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Ultrasound scanner—Teaching tool

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Abstract

Ultrasound imaging, one of the most widely used diagnostic modalities, anchors the fields of medicine, physics, and engineering. In university classrooms, however, ultrasound imaging is often taught passively with a lack of practical element as the clinical machines are not easily available and there are very few alternative teaching tools available on the market. As part of an undergraduate student project, we have developed a teaching toolkit featuring an inexpensive ultrasonic range finder to demonstrate the pulse-echo imaging process. The primary focus is the construction of equipment to enable known pedagogic principles (relating to active learning) to be applied to the subject area of ultrasound. Although operating at an acoustic frequency considerably lower than that employed clinically (and therefore achieving a much lower spatial resolution), the toolkit provides students with large observable effects while keeping cost to the minimum. Completed with an easy-to-use user interface and a set of carefully designed supplementary material (https://stacks.iop.org/EJP/42/055703/mmedia) including worksheets and lab technician guide, this toolkit aims to teach students the fundamental principles of ultrasound imaging via hands-on practice. We have designed it to be cheap, easy to set up, and portable. The effectiveness and impact of the toolkit were evaluated by ten undergraduate students who responded in the form of satisfaction questionnaires. To minimise the selection bias, we chose five students who had received no prior university-based instruction on ultrasound and five third-year biomedical engineering students who had learned about the topic previously. They demonstrated a strong interest in using the toolkit for a lab session and described it as user-friendly and highly engaging.

Keywords: ultrasound imaging, teaching, toolkit

S Supplementary material for this article is available online

(Some figures may appear in colour only in the online journal)

1. Introduction

1.1. Pedagogical need

Ultrasound imaging is a diagnostic imaging modality that uses high-frequency acoustic waves to detect and produce images of structures within the body [1]. The topic is a core component of most undergraduate biomedical engineering and medical physics curricula and provides an exemplar of how principles of physics and engineering can be applied to healthcare. It is also a multidisciplinary area of which a solid understanding is expected to help students in any science-related discipline to appreciate a wide range of other core learning objectives (LOs) in higher education [2, 3]. Unfortunately, it is usually taught passively by means of equations and picture, primarily because diagnostic ultrasound machines are often too bulky or expensive to be made available for classroom use. Furthermore, these machines are built for clinical use with the majority of the intermediate processes hidden from view [4].

In pedagogical literature, it is long established that students tend to have an enriched understanding of a topic if they participate in the learning process. The active learning leads to sparkles of interest and improvements in academic performance [6–9]. We thereby propose a simplified, economical, easy-to-make device that preserves the core engineering and design while emphasising user participation.

There are mainly two reasons behind the lack of a satisfactory solution to this problem. Firstly, clinical imaging machines have complicated designs that are challenging to reproduce. Secondly, even when people publish work describing a hacked, recreated ultrasound machine, the individual components can be too expensive for a university laboratory to mass purchase. The audience of such expensive and complex homemade ultrasound scanner is usually the technology-enthusiasts or electronic specialists rather than university students [5].

1.2. Background material

1.2.1. Pulse-echo principle. The governing principle of ultrasound imaging is echo-location, where reflections of pulses of sound are used to determine the location of surrounding objects. Assuming a constant speed of sound in the medium, the time of arrival of an 'echo' enables the distance of the reflecting object to be known. Animals such as bats and dolphins employ echo-location as a means of navigation. Human development of technology based on echo-location was prompted by the sinking of the Titanic in 1912 when 'sonar' (sound navigation and ranging) was developed as a way of detecting icebergs. Echo-location using radio waves later became the basis or radar. In both technologies, a beam of pulses is usually swept over 360 degrees to achieve ranging over a circular field [10].

1.2.2. A-mode and B-mode. The development of imaging of the human body using pulses of high-frequency sound (ultrasound) began in the 1940s. A so-called transducer is electronically excited and sends a sequence of pulses into the human body (or some material). When the pulses propagate from one medium to another, the difference in acoustic impedance (Z) of the two media, however subtle, causes a fraction of the ultrasound to be reflected and then detected by the same transducer. The reflection is known as an echo. In the early ultrasound systems, the amplitude of the returning echoes was displayed against arrival time on an oscilloscope trace, which is commonly referred to as an A-mode (amplitude-mode) display. Note the amplitude of the voltage produced by the piezoelectric transducer is proportional to the intensity of the received ultrasound echo [10, 11]. Subsequently, engineers developed means of mechanically scanning the ultrasound beam of pulses back-and-forth to enable so-called B-mode (brightness-mode) images to be generated, where echo amplitudes are encoded in the brightness of pixels displayed within a two-dimensional plane. Later, thanks to the advancement in computing and electronics, scanning was achieved electronically using arrays of small transducers [10, 11].

1.2.3. Attenuation. The intensity of an ultrasound pulse diminishes as it travels through a medium due to absorption, where acoustic energy is converted into heat, and scatter, where some energy deviates from its original line of propagation. The intensity of a planar wave decays exponentially with distance, which can be expressed as $I = I_0 e^{-\mu x}$, where I_0 and I represent the intensity before and after the attenuation and μ is the intensity attenuation coefficient of the wave travelling in the x-direction [11, 12].

1.2.4. Resolution. One of the key characteristics of an ultrasound imaging system is spatial resolution, which is the ability to distinguish two points as separate in space. For diagnostic ultrasound, this is further categorised into axial resolution and lateral resolution. Axial resolution refers to the minimum distance that can be differentiated between two reflectors located at different depths along the beam axis, while the lateral resolution is a measure of the ability to distinguish two reflectors at the same depth (which is applicable when scanning the beam across a plane) [13].

1.2.5. Modern ultrasound machines. Modern clinical systems rapidly scan the beam back and forth in order to acquire and display images at video rates. The detected echoes are digitised and post-processed before the ultrasound image is constructed and displayed on a screen. An important step in the post-processing stage is the so-called time gain compensation (TGC), where the detected signals are amplified by an exponentially increasing factor to compensate for the attenuation of the ultrasound in tissue [14].

2. Methodology

The chosen LOs of the toolkit are as follows:

(a) Understand the pulse-echo principle
(b) Observe the attenuation effect and understand the function of a TGC algorithm
(c) Understand the general concept of axial resolution
(d) Relate the scan obtained with the phantom (i.e. the object being scanned)

To deliver these LOs, we designed four activities (section 2.2) for students to complete using the toolkit.

2.1. Building blocks

The key to delivering these LOs lies in the choice of ultrasound ‘probe’. On one hand, it needs to demonstrate the important characteristics of ultrasound. On the other hand, we intend to keep the cost to the minimum such that reproducing this toolkit is realistic for university lab budgets. Fortunately, an ultrasonic range finder (HC-SR04) proves to be a good fit for this purpose. Conventionally, ultrasound ranging is only concerned with the travel time of the pulse, such that the distance from the ranger to a surrounding object can be determined, but with HC-SR04 it is possible to access the pulse and echo signal at certain points on the circuit [15]. Moreover, it is cost-effective, readily available on the market, and easily portable.

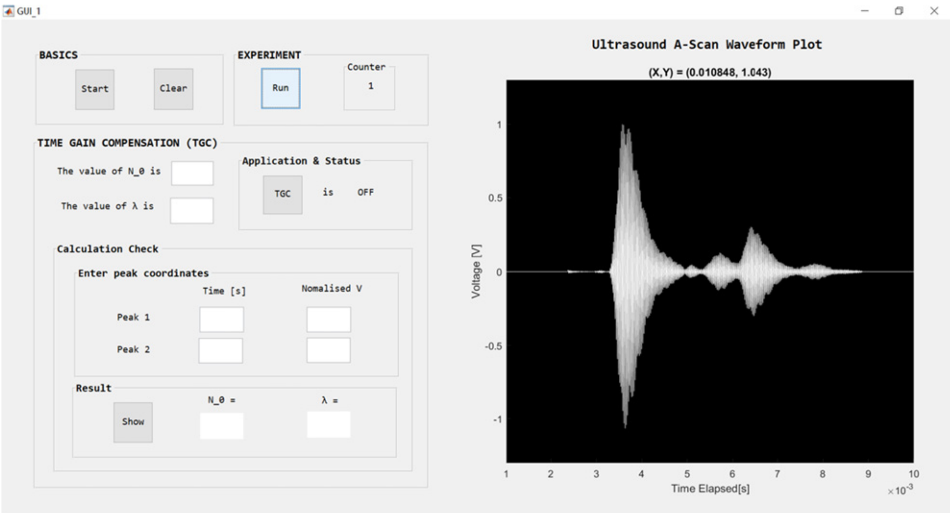


Figure 1. The user interface developed in MATLAB R2018a using the in-built GUIDE function. There is a control panel on the left-hand size and a display of the waveform on the right-hand side (voltage/amplitude against time).

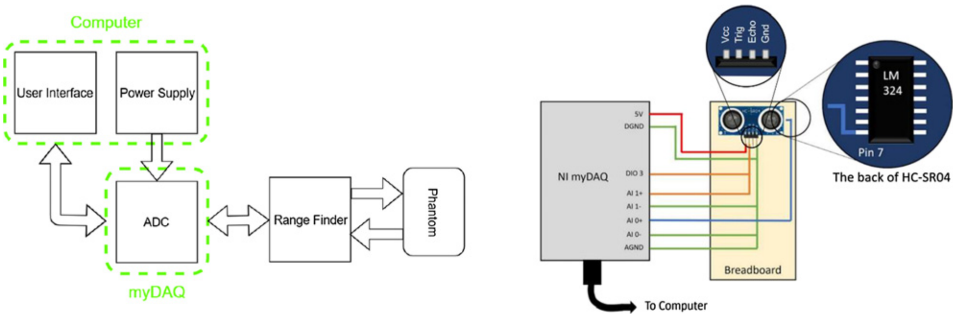


Figure 2. (a) (left) The block diagram of the toolkit. (b) (right) The schematic diagram showing the all of the wire connections between the range finder (HC-SR04) and NI myDAQ.

For device manipulation and data visualisation, we developed a user interface in the form of an APP in MATLAB R2018a[1] (figure 1). It has a control panel, a signal display (normalised amplitude against time elapsed from triggering the scan), and some TGC-related features.

To bridge the HC-SR04 and the computer, an analogue-to-digital converter(ADC) is needed. As the range finder produces 40 kHz waves, to avoid signal aliasing, the ADC needs to have a sampling rate of over 80 kHz. Two solutions were considered in developing the toolkit: either an Arduino UNO used with an external add-on ADC (AD7819), or an NI myDAQ device[2]. Our final choice was the NI myDAQ device because of its high sampling rate (up to 200 kHz), ease of communication with MATLAB, and availability in our laboratory. The former solution

[1] https://uk.mathworks.com/products/new_products/release2018a.html.

[2] https://ni.com/en-gb/shop/select/mydaq-student-data-acquisition-device?modelId=134166.

is also expected to work as the sampling rate of AD 7819 is also above the Nyquist frequency, but only with further programing and debugging, which was not achievable within the set timeframe of this project.

Finally, we refer to the object being imaged as the 'phantom'. At the current stage, it is a cuboid-shaped box made of card-paper. The ultrasound pulse originated at the range finder could not penetrate this type of material, so we simulate the different layers that would have been detected should pulse penetration be possible, by manually moving the phantom to different 'depths', i.e. different perpendicular distances to the range finder.

Figure 2(a) shows the block diagram of the whole toolkit and its general workflow.

2.2. The activities

The pulse-echo principle lays the foundation of ultrasound imaging, regardless of the display mode or application, hence it is essential that students have a solid grasp of it before moving on to any other concepts.

TGC was chosen because it was an indispensable part of ultrasound postprocessing. In commercial ultrasound imaging devices, the beam is focussed and suffers an exponential decrease in amplitude due to absorption by the body tissue, thereby showing the importance of a TGC algorithm. However, the beam used in this project is not focussed but spreads out to cover a fan-shaped area. Nevertheless, the amplitude of the signal also suffers from an exponential decrease in amplitude. Although the likely cause is the spreading out of the pulse rather than absorption, the need for a TGC algorithm remains.

Axial resolution was deemed important because it is one of the key criteria of an ultrasound system. Different to clinical ultrasound, the pulses from the range finder cannot penetrate the surface of the phantom and only the front face can be detected. Our solution is to manually move the testing phantom to different depths and overlay the various waveform plots on top of each other, after which it is possible to find the axial resolution on the graph. Students will also find the theoretical axial resolution, compare it with the experimental result, and discuss if there is any difference between the two values.

To implement the very last LO, we designed an activity called the pseudo-2D scan. During physical examinations, it is common practice for clinicians to move the probe around on the skin. In this project, this was mimicked by asking the user to manually move the hardware horizontally (without changing the perpendicular distance between the range finder and the phantom) and obtain an image at each of the positions. This is the only activity where there was more than one cuboid in the phantom. More cuboids could be used, and their geometry will also be reflected in the waveform plot, but two of them were already adequate to deliver the LOs. Multiple objection detection in one scan was possible given the spread-out nature of the pulse generated by the range finder.

The range finder exhibits two interesting characteristics that make pseudo-2D scans possible. The first one is that the peak of the echo waveform of an object perpendicularly closer to the range finder appears earlier (in terms of time) than that of a perpendicularly further one. The second feature is that the pulse intensity is the highest directly in front of the range finder. As a result, if the phantom contains two cuboids placed at different perpendicular and horizontal distances from the range finder, then it is possible to obtain two peaks (due to the difference in the perpendicular distance) with different amplitude (due to the difference in the horizontal distance).

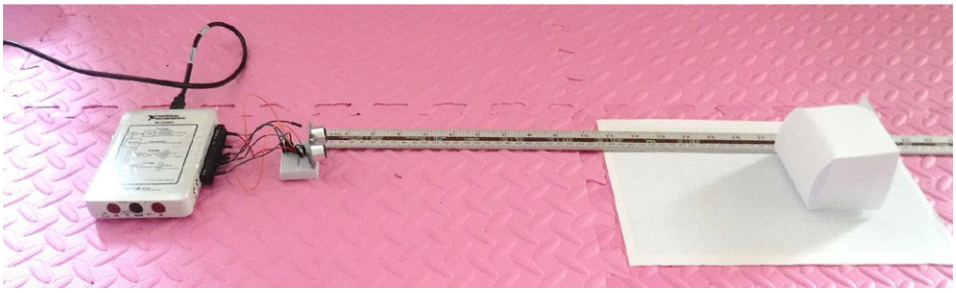


Figure 3. A photo of the equipment (phantom included) showing the setup of the lab practical.

3. Methods

3.1. The probe

The ultrasonic range finder (HC-SR04), acting as the probe of the toolkit, has two transducers, one for pulse transmission and the other for echo detection.

3.2. The ADC

As shown in figure 2(b), the range finder had its Vcc pin connected to the 5 V power line on myDAQ and the trig pin to both the DIO3 and AI1+ channels of myDAQ. Note that DIO channel 3 was used in this project as it was the only channel that can send clocked pulses. The exact channel number is hardware-determined and can be easily acquired through MATLAB. The pin 7 of the LM324 operational amplifier, situated at the back of the receiving transducer on the range finder, was connected to AI0+. For ease of connection, we recommend soldering one end of a connective wire at pin 7 of LM324. To ensure a common ground, all the ground channels in the hardware were connected: the Gnd pin of the range finder, and the DGND, AGND, AI0−, AI1− channels of NI myDAQ.

3.3. The user interface

Developed as an APP in *MATLAB R2018a*, the user interface allows for the initiation of scans (including a counter), visualisation of the returning echo, and the implementation of the TGC algorithm. In addition, extra code has been implemented to get rid of the crosstalk and perform amplitude normalisation.

3.4. The lab session

The two sets of worksheets in the appendix contain step by step instructions on the four chosen activities. The basic process of using the toolkit is to place the phantom, composed of either one (for activity 1 and 3, see figure 3) or two (activity 4) paper cuboids, in front of the range finder as instructed, then use the user interface to take scans and observe the resultant waveform plot. Illustrations of the two-phantom setup can be found in the supplementary worksheets. In activity 3 (axial resolution), three to four scans were taken for each plot, each scan taken with the phantom at a different distance from the range finder. Activity 2 is purely software-based, where the user works out the exponential decay from the coordinates of the peaks in the waveform plot and then input its characterising parameters to the user interface to implement the TGC algorithm.

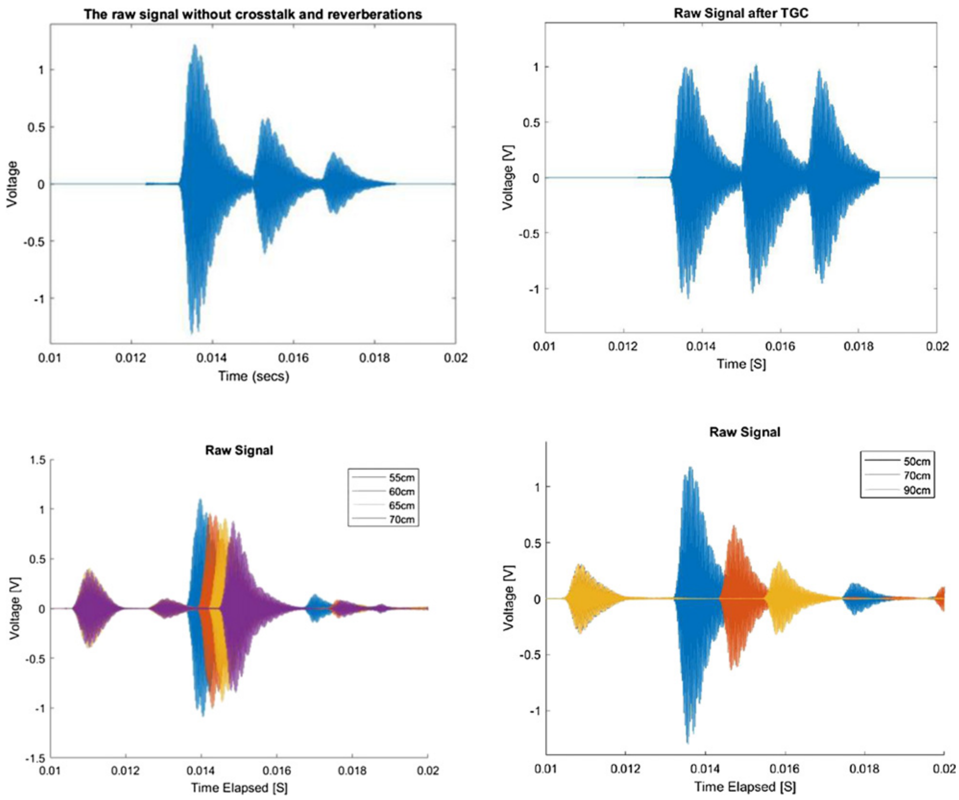


Figure 4. (a) (top left) The waveform plot before applying TGC algorithm. (b) (top right) The waveform plot after applying TGC algorithm. (c) (bottom left) The waveform plot showing resolvable peaks. Here the distance D between adjacent positions of the phantom is 20 cm and this is larger than the axial resolution of the range finder. (d) (bottom right) The waveform plot showing unresolvable peaks, with $D = 5$ cm ($D <$ axial resolution).

3.5. User feedback

Ten undergraduate students were invited to try the toolkit and complete a user satisfaction questionnaire: five with no universality teaching on ultrasound imaging and five with a background in biomedical engineering. The questionnaire was designed with reference to the one developed by Wolff *et al* [16] Briefly, there were ten questions on the various aspects of the toolkit and students would give a rating between 1 to 5 (a higher score indicates more agreement). Each student was introduced to the toolkit and the worksheets. They subsequently performed the four experiments before answering the questionnaire individually.

4. Results

Both the hardware and software were fully functional, and the toolkit clearly demonstrated that the travelling distance of the ultrasound pulse is twice the distance between the range finder and the reflecting surface, thus fulfiling the aim of activity 1 (pulse-echo imaging). In applying activity 2 (TGC), the peaks in a single waveform plot tend towards the same amplitude as expected figures 4(a) and (b). For activity 3 (axial resolution), the waveform was able to show the difference between resolved (figure 4(c)) and unresolved (figure 4(d)) peaks. In addition, the relative positions of two cubes were successful determined using activity 4.

Table 1 in the appendix shows the student feedback reflected by the questionnaires. Notably, all of the students agreed that the software was really easy to use. Many also agreed that the toolkit was engaging and helped to visualise the concepts. Three of the four activities received highly positive feedback and there was room for improvement on the TGC activity. It was also demonstrated that the students think the toolkit was better at visualising the topic than helping them to remember it.

5. Discussion

A simplified, pedagogy-oriented ultrasound device has been designed and built so that each step of the imaging process is observable and controllable. The use of an ultrasonic range finder in replacement of the diagnostic ultrasound transducer has proven to be advantageous in many aspects. First, it produces larger, more observable effects. With a high-frequency ultrasound pulse, the axial resolution is very small (likely to be below 1 cm). While this is favourable for imaging purposes, a small distance is hard to achieve for a teaching lab session and the effects of going below or above the axial resolution are also going to be too small to be observed. In addition, our chosen range finder is significantly cheaper than the majority of ultrasound transducers on the market. Furthermore, the lower the frequency, the easier the digitisation process.

On the other hand, the range finder does have a few inherent artefacts including crosstalk and reverberation. The latter one is also a frequently observed artefact in diagnostic ultrasound, but the former is a drawback of the range finder itself [17]. The most likely cause for crosstalk is the lack of damping material in the range finder. Clinical ultrasound probes contain a block of backing material situated behind the transducer to quickly dampen any left-over vibrations from pulse generation, prior to receiving the returning echoes [11].

The strengths of this project lie in the functionality of the toolkit. The hardware works exceptionally well with the software in delivering the four designed activities. The myDAQ provided high-quality data that can be rigorously visualised using the software. Furthermore, worksheets with step by step guidelines were developed (in a style similar to the IGCSE physics experiment exam paper) so that the toolkit is appropriate for a lab session [18]. There are two sets of worksheets, one introductory and the other advanced, in order to accommodate the different background knowledge of the students. They were designed such that the language is clear, and the format is easy to follow, with illustrations, tables, and thinking exercises to facilitate the learning process. Additionally, to help with the preparation for the lab session, an instruction sheet for the lab technicians was developed. It includes a detailed component list, a schematics page showing every connection in the hardware, a printout of the phantom, and a step-by-step guide on how to make the shielding device for activity 4 (pseudo-2D scan).

The toolkit performance was found to be optimal under the following conditions: as signal saturation was observed when the phantom was placed closer than 45 cm to the range finder, it is best to prepare an empty bench longer than 45 cm. The maximum distance we used in this project was around a metre, above which the amplitude of the echo signal decreases too much to be accurately detected. Furthermore, it is important to ensure the surface of the phantom is at a 90-degree angle with the primary direction of travel of the ultrasound pulses to avoid a decrease in the amplitude of the echoes. One possible way to ease this procedure is to place a large sheet of 1 mm squared paper on the bench, which has not been tested within this project but is a reasonable solution to try in practice. Furthermore, because the normalisation process uses the amplitude of the peak in the first run as the divisor, the phantom has to be placed from close to far (amplitude decreases) so that the normalisation does not result in erroneous results.

While the toolkit was under iterative developments, informal student feedback was used to progressively improve the software. For example, one comment was that a calculation check for the parameters used in the TGC algorithm would help students gain more confidence in this experiment, and this was reflected in the final software design.

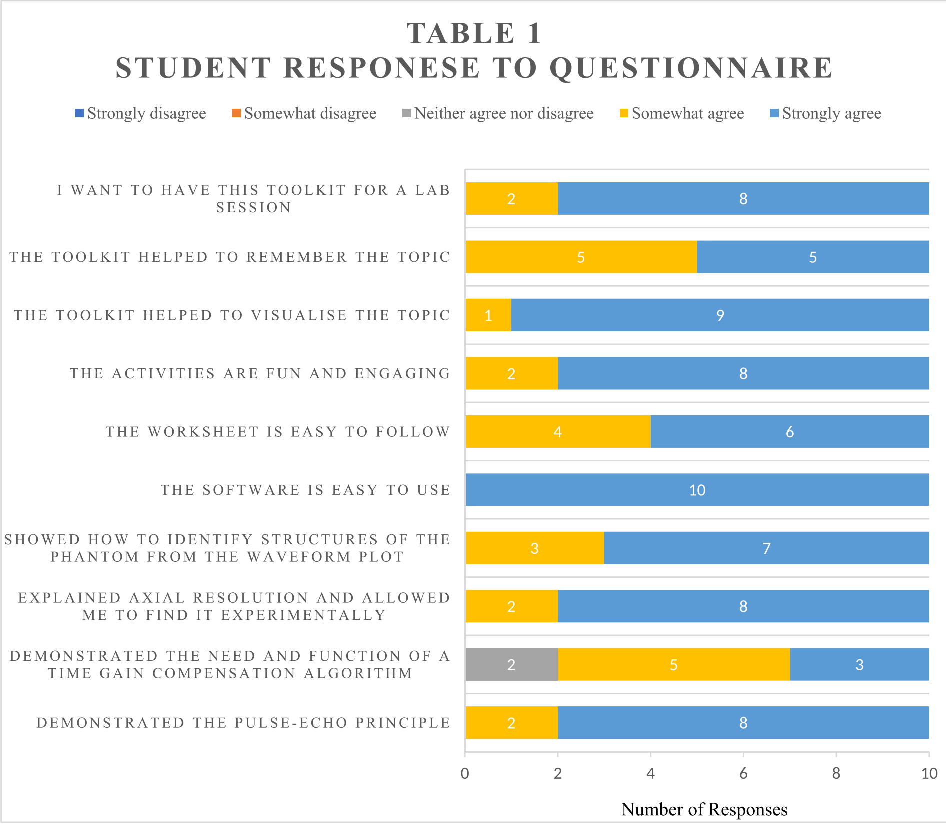
Ten different students attempted the practical and completed satisfaction questionnaires that contained ten carefully selected questions. All of the students were pleased with the straightforward design of the user interface. They generally found activities 1, 3, and 4 easy to understand. However, activity 2 (TGC) seemed to have caused some confusions, especially with the group without prior universality knowledge on ultrasound imaging. This indicated poor delivery of LO 2. The biomedical engineering students suggested that changing the wording or phrasing and adding more preparatory material for TGC on the introductory worksheet might ease the process of grasping the concept. The alternative solution is to remove LO 2 when delivering this practical to a cohort of students who have not studied this topic at university.

Feedback on the worksheet was also quite positive. Students verbally commented that the worksheet might be too long for a single lab session in terms of time and that some pages are very text heavy and might add pressure to the learning process. To address this issue, the worksheets can be divided to be done in two lab sessions instead of one and some of the concepts can be explained by figures rather than chunks of texts that might appear daunting to the students.

Most of the student agreed that the toolkit helped them to visualise the topic, but it was not as good in terms of helping them to remember the topic. A possible solution is to introduce more thinking exercises in the worksheets to trigger more critical reflection (high-level learning), as all of the students found great enjoyment in doing the one included in part 4 of the worksheet. Orders of learning is conventionally defined by the Bloom's taxonomy (revised), where cognitive processes are categorised (from simple to complex) into remember, understand, apply, analyse and create [19]. Overall, students perceived that the practical helped with their higher-level skills of understanding and comprehension of the topic, rather than merely remembering concepts. The majority of students agreed that they would like to have this toolkit for a lab session, and that marks a key success of this project, as the most important part of any teaching process is a strong will to learn. As the biomedical engineering students had a module of learning on ultrasound without practical work, their response also suggests that the addition of the intervention (i.e. the ultrasound practical which this toolkit is designed to deliver) could be potentially beneficial to an ultrasound module that is currently taught purely by lectures.

We acknowledge that the questionnaire presented in this paper was a pilot evaluation. There is a rich body of work in physics education research that probes into the application of scientific methods to test student learning [20]. In order to evaluate the pedagogic usefulness of the toolkit, we suggest the following steps. First, design a questionnaire that assesses both the conceptual understanding (via multiple-choice test [21]) [22–24] and the emotional engagement (Likert-scale-based surveys) [25, 26]. At the end of the teaching year, issue it to one class of undergraduate students (60–100 students) on a relevant module who have not had access to the practical described here. In the next year, add in the practical while keeping the other changes to the course to a minimum. Then repeat the same questionnaire at the end of the year. The hypothesis is that the group that did the practical demonstrates superior knowledge retention and comprehension, as well as enthusiasm for the subject and perceived level of understanding. Alternatively, the survey can be delivered to one group of students twice: before (but after classroom teaching) and after doing the practical. Regarding the statistics, the 'scores' for the section on knowledge retention and understanding could be compared with a t-test, where the

Table 1. The vertical axis lists the items in the questionnaire and the horizontal axis denotes the number of responses. The length of coloured bar for questionnaire items = the number of students giving a certain rating.



null hypothesis is that the mean score of the group without the practical equals that of the group with the practical. In terms of the Likert-scale-based component on emotional engagement, the median response for each question could be compared with a Mann–Whitney-U-test.

Regarding the cost, for the UCL medical physics and biomedical engineering lab, where myDAQs were readily available, the additional cost was as little as 1 pound (for purchasing the range finder), thus the current design was chosen for this project. For a lab without myDAQ devices, it is possible that the current design does not fit the budget. In which case, the alternative is to replace NI myDAQ with an Arduino UNO and an external ADC. However, this design needs further testing and adjustments in software design.

The phantom is an important area for future research. At the ultrasound frequencies used, the difference in acoustic impedance between air and other materials (solid or liquid) is so great that almost total reflection occurs. The paper cuboids used are good reflectors, readily available in our lab, and are sufficient to deliver the four chosen LOs. The parking sensor is not suitable for immersion in liquid, and we deemed that the additional complexities and cost of doing the experiments under water outweighed the pedagogic benefit, but would recommend further research into this.

6. Conclusion

In this project, a fully integrated ultrasound teaching toolkit was developed to fulfil this unmet pedagogical need. The hardware was designed using ready-to-use components which are common in a physics/engineering laboratory; the software, which includes an easy-to-follow graphical user interface, was developed in MATLAB; the worksheets were written to detail the experimental procedures for a lab session; the instructions for lab technicians was developed to help with the lab preparation. In conclusion, this toolkit offers a unique opportunity for students to actively engage with the imaging process, thus advancing their level of comprehension of ultrasound imaging.

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Appendix

See table 1.

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