Development of Laboratory Activities for Teaching Ultrasound Concepts in an Undergraduate Medical Physics Classroom

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Abstract— **Ultrasound (US) is widely used in areas such as medicine, engineering, physics and geology, among others. In our undergraduate medical physics course we try to demonstrate the practical side of the modality to large groups with hospital equipment, where low-level functionality is not accessible. Students do not have laboratory sessions with simple equipment, in which they can explore the transducer's core physical principles and the ultrasound generated. We identified low-cost apparatus for pairs of students to perform some simple experiments about the principles of US, using PCs, Arduino Microcontrollers, already available in our lab, the Arduino HC-SR04 US sensor, and cheap materials found in the laboratory or at home. Next we developed some simple experiments for a two hour laboratory session: (i) estimation of the speed of sound in air; (ii) approximate profile of the US beam; (iii) description of acoustic properties of different materials; (iv) concept of B-mode ultrasound, the profile of an object obtained from multiple scan-lines. The experiments have good educational value, but might be improved by using a stepper motor to emulate a sector format transducer to create a B-mode like outline, and using multiple sensors to introduce students to principles of beamforming.**

Keywords— **Ultrasound, Medical Physics teaching, Arduino, HC-SR04 ultrasound sensor, beam pattern.**

I. INTRODUCTION

Our undergraduate degree in Biomedical Engineering at Federal University of ABC (UFABC), São Bernardo do Campo, São Paulo, Brazil, contains courses in Medical Physics, including the physical principles of modalities including X-ray, CT, magnetic resonance imaging, nuclear medicine (NM) and ultrasound (US). While we have a single hospital US scanner available for educational purposes, it is commercial equipment and the working principles of US that we would like to demonstrate are integrated in the commercial design and not accessible for didactic experimentation.

We believe there is a need for low-cost teaching resources to demonstrate simple US principles and provide practical experience for students alongside theoretical content in the classroom. Hospital ultrasound equipment is not practical for a laboratory of students, due to its high cost, and it does not provide intuitive access to the transducer's behaviour, and therefore, to the physical principles which we want to teach.

II. THEORETICAL FOUNDATIONS

US can be used in many areas of engineering, but in medical diagnosis it is one of the most widely used non-invasive modalities. Since it does not use ionizing radiation, it is the preferred imaging modality in obstetric and pediatric medicine. Brightness mode (B-mode) US images are cross-sectional images which show boundaries between organs and structures as well as tissue [1].

In a B-mode US examination in a hospital setting, the transducer (source of ultrasound) is placed in contact with the skin. Bursts of mechanical waves with high frequency are sent into the body of the patient. The transducer receives the returning ultrasound, from which an image of structures inside the body can be built. US transducers are often made of special ceramic crystal materials called piezoelectrics, and these kinds of materials are able to produce sound waves when an electric field is applied, and work in a reverse way, producing an electric field when the returning sound wave impinges upon it [2].

Each burst is directed along a narrow beam-shaped path, is reflected or scattered, and returns to the transducer along the same path, where it is received and recorded. To form an image, the US system needs to know the range at which the signal was reflected, obtained from a measurement of the time of travel and the direction of the reflection, in clinical practice obtained from the angle between the US beam and the skin.

The question of how US measures distances can be taught using the principal of pulse echo. The time, t, is measured for the US pulse to travel from the transducer to a site of reflection or scattering and back. This is equal to twice the distance from the transducer to the object, d, divided by its speed. In these experiments the speed in air is computed, v_{air}, as shown in equation 1 [1].

$$v_{air} = \frac{2 \cdot d}{t} \tag{1}$$

v_{air} can be calculated at different temperatures using equation 2 [3], given the ambient temperature, T, in Celsius [1]:

$$v_{air}(T) = 331.227 \cdot \left(\frac{T + 273.15}{273.15} \right)^{\frac{1}{2}} [m/s] \tag{2}$$

The acoustic impedance of a material, z, measures the local speed of particles, v_p in this medium given a pressure, p, defined by equation 3:

$$z = \frac{p}{v_p} [rayls, Ry] \tag{3}$$

The acoustic impedance of air, $z_{air} \approx 400$ Ry. [5]

The fraction of the transmitted US wave energy reflection as it moves between different materials depends on the acoustic impedance of these materials. Let the acoustic impedance of the two materials be z_1 and z_2; a large difference in z will produce a strong reflection of acoustic energy and a small change will produce a weak one, as can be seen in equation 4, Reflection Coefficient of intensity, R_I [1]. Air has a much smaller acoustic impedance than most solids, and for US experiments performed in air with solid reflectors, R_I is close to unity.

$$R_I = \left(\frac{z_2 - z_1}{z_2 + z_1} \right)^2 \tag{4}$$

III. Objectives

1. Identify low-cost apparatus for teaching the principles of US in a university laboratory;
2. Develop a set of didactic experiments to assist in teaching some basic concepts of US.

IV. Materials and Methods

After viewing options for US sensors and microprocessors, we decided to use an Arduino (a low cost microprocessor) setup. Our university already has PCs in the laboratory, available for student use; we possess breadboards and Arduinos for 30 students, working in pairs, but do not have enough ultrasound sensors. The HC-SR04 sensor seems to be the cheapest, available at low cost (around R$10 at the time of writing).

Other materials for experimental use can be found in a laboratory or at home, and are very cheap or without cost. It is possible that, over time and with experience, better or more standardized materials could be found, built or acquired for these experiments, but this set of pilot experiments were set up very quickly and seemed to produce adequate results for learning. The following list shows the items used in experimentation:

- Arduino Uno R3 Board and Cable (Elegoo, Inc., Shenzhen, China), breadboard and cable connectors;
- Ultrasound sensor (HC-SR04). Datasheet available online [6]. Selected information about sensor shown in Table 1.

Table 1: Information about the HC-SR04 US sensor from datasheet [6]. The beam pattern of the sensor is not provided.

Specification	information
IO trigger	at least 10 μs
non-contact measurement	2-400cm $\pm$ 3mm
signal	8$\times$ 40kHz pulses

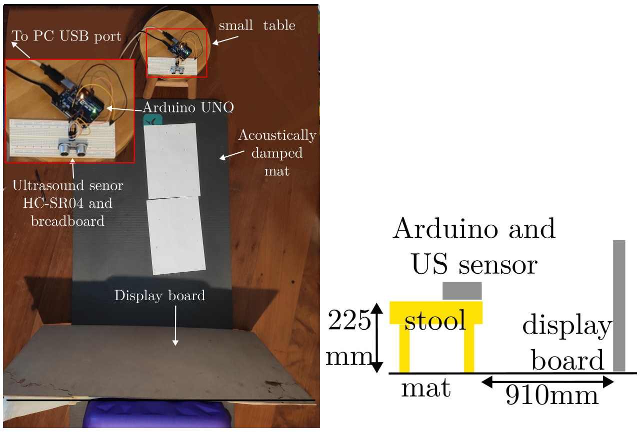
- PC (running Linux Pop/OS) to upload program to Arduino and receive output from transducer;
- Python 3, `matplotlib` library, Arduino IDE 1.8.15;
- Sponge mat to cover hard floor;
- Small stool (225mm high) ruler, tape measure, protractor.
- A variety of materials for tests, including:
  - · A piece of laminated display board (810×460×2 mm), placed at 910mm from the transducer;
  - · Kitchen sponge; wire wool; paper serviette;
  - · Surgical gauze; classical guitar.

Figure 1(a) shows the experimental setup. The display board was positioned vertically and the normal to its plane pointed at the sensor. In figure 1(b) we see the side view of the experiment. We perform all experiments over a mat to reduce strong acoustic reflections from the floor. The stool sets the transducer above floor level, which reduces possible false reflections. The transducer was placed so at to reduce reflections from the stool.

The Arduino set up was performed as per the circuit and program in the datasheet [6]. Software was uploaded to the Arduino using the Arduino IDE, and values returned to the PC were visualized using the IDE monitor. The program was modified to return only the round trip time in μs, which the apparatus measures, and not distance, which requires the assumption of the speed of sound, a quantity which will be measured experimentally in subsection A.

We consider four basic experiments with US that could be performed in a 2 hour laboratory session: (i) Estimation of the speed of sound; (ii) Approximate profile (width) of the beam; (iii) Determination of acoustic properties of different materials; (iv) Concept of B-mode US: a sweep along parallel scan lines to estimate a shape outline.

[1] Additionally, [4] shows an equation where v_{air} depends on temperature and relative humidity, RH: $v_{air}(T,RH) = 331.4 + 0.6 \cdot T + 0.0124 \cdot RH$



(a) Experimental setup in plan view (b) Experimental setup in side view.

Fig. 1: Plan and side views of the experimental setup

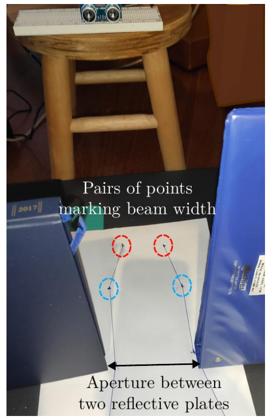


Fig. 2: Method for determining beam profile. The space between the reflective plates is the aperture, of width ℓ_p, at a distance ℓ_s along the scanline. We mark the position of the plates with two points on the paper.

A. Estimation of the speed of sound in air, v_{air}

The speed of sound in a given material allows conversion of travel time into distance, assuming that speed in the medium is constant.

The US sensor has transmit (T) and receive (R) sensors. The time for a pulse, emitted from T, to arrive back at R, is then computed. Therefore, to estimate v_{air}, we position a surface which is a strong acoustic reflector, at a known distance away from the transducer, here 91cm, measure the time, t, for the ultrasound to reach the target and return, then use equation 1 to compute v_{air}. Software was written in Python on the PC to output the mean and standard deviation of t, $\bar{t}$ and σ_t respectively, for 10 measurements. The accuracy of the computed value of v_{air} was determined by comparison with a theoretical value, which is a function of air temperature (equation 2). Finally, our estimation of v_{air} from experiment was used in the Arduino software to convert round trip time to distance in the remaining experiments.

B. Approximation of beam profile

Datasheet [6] does not provide information about the beam profile. We designed an experiment to approximate this at various distances from the transducer. We assume the beam has maximum power in the direction of the transmit and receive sensors, i.e along the scanline, and that power falls to zero as the angle from the scanline increases. Figure 2 shows the experimental setup, with the laminated backboard behind the camera.

- The backboard, a reflective surface, was placed at a distance of 91cm, perpendicular to the sensor's scanline.
- The following procedure was repeated for distances along the scanline, ℓ_s from 12 to 68cm from the transducer in steps of 8cm:
  1. Two reflective plates were placed with their edges meeting on the scanline, perpendicular to the scanline, at a distance ℓ_s from the transducer. We use the term aperture to describe the distance between the plates, ℓ_p. The US device should initially measure the distance to the plates.
  2. The plates were separated, symmetrically, from the scanline, increasing the width of the aperture, ℓ_p. There is a point at which the distance ℓ_s jumps to 91cm, and then we record ℓ_p by marking points on the paper. At this value of ℓ_p we assume that the beam energy reflected from the plates is small compared to that reflected from the backboard, points are marked to represent the beam profile at ℓ_s.

C. Description of acoustic properties of different materials

We present different materials to the ultrasound beam at a mid distance between the probe and backboard, and, based on the distance value returned, classify them as:

1. Absorbers: These material absorb enough of the acoustic energy that the US sensor does not receive a detectable reflection;
2. Reflectors: We can find some angle (e.g. normal) at which there is a strongly reflected signal;
3. Scatterers: spreads the energy over a wide range of angles. In our simple experiment, this category will be hard to distinguish from a non-planar reflector;
4. Materials with low US interaction: Some materials may

interact little with the beam and not be detected. To distinguish these from absorbers, we place the backboard behind the materials, and expect to measure the distance to the board in the case of little interaction. In contrast, absorbers will allow very little energy to pass through them twice on a round trip to the backboard.

D. Concept of B-mode ultrasound

The pixel values of a B-mode image are formed from a set of returning pulses along scanlines, whose values are converted to grayscale (brightness). A limitation in our experiment is that the US device provides only a single distance value for each scanline. While this is different from the time-history of the pulse used to form a B-mode image in a hospital scanner, we believe that the experiment has validity for teaching purposes. It provides students with a clear idea about how returned signals from various scanlines are required to build up the ultrasound image, just as we build up a contour of the object from different scanlines in this experiment.

As a teaching point it is hoped that the student may learn that commercial US equipment may: (i) use multiple transducers, whereas we use only one, which we must manually position; (ii) rotate the sensor through multiple angles, physically or electronically.

Transducers can use different scanline arrangements. Two common arrangements are linear, where the scanlines are parallel and equally spaced, and sector format, where the transducer is rotated through a series of angles. For simplicity, we reproduced the linear arrangement, moving the scanline by 2cm along the curve in each measurement of distance.

In the experimental procedure, we sought to reproduce the outline of the curves of a classical guitar, from distance measurements from a single ultrasound sensor stepping through multiple parallel scanlines. The guitar was positioned at an appropriate height and angled so that a curved part was traced by the scanlines. Moving the sensor along the parallel scanlines, the values in Table 2 were recorded. Figure 4a. shows the experimental setup.

V. Results

A. Estimation of the speed of sound in air, v_{air}

We took 10 measurements of the round trip time, t, which provided $\bar{t} = 5254.6 \pm 34.9 \mu$s. The estimated room temperature was 29 degrees, relative humidity 33% and distance between transducer and board 91.0cm. v_{air} was estimated using equation 1 as 346.4 ± 2.3 m/s, assuming no uncertainty in distance.

Using equation 2 and the ambient temperature, we achieve 348.4m/s. Our value was 0.56% lower than this value, which is a good degree of accuracy for a simple experiment. Using the equation in [4] we obtained 349.2 m/s.

B. Approximation of the beam profile

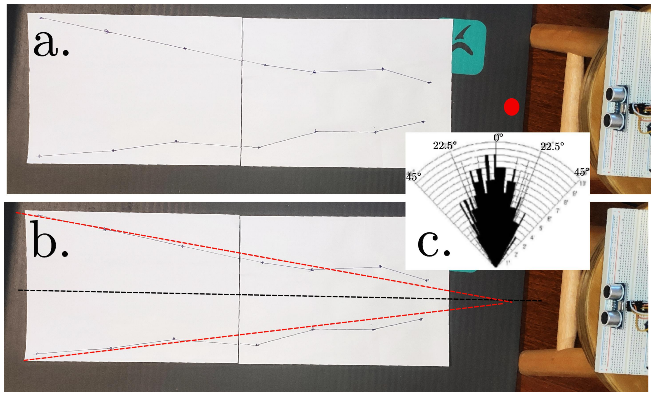


Fig. 3: (a.) Beamwidth data recorded; (b) fitting of straight line through data; (c.) Directional pattern by angle for the HC-SR04, adapted from [7]

Figure 3 shows the results: (a.) Lines were marked on paper at various distances, marking the points at which the measured distance jumps from that of the two surfaces to the board at 91cm. (b.) The points were found to be fairly linear, i.e. radial lines from the US sensor, indicating a range of angles at which the US transducer produces higher energy. Radial lines were drawn and a protractor used to measure the beam angle, which was approximately 18°.

C. Description of acoustic properties of different materials

The sponge produced a round-trip time and distance of 13585 μs and 2354m, which means that the incident wave energy was largely absorbed by the sponge and, since a reflection with sufficient energy was not received, a very large value was produced, signalling a lack of data.

A sample of wire wool was chosen at an appropriate thickness, determined using a visual test (sufficient to block light between the strands). A signal was detected by the receiver at the distance of the wire wool. Also, when rotating the wire wool, detections were also produced. Since the surface of the object is made of strands of iron, we believe that US is scattered or reflected in different directions rather than producing a reflected signal in a single direction.

A single thickness of paper serviette normal to the sensor was reflective enough to provide a detection. But rotating it through 30°produced large distance values, meaning that it reflected little US energy in the direction of the transducer.

Table 2: Distance Measurements in Experiment D: for each offset distance, D_O the distance to the guitar is measured using US, D_U

D_O(cm)	0	2	4	6	8	10	12	14	16	18	20	22
$D_U(cm)$	46.5	45.5	45.5	45.8	45.8	47.4	49.0	172.0	45.6	45.4	44.9	44.9

A gauze was unwrapped to produce a single thickness, which did not reflect the ultrasound, and the distance measured was found to be 91cm, i.e. the US passes through the gauze, reflects from the backboard, and travels back through the gauze to the receiver. We doubled the gauze up to 8 thicknesses, which produced an identical result. The gauze is composed of very little material per unit area, and sound can easily pass through its wide holes.

D. Concept of B-mode ultrasound

The distances measured by US, D_U at the offset distances, D_O, distance of sensor along a straight line from the initial value, were seen to approximate the curves of the classical guitar fairly well. The meaning of distances D_U and D_O are shown clearly in Figure 4a. An outlier was found, $D_U = 172.0$ cm at $D_O = 14$cm and removed. Figures 4b. and the plot in c. shows how the US measurements approximate the guitar's curves.

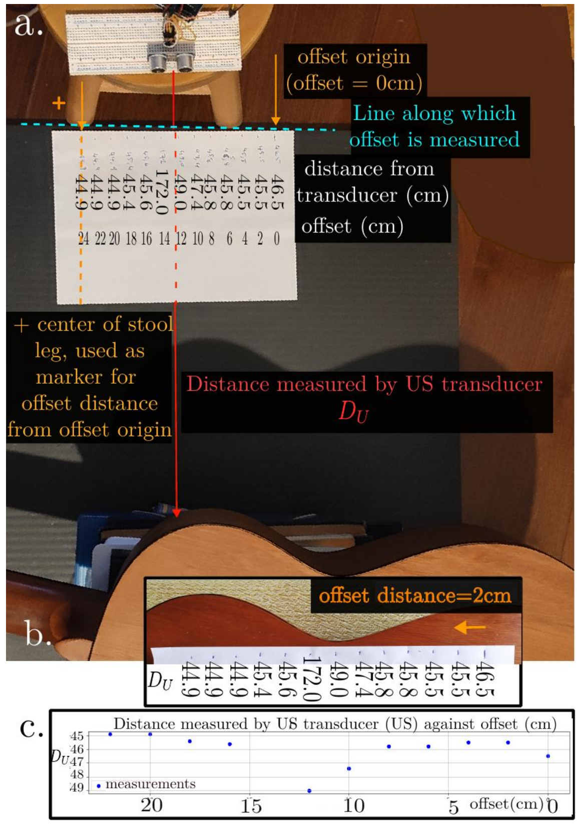


Fig. 4: Experimental setup and results for B-mode US experiment. (a.) Setup of transducer, guitar, stool and paper. The center of the stool leg (red dotted line) measured offset distance (D_O, [cm]). The US scanlines were determined by sliding the stool 2cm across the edge of the mat for successive readings, which were marked on the page, along with D_U. (b.) D_U values, overlaid on the guitar, set at approximately the same angle and scale as the guitar in (a.). (c.) Data were plotted with inverted vertical and horizontal axes and presented to see how well they fit the guitar curves.

VI. Discussion

Our objective is to teach ultrasonography, which takes place in a body which has a large water content and uses ultrasound in the range of MHz, while we have used a sensor with a frequency range of approximately 40kHz in air. We believe that the methodology is valid for students to learn physical principles of acoustic wave propagation, but care should be taken to describe limitations of the experiments.

These simple experiments could be performed by students in a two-hour laboratory session. Some students could have problems with Arduino setup, wiring of the breadboard, and using the IDE to upload programs.

A. Estimation of the speed of sound in air, v_{air}

The value of speed of sound estimated from experiment was close to that computed from equation 2. This experiment shows the student that sound is transmitted, travels to the reflector and back to receiver. It also shows that the US scanner measures time, not distance, and makes assumptions about the speed of sound in the medium. US in the clinical setting assumes a constant speed in the body ($\approx 1540m/s$) whereas speed varies in different tissues, leading to image distortion.

We might investigate the variation of v with temperature and humidity in a lab, perhaps cooling the air or using hot and humid air from an open autoclave.

B. Approximation of the beam profile

While datasheet [6] does not provide a beam angle, [7] quotes the effectual angle as $< 15°$ and shows a directional pattern (Figure 3c) where the main beam energy is concentrated at $\pm 20°$. Our result, 18°, is in reasonable agreement. We note that this experiment was difficult to carry out accurately, as the plates had to be moved symmetrically. Reference [8] provides further information about angule beam testing.

C. Description of acoustic properties of different materials

This experiment allows students to discover how sound interacts with different materials. Acoustic absorbers, reflectors, scatterers and materials with low US interaction were used. Relating our results about reflective and low interaction materials to equation 4 (R_I), we deduce that the gauze has a very similar z to air, whereas the z for the serviette is more different. Absorption of ultrasound by a sponge may be intuitive to students, since materials which dampen reverberation in a room are often spongy. The wire wool is difficult to categorize as a scatterer, and in future experiments we might rethink this choice of material.

D. Concepts of B-mode ultrasound

This experiment provides experience with B-mode principles, manually setting the different scan lines. The results of experiment were reasonable, and show that ultrasound can determine the shape of the guitar body. We had an outlier, and believe this occurs because the beam energy is reflected away from the receiver at this point. Perhaps wrapping the curves with slightly crunched aluminium foil could provide an additional step to the methodology, since the resulting scattering might provide enough signal for a detection.

VII. Conclusion

1. Low-cost equipment was chosen for teaching US principles, including the HC-SR04 US sensor attached to an Arduino Uno, partly influenced by equipment already available in university laboratories.
2. We developed a set of didactic experiments to assist teaching of basic US concepts, obtained reasonable results: determining the speed of sound; estimating the angle of the main beam of the US transducer; describing acoustic properties of materials; and determining the profile of a classical guitar using a B-mode style acquisition with parallel, equally spaced scanlines. We believe these will provide excellent learning experiences for students with a simple 40kHz sensor in air, from which they can explore ultrasonography in MHz frequencies and obtain a better understanding of theoretical concepts.

In future work we would like to build upon this base of experiments and refine those described. There are websites (e.g. [4]) which describe modifications to the sensor, which could be useful for creating new experiments and more suitable equipment. We may use a stepper motor to rotate the sensor in different directions, providing a sector format B-mode experiment, or perform beamforming experiments with multiple US sensors to steer the beam electronically.

VIII. Compliance with ethical requirements

Statement of human and animal rights

No human or animal subjects were used in this study.

Conflict of Interest

The authors declare that they have no conflict of interest.

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