that without knowledge of biomechanical parameters, such as size, weight and dimensions of body segments, or the use of imaging, it was not possible to rely on clinical palpitation data.

In practice, the accurate performance of manual palpation on the abdomen is limited to more superficial or larger organs, and may not successfully detect abnormalities if the condition resides deep in the abdomen or where small organs are obscured by overlying tissues[7,8]. Mechanical and acoustic properties, such as stiffness, absorption, attenuation and reflection, between the outer surface of the body and the underlying organ of interest will have an influence on the 'feel' observed by the clinician. What is missing in the literature is quantitative data on the transmission of a mechanical signal through tissue, and the influence that the tissue might have on the transmitted signal.

Bowel sounds have long been used as a means of identifying abdominal conditions[9,10,11]. Abdominal sounds are evaluated by listening to the abdomen with a stethoscope (auscultation) and they accrue from movement of the intestines as they push food through[12]. The intestines are hollow, causing the bowel sounds to propagate throughout the abdomen. Sarr *et al.*[13] concluded that more than 30% of diagnoses of intestinal strangulation obstruction using auscultation, are incorrect and, in many instances, lead to unnecessary surgery and increased hospital costs.

A measure of the energy level of bowel sounds can provide a sensitive index of gastrointestinal activity, making it possible to quantify the effects of abdominal disorders. It was found by Politzer *et al.*[14] that, the contents of the intestine influence the frequency content of the sounds as well as the energy of the sounds. In addition, it was found that different regions of the abdominal tract are likely to produce sounds with different characteristic frequencies and amplitudes[15]. A study by Yoshino *et al.*[16] concentrated specifically on the frequency of sounds detected at a single location on the abdominal wall. It was reported that not only did the sounds recorded in all of the healthy subjects have similar constituent frequencies, but also that the peak frequency and constituent frequency range of the sounds were significantly different in the presence of many abdominal disorders. By

categorising the bowel sounds according to their frequency content, it was reported that the objective diagnosis of several types of abdominal disorders was possible.

Tissue consistency and activity level also influence the values of the acoustic properties. One of the pioneering studies in this area was measurements of vibrations from a surface-mounted accelerometer attached to the skin overlying the quadriceps muscles of the leg[17]. The acceleration signals indicated that the soft tissue oscillated with under-damped vibrations, and it was believed that the frequency and absorption of the vibrations are a function of the level of muscle activity. Research shows that running activity increased the median frequency of muscle from 60 Hz to about 90 Hz if the hardness of a running surface is changed from concrete to a softer surface[18 19]. Muscle activity in the lower extremity is used to damp soft-tissue resonance which occurs at heel-strike during walking. There are other studies in the literature on signals in the ultrasound frequency range being transmitted through tissue[20,21]. However, none of these studies report on how the tissue type and thickness influence the quality of the transmitted signal at lower frequencies (i.e. in the 0 – 100 Hz range of sounds typically generated from within the abdomen). Clearly, to understand the behaviour of biological tissue to vibration and sound, further tests need to be carried out on the properties of biological tissues themselves.

This study is concerned with investigating the acoustic transmission characteristics of abdominal wall tissue. The hypothesis is that, within typical physiological frequency ranges of vibrations and sounds, the level of transmission is significantly influenced by the physical dimensions of the tissue and its constituents. A sub-hypothesis is that, the difference between the characteristics of an acoustic signal detected on the body surface, from the actual transmitted source within the body is a function of the relative locations of the source and the detector/pick-up device.

2 METHOD

The first experiment was concerned with establishing the change in a signal that occurs as a vibration is transmitted through abdominal tissue of differing composition. An oscillating probe is placed against the inner surface of a sample of abdominal wall, and the resulting vibration on the outer surface of the abdomen is monitored.

An electro-mechanical shaker (Gearing-Watson Vibrator Model V.4) was located underneath a tissue sample, with the oscillating probe in contact with the tissue. The shaker was driven by power amplifier (model Gearing-Watson PA30), which received it's signal from a pulse analyzer (Brüel and Kjaer), which generates a sine wave over a wide band of frequencies. An array of 4 accelerometers (Brüel and Kjaer Type 4507 B 005) were placed on the upper surface of the tissue. The accelerometers were miniature high sensitive piezoelectric element (type PZ 27, 4.3 gram) with an in-built preamplifier.
A mounting plate (UA1564, 5.7 gram) was attached to the accelerometers, to increase the surface area of contact with the tissue, which was in turn attached to the tissue using double-sided tape.
Signals from the accelerometers were received in the time spectrum and transformed into the frequency domain using a fast Fourier transform analyzer (PULSE 3060C 6 channel analyser). The signal intensity was displayed in dB as a ratio of the applied force on the sample relative to gravity.
The analyzer has a 24-bit A/D converter and covers the frequency range, 0 – 25.6 kHz. The data was analysed using Brüel & Kjaer Pulse software (V 7).

The tissue was subjected to continuous oscillating motion against the inner wall of the tissue (see Figure 1). Fresh underbellies of swine carcasses (unfrozen and unsalted) were used, as they are similar in composition to human abdominal tissue and are readily available. Samples were harvested from the lower side of the abdomen of the pig between the ribcage and hind quarter (i.e. the front wall covering the intestines). The specimens contained the major components of, the abdominal wall, including fascia, major muscle groups (external oblique, internal oblique, transversus abdominis) and extra-peritoneal fat.

The outer layer of skin was removed as it was found to be significantly tougher than human skin. Samples were kept moist and all experiments were carried out at room temperature. The sample was supported by a thin rubber membrane located over the oscillating probe, with the internal

surface of the tissue face down. An accelerometer was attached to the membrane near to the probe, in order to record the source signal applied to the tissue (this was necessary because the shaker was open loop control). Measurements were taken at four different locations on the upper (skin) surface of the tissue. Tissue vibration transmissibility was calculated by dividing the acceleration at each point on the surface of the sample by the acceleration at the membrane. All experimental measures were repeated several times to ensure consistency of the data.

In the second experiment, a 100 mm diameter, vertically mounted standing wave tube was fitted with a Sony loud speaker The speaker was rated 25 W, with a peak of 110 W and a sensitivity of 88 dB/W/m, up to 22,000 Hz. The speaker was mounted at the bottom end of standing wave tube. A slab of swine tissue, from the underbelly (see experiment 1) was placed at the opposite end to the loud speaker, directly on top of the tube. The sample was prepared so that it had uniform thickness across the full outlet of the tube. The outlet diameter of the tube was reduced to 22 mm, in order to restrict the flow of the sound to a specific location on the tissue. The loud speaker was driven by a Brüel & Kjaer ZE 0769 amplifier. A sine wave was produced by a computerised signal generator (Brüel and Kjaer portable PULSE 3060C) and transmitted through the amplifier to the speaker.

Four accelerometers were mounted on the outer surface (skin side) of the sample at equal radial distances from the center of the tube (as shown in Figure 2).the distance was then varied. Data was recorded using a six channel a FFT analyzer (see experiment 1). A comparison was made between the signal received at the accelerometer positioned in the center and the radially positioned accelerometers. The tissue was of uniform 30 mm thickness across the diameter of the tube. The experimental configuration was calibrated using both foam and rigid plastic materials and compared with data in the literature [22].

3 RESULTS

For the vibration experiment, three thicknesses of tissue were investigated, 30 mm, 55 mm and 80 mm. In general, as the tissue thickness increased, so too did the level of vibration absorption. It was also observed that, the level of absorption was not the same at all frequencies of transmitted vibration (Figure 3). In the lower range of frequency, between 0 and 60Hz, the input signal is actually attenuated as it passes through the tissue for all three samples (Figure 3, a, b, c). For the thicker tissue, the signal was observed to be absorbed as the frequency reached 60 Hz (50 mm thick) and 43 Hz (60 mm thick) – i.e. the absorption occurred at lower frequencies for thicker tissue. In all cases, the input and output signals were observed to be in phase.

To further investigate these phenomena, the output signal was normalised with respect to the input (Figure 3d). Results show that for tissue of 30 mm thickness, the low frequency vibration was attenuated by up to 15%. As the frequency increases to 100 Hz the output signal increases by approximately 6 to 11 % of the input signal. For tissue of 50 mm thickness, attenuation occurred up to 55 Hz, above which the output signal was observed to be absorbed by approximately 7% of the input signal. For the 60 mm thick tissue, absorption starts to occur at lower frequencies, i.e. 40 Hz, by up to 16% of the input signal.

Similar trends were noted for the sound transmission results. The data from the four radial accelerometers was compared and the difference found to be in the range 0 to 4% maximum, for any set of readings. Therefore, the average of the four accelerometer readings was used in the reported data. The level of absorption was not consistent over the full spectrum of frequencies (Figure 4). The sound intensity, normalized with respect to the shortest passage through the tissue, was plotted as a function of radial distances from the pick-up sensor, demonstrating more clearly the relative absorption or attenuation (Figure 5). It was observed that, for frequencies in the range 30 to 100 Hz, the sound detected was consistently less than the that at the centrally located sensor, by a factor of 0.8 at a radial distance of 55 mm, and by 0.6 when the sensor is located 80 mm from the central position. At higher frequencies, the absorption continues.

4 DISCUSSION

Distortion of an acoustic signal as it passes through different media is an energy conversion process, i.e. the kinetic energy of the sound/vibration is converted to different energy, such as heat energy. When a vibration/sound strikes an internal organ, or passes through tissue, it is either dissipated or is transmitted through a particular path. The ability of tissue to propagate vibration/sound depends on the activity state of the tissue and it's composition. For example, if a tissue is in a relaxed state, the internal fibres, fat and liquid constituents will have certain orientation. Under tension (which might occur, for example, when the tissue is under stress, or engaging in an action, such as an Ileus[23]), the internal state of the constituents will change. These different states will influence the way in which a signal passes through the tissue.

In this study we show that, low frequency sound pass through tissue with less distortion than high frequency sounds. This explains why clinicians can hear sounds through the chest (0 - 60 Hz,[24]), the sounds of air intake into the lungs (60 Hz,[24]).Not only will frequency have a bearing on the level of acoustic absorption but the absorption also changes with thickness and composition of the tissue. The results from both of the experiments show that thin sections of biological tissue will not absorb as much low frequency sound compared with thicker sections.

This study shows quantitatively, for the first time, the way in which the detection of an acoustic signal transmitted through tissue is altered by the dimensions and, therefore, varying biological composition, of the tissue. This is important in the development of models of signal transmission through tissue. It is apparent from this study that in any such model, an acoustic signal having passed through tissue would be some function of the signal at source and of tissue type and tissue dimensions, within certain frequency bands (*fx)*, i.e.

$$S_r = S_s \times g(T_t, T_d)\big|_{fx} \qquad \text{Equation 1}$$

Where *S* is a measure of the intensity of the signal, *T* is a tissue property, *g* is a functional relationship, and the subscripts *r* = the signal received having passed through the tissue, *s* = the source signal, *t* = tissue type (e.g. fat, lean, muscle, lining) and *d* = tissue thickness dimension in mm. Based on the limited information available from this study, there is insufficient data as yet to present a sensible model – i.e. we cannot yet predict what is the nature of the functional relationship, *g*, in equation 1.

This study also shows how the sound signal detected on the surface of the abdomen reduces in intensity as a function of how far the listening device is away from the source of the sound. While appearing to be obvious, quantitative data on this fall-off in the intensity of an internal sound is nonetheless, new. Clearly, the practitioner does not hear the exact sound generated in the abdomen, and the actual intensity of this sound they hear will depend on where on the outer surface of the abdomen they are listening relative to the source of the sound. The data presented here indicates that there could be as much as a sixteen percent reduction in the sound intensity detected in the outer surface of the abdomen (Figure 3d). The accurate positioning of the stethoscope by the practitioner is also a crucial factor a skill that is sadly neglected[26]. If the stethoscope is positioned on the abdominal surface at a radial distance of 80 mm from the source signal, the intensity will be further reduced by 40% (see Figure 5). Of course, an issue which immediately arises, and which has not been addressed in this study, is the relationship between what the clinician hears (i.e. the quality of their hearing) and the sound[25]. Figure 6 shows the relationship between frequency and relative intensity for the same data set. This highlights more dramatically the point that vibration will undergo different absorption at different frequencies. Certainly, this warrants further investigation.

It should be noted that there are limitations as to what clinically relevant conclusions may be drawn from this work. In order to more completely demonstrate the relationship between frequency, level of signal transmission, and tissue composition and thickness, more data is required on the behaviour of the separate biological constituents of tissues and for a greater range of tissue thicknesses. Also, a more physiologically representative model and source signal could be used in order to investigate the change in acoustic characteristics for real-time changes in frequency and

amplitudes of signal under more anatomical accurate conditions (e.g. sounds generated from within the intestine, within the abdominal cavity).

5 CONCLUSION

Two experiments were proposed to investigate the transmission of vibrations and sounds through biological tissue. In particular, the relationship between frequency of the transmitted signal and the tissue composition and thickness were investigated experimentally. It was found that tissue tends to attenuate signals at frequencies up to 50 Hz, while it may dissipate signals at higher frequencies. Such absorption increases with the thickness of the tissue. In general, thicker tissues will dissipate/absorb a signal, however, signal attenuation did occur for tissue in the range of 10 to 40 mm thick. Finally, quantitative data was reported indicating the rate loss of sound passing through tissue, which is detected at increasing distance from the source of the sound.

6 REFERENCES

1 M.A. 'Ascoli, Artifice of abdominal palpation', The Lancet, 616 (1920)
2 H.W. Christensen, .W. Vach, and C.Manniche, 'Palpation for muscular tenderness in the anterior chest wall: an observer reliability study Manipulative and Physiological Therapeutics' Manipulative and physiological therapeutics, 469-475 (2003)
3 J. Bullock-Saxton, L. Chaitow, P Gibbons, S. Goosen, D. Lee, K. Lewit, C. Liebenson, D. Murphy, D. Simons, P. Tehan, 'The Palpation Reliability Debate: The Experts Respond', Journal of Bodywork and Movement Therapies, 6 (1) 18 (2002)
4 T.L Angtuaco,. J. Evans., .L .Harrell, A.M. Hussein, and .R.H. Sandler, 'The effect of abdominal palpation on gastrointestinal sounds (GIS) in healthy subjects: A quantitative investigation using computerized analysis', American Jounral of Gastroenterology, 95 (9) 2491 (2000)
5 S. Kitazaki and M.J. Griffin. 'A data correction method for surface measurement of vibration on the human body'. Biomechanics 28 (7) 885-890, (1995)
6 J.A. Hession, I. Ahmed, and B.A.O McCormack, 'Auscultation: are you hearing everything' Proceedings of the 8th Annual meeting of Bioengineering in Ireland, Sligo, January, 2002, p 18
7 B. Tokar, R. Ozkan, A. Ozel,and N. Koku. 'Giant rectosigmoid lithobezoar in a child: four significant obtained from history, abdominal palpation, rectal examination and plain abdominal X-ray'. Radiology Extra 49 23–24 (2004).
8 M. Fatemi and J.F. Greenleaf. 'Probing the dynamics of tissue at low frequencies with the radiation force of ultrasound'. Phys. Med. Bio. 45 1449-1464. (2000)
9 L.W. Baker, H.A.F. Dudley, 'Auscultation of the Abdomen in Surgical Patients', The Lancet, 2, 1961, 517-519
10 E.A. McConnell. 'Loosening the grip of Intestinal Obstructions', Nursing, 34-41 March, (1994)
11 T.G.I. James. 'Value of Auscultation of Acute Abdomen', Practitioner, 132:495 (1934)
12 E.A. McConnell 'Auscultating Bowel Sounds: The Clinical Do's and Dont's', Nursing, 20 (5),106 (1990)
13 M.G. Sarr, G.B. Bulkley, G.D. Zuidema. 'Preoperative Recognition of Intestinal Strangulation Obstruction: Prospective Evaluation of Diagnostic Capability', *Am. J. Surg*., 145,176-181(1983)
14 J.P. Politzer, G. Devroede, C. Vasseur, J. Gerard, Thibalt 'The Genesis of Bowel Sounds: Influence of Viscus and Gastrointestinal contents', Gastroenterology, 71, 282-285 (1976)
15 D.C. Martin, G.L. Beckloff, J.D. Arnold, S. Gitomer. 'Bowel Sound Quantitation to Evaluate Drugs on Gastrointestinal Motor Activity', J. Clin. Pharmacology, 11,42-45 (1971)

16 H. Yoshino., T. Yoshino, K. Ohsato., 'Clinical Application of Spectral Analysis of Bowel Sounds in Intestinal Obstruction', Dis. Col. Rect., 33, 753-757 (1990)
17 J.M. Wakeling, B.M. Nigg, 'Soft-tissue vibrations in the quadriceps measured with skin mounted transducers', Journal of Biomechanics 34, pp539 -543 (2001)
18 B.M. Nigg, W Liu, 'The effect of muscle stiffness and damping on simulated impact force peaks during running',. Biomechanics 32, 849-856 (1999)
19 J.M. Wakeling, A.M. Liphardt, B.M. Nigg, 'Muscle activity reduces soft-tissue resonance at heel-strike during walking', Biomechanics 36, 1761 1769 (2003)
20 N. Hozumi, R. Yamashita, C. K Lee, M. Nagao, K. Kobayashi, Y. Saijo, M Tanaka, N Tanaka, S Ohtsuki, 'Time frequency analysis for pulse driven ultrasonic microscopy for biological tissue characterization', Ultrasound in Medicine and Biology 29,(9) 1367–1372, (2003)
21 E.E. Konofagou, 'Quo vadis elasticity imaging'., Ultrasonics, 2004, www.elsevier.com/locate/ultras
22 G. Dutilleux, T. E. Vigran, .U. R. Kristiansen. 'An in situ transfer function technique for the assessment of the acoustic absorption of materials in buildings', Applied Acoustics, 62, 555-572 (2001)
23 B.W. Miedema, S. Schillie, J.W. Simmons, S. V Burgess, T. Liem, D. Silver, 'Small bowel motility and transit after aortic surgery'. Vascular Surgery, 36, (1) 19-24 (2002)
24 G. Rasmussen, 'Human Body Vibration Exposure And Its Measurement', *www.zainea.com/body.htm*
25 Richard C., 'The Stethoscope: The Forgotten Instrument in Cardiology', *Clinical Cardiology*, 20 (11), 911-912 (1997)

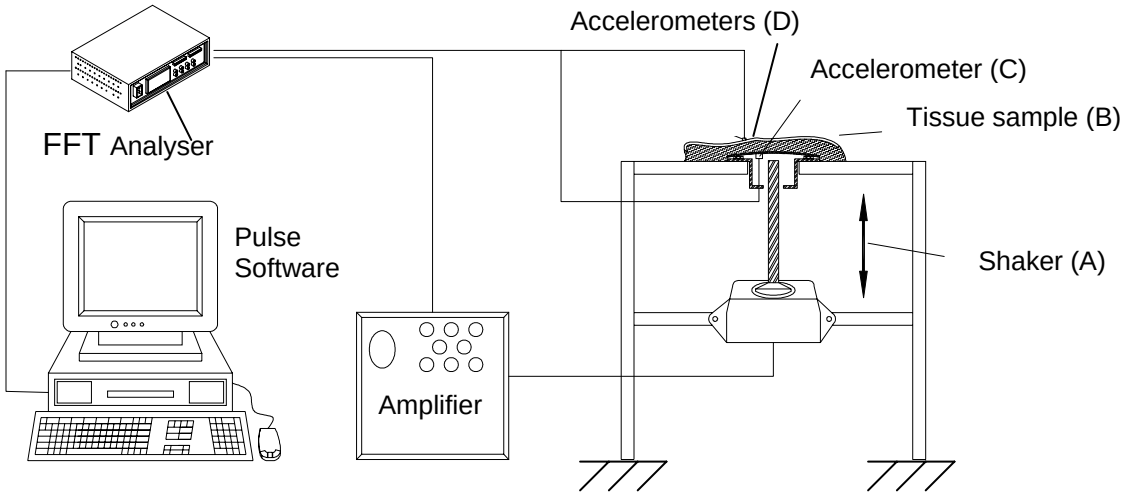

Figure 1: Vibration transmitted through tissue. The oscillating probe of the shaker (A) transmits a vibration of known characteristics to the internal (underneath) surface of swine abdominal tissue (B). An accelerometer (C) monitors the source vibration. Four additional accelerometers (D) monitor the vibration on the outer (top) surface of the tissue. These are attached to a face plate which is then attached to the tissue using double-sided tape. Data is recorded using a FFT analyser. The rig was located on a concrete floor in an acoustically isolated room in the basement of the research building.

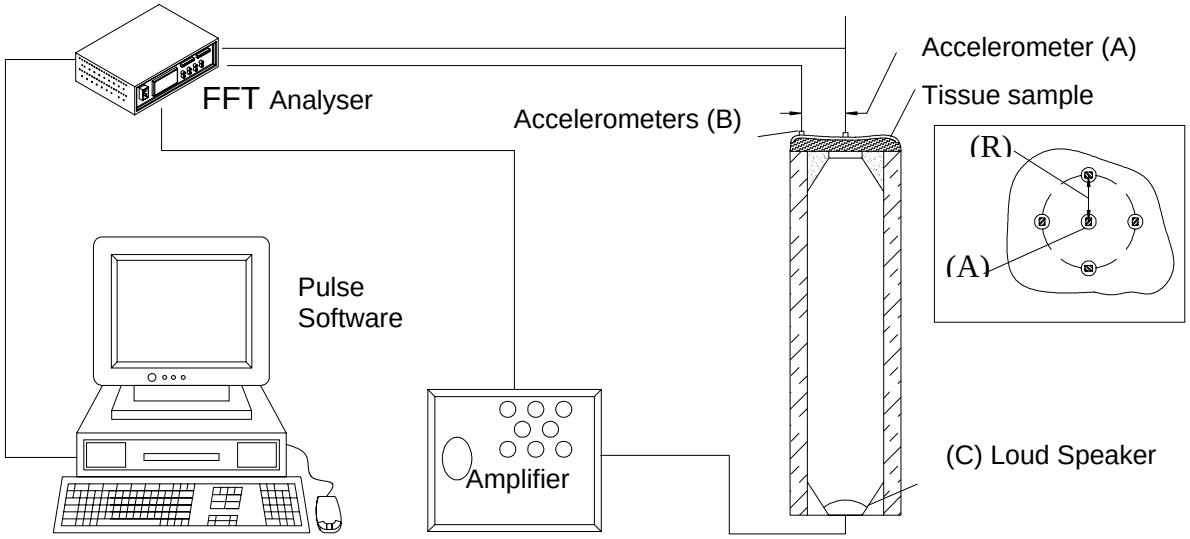

Figure 2: Sound transmission through tissue. One accelerometer (A) was placed directly over the exit of the tube on the adjacent side of the sample. This acts as a reference for four other accelerometers (B) which were placed in a circular array around the centre. The radial distance (R) of these other accelerometers from the centre is varied throughout the experiment in order to provide data on transmission characteristics at different distances from the underlying source signal (C). The rig was located on a concrete floor in an acoustically isolated room in the basement of the research building.

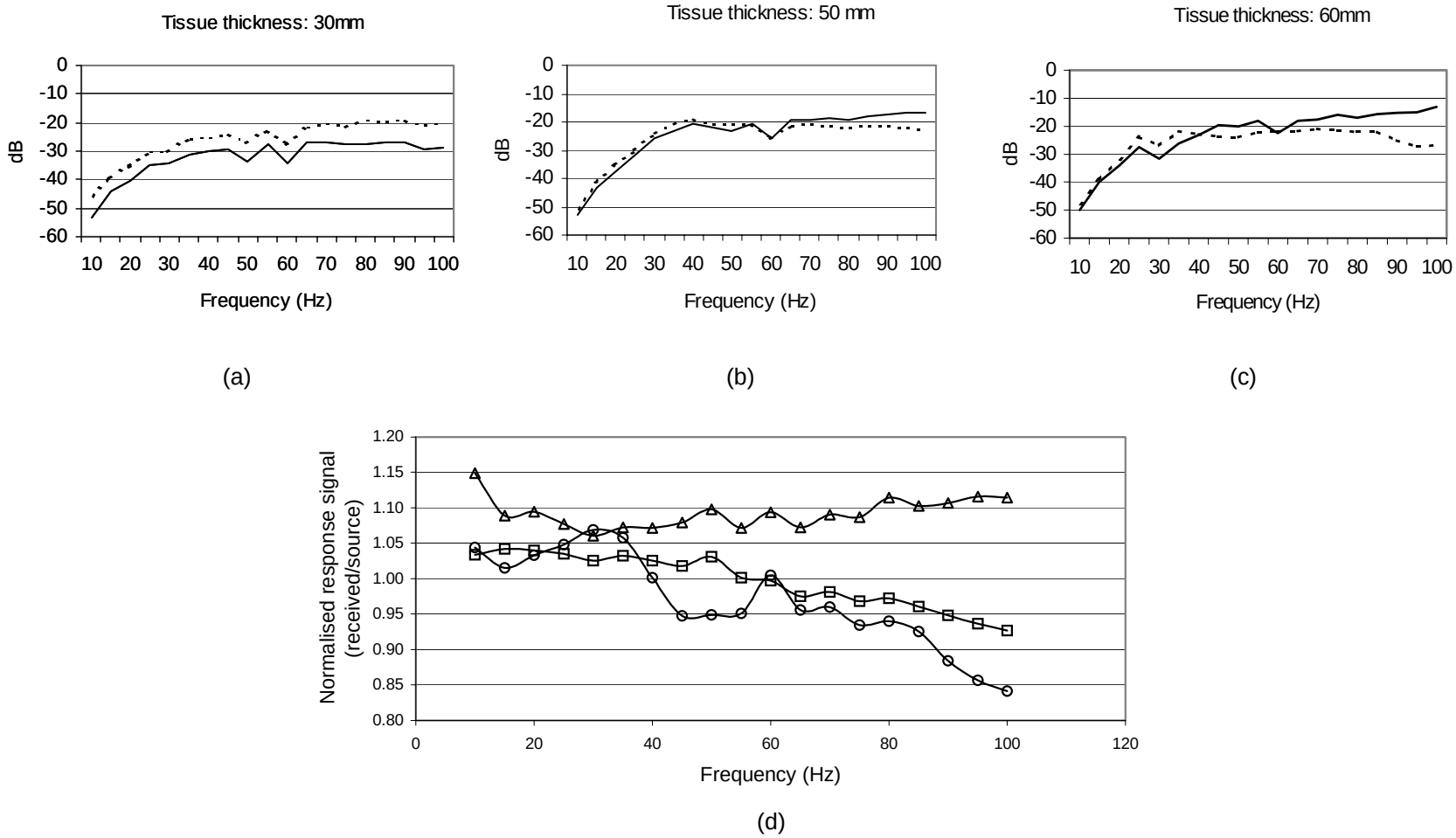

Figure 3: Transmitted vibration for three tissue thicknesses, 30 mm, 50 mm, 60 mm. Only typical physiological frequencies are shown. In (a), (b), and (c) the solid line is the source signal and the dashed line is the received signal. In (d), the data for 30m 50 and 60 mm is represented by triangles, squares and circles respectively.

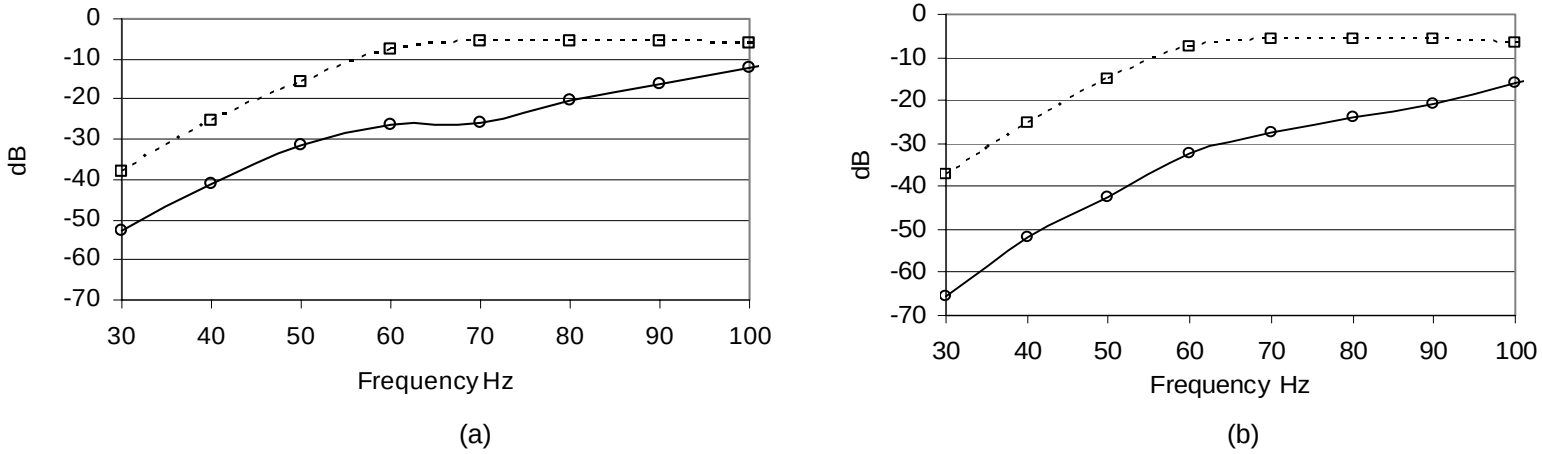

Figure 4: Reduction of intensity of sound as it is transmitted through tissue. The dashed line is the transmitted signal detected from the sensor placed on the top surface of the tissue directly over the source, and the solid line is the signal detected by sensors placed on the surface at a radial distance (R) away from the source. Figure (a) is for R = 55 mm and (b) is for R = 80 mm.

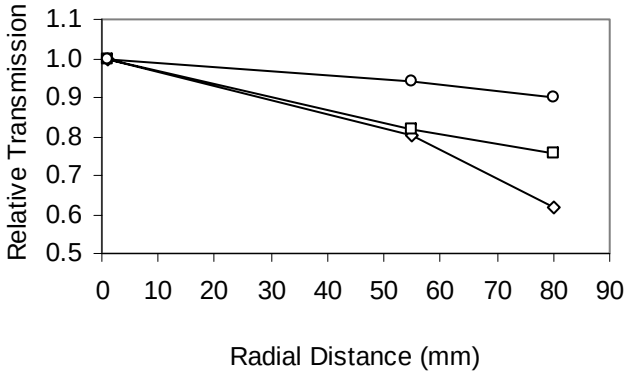

Figure 5: The relative reduction in the intensity of sound as it passes through tissue, over a range of frequencies, at different radial distances away from the source. The data for 30 Hz, 60 Hz and 100 Hz are represented by diamond, squares and triangles respectively.

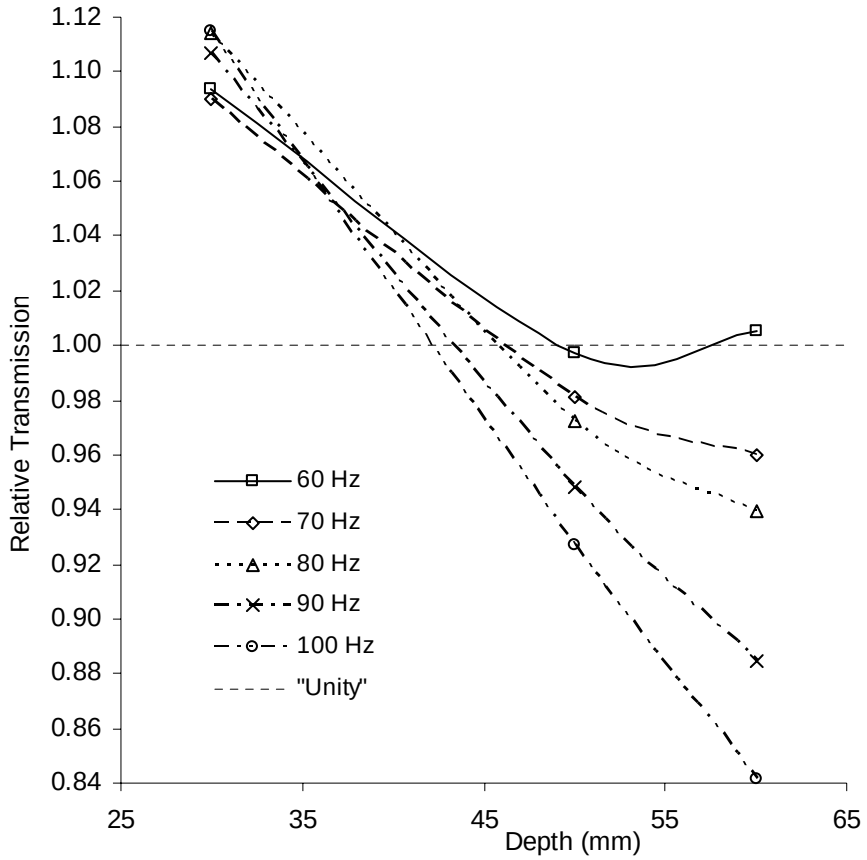

Figure 6: Comparison of vibration attenuation/absorption between tissue samples of different thickness. The data has been normalized with respect to the source signal.