Development of a novel fetal heart rate triangulation algorithm for multiple gestation pregnancies

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Abstract

Fetal heart rate (fHR) monitoring is critical for assessing fetal health *in utero*, especially in pregnancies involving twins, triplets, or higher order pregnancies, where standard monitoring techniques may struggle to distinguish individual heart rates due to the close proximity of fetuses. Given that Doppler Ultrasound (US) is the *de facto* standard for fHR monitoring, it is crucial to improve its accuracy and effectiveness in multiple gestation scenarios. Doppler US works by measuring an object's distance by the reflection of transmitted ultrasound waves through a given medium over time. We aimed to create a phantom model with medical gel that replicates the uterus tissue, as well as speakers that would act as the heart beats, and piezoelectrics that acted as the sensor array in a given position. With this, we aimed to collect data from the speakers and Arduino code attached to the piezoelectrics to use this data as the heart signals that we would later deconvolute and use. Additionally, we designed an algorithm that utilizes ultrasound data generated in MATLAB, applying Fast Fourier Transform (FFT) and bandpass filtering to isolate specific heart rate frequencies. We then used this data in a non-linear least squares optimization approach for Time Difference of Arrival (TDoA) calculations to triangulate the fHRs in three-dimensional space. The results demonstrate that the algorithm can effectively separate and locate two unique fHRs, with potential implications for enhancing fetal monitoring in higher order gestation pregnancies. Our work represents a step towards improving fetal monitoring techniques, offering a promising tool for obstetric care in multiple gestation pregnancies.

Keywords: fetal heart rate (fHR) monitoring, triangulation, multiple gestation pregnancies, Doppler ultrasound (US), Time Difference of Arrival (TDoA), signal processing, non-linear least squares optimization

Introduction

Multiple gestation (twin, triplet, etc.) births constitute approximately 3% to 4.5% of all births. These births often result in premature delivery and produce infants who are small for the gestational age and have lower birth weights.[1] Notably, the neonatal mortality rate for black twin infants is twice that of white twins, highlighting health disparities in multiple gestation pregnancies. Improvements in technology that improve outcomes for these infants–such as birth weight and mortality rates–are necessary for addressing these healthcare gaps. Doppler ultrasound (US) is the *de facto* technology for fetal heart rate (fHR) monitoring in pregnant women, operating by measuring distances through the reflection of US waves through mediums over time. This technology currently presents two problems: it can obstruct the lower back of the pregnant person, complicating the efficient and effective administration of an epidural during labor, which can be highly desired during labor and delivery. Furthermore, while standard clinical fHR monitors wrap around the lower back, they typically can monitor only one heart rate at a time. This limitation makes it difficult to differentiate between multiple heart rates in the case of multiple gestation pregnancies. This year's project aimed to design a gel phantom that mimics the environment of multiple gestations. This gel phantom was used to test a heart rate monitoring device capable of receiving voltage data from multiple sources. Finally, an algorithm was developed to filter, analyze, and identify simultaneous fHRs.

Doppler Ultrasound

In clinical practice, the *de facto* method for fHR monitoring is the Doppler US. This method is used to monitor the fHR before and during labor and is performed using a US transducer that is either fixed on the abdomen or handheld by a medical professional. The continuous monitoring of the fHR and of the uterine activity is known as cardiotocography[2] (CTG), and a monitor is fixed on the abdomen in this case. For intermittent fHR monitoring, a handheld Doppler US is used. The primary objective of fHR monitoring is to reduce fetal mortality and morbidity by identifying the fetuses' heart rates and risks, as well as the optimal timing for delivery. However, the use of Doppler today ranges from assessing blood flow in the fetus and umbilical cord, to even flow patterns in the heart. The Doppler US had a huge innovative progression from the 1960s up until the late 1990s, from a simple audio signal to a predominantly subjective image format.[3] However, since then, there have been no major innovations to this technology.

Significance

Twin pregnancies have higher rates of neonatal death and fetal death during labor than a singleton,[4] due to the fact that around 70% of twin births are premature.[5] However, monitoring fetal heart beats in the third trimester (29-40 weeks) is more pertinent to the fetal outcome at the time of birth.[6] In multiple-gestation pregnancies, which are inherently high-risk, the health of the fetuses is paramount to minimize complications for both the fetuses and the pregnant individual. Fetal health is typically assessed by monitoring the fHR of each fetus through the gestation period. Although fetal heartbeats can be detected as early as five to six weeks, current Doppler US technology does not reliably identify individual heartbeats until 10-12 weeks of gestation.[7] Accurately monitoring distinct heart rates in multiple gestation pregnancies is challenging with Doppler US due to the limited space within the womb and relative positioning of the fetuses, which complicates the detection of separate heartbeats. Furthermore, monitoring twin heart rates often involves using up to two Doppler US transducers. This setup can lead to errors where one fetus's heart rate is recorded twice, leaving the other twin unmonitored.

Specific Aim 1

To safely test our novel algorithm, we aimed to optimize the method for integrating sound emitting devices into the gel phantom, a gelatinous model used to replicate the acoustic impedances of human tissue for US imaging. In order to optimize the method for creating a phantom model, we aimed to develop a non-invasive method to seamlessly generate phantom heartbeats through the integration of microphones into a gel that mimics the various layers of human tissue that surround a typical uterus, while avoiding the creation of unintended artifacts.

Specific Aim 2

We aimed to redesign the Doppler US device array to enhance the detection of multiple fHRs from different sensors positioned along the abdomen and extending down the side of the mother. This redesign was necessary because the initial sensor configuration attempted to triangulate the fHRs from sensors placed solely on a single plane above the fetuses, which proved inadequate. The MATLAB processing framework struggled with this configuration, often inaccurately identifying the locations of the target hearts, and thus inaccurately calculating their heart rates. By expanding the sensor array to wrap over the abdomen and down the side, we improved the distribution of the sensors and enhanced their ability to accurately triangulate the heart rates in three-dimensional space.

Specific Aim 3

The final and main aim of this project was to develop an algorithm to filter and analyze ultrasound data to identify the heart rates of multiple fetuses in a womb. This code was generated in MATLAB and aimed to filter the signals, Fourier transform, and triangulate the heart beats using Time Difference of Arrival (TDoA) to get the unique positions of the hearts in three-dimensional space, while also accounting for the impedances and attenuations of the signal from the uterus to the sensors.

Materials

Gel Phantom Material

Two pounds of unprepared Gelatin #3, equivalent to 64 cubic inches, were purchased from Humimic

Medical[8] for our gel phantom model. This gel was selected because its acoustic properties are optimally suited for replicating uterine tissue, as described by the manufacturer. Given that the device is designed for clinical use with pregnant individuals and needs to model a system with twins *in utero*, this gel was deemed ideal.

Gel Phantom Fetal Heartbeat Generator

An Arduino Uno[9] was purchased from Arduino to construct our fetal heartbeat generator. Additionally, two 2-Watt 8 Ohm speakers were purchased from Amazon, which were used to emit heartbeat mimic signals within the gel phantom.

Fetal Heart Rate Monitor

The piezoelectrics and electrical tape for the fHR monitor were purchased from Amazon, while the wires were included in our Arduino Uno kit. The Arduino Uno board, purchased from Arduino, was used to import the data from our fHR monitor.

Methods

Gel Phantom Model Development

The gel phantom was created using the following steps: Initially, 2 lbs of gel phantom material was divided by hand into approximately 1 cubic inch portions, as recommended in the manufacturer's instructions that accompanied our gel purchase. We then placed these chunks into an oven-safe glass dish that yielded a pie-shaped gel phantom with dimensions of 3.5 cm in height, 19 cm in upper diameter, and 23 cm in lower diameter (refer to Supplemental Figure 1 for visual reference). The dish was then heated in a conventional oven set at 250 ℉ (121 ℃) for four hours, or until no bubbles remained in the gel. Once fully melted, the gel was removed from the oven and allowed to cool at room temperature for 12 hours, covered with aluminum foil to protect against contamination by foreign materials during the cooling process. After the cooling period, the solidified gel was carefully removed from the baking dish and placed on a plate, then covered with aluminum foil once more to protect it from contaminants. To facilitate cleaner cuts, a heated knife blade was used to slice a 4 cm section into the side of the gel. Two speakers were inserted 7 cm apart within the gel to simulate "phantom fetal heartbeats" designated as "Fetus A" and "Fetus B." The gel does not require special storage conditions and was kept covered at room-temperature, approximately 70℉ (21℃).

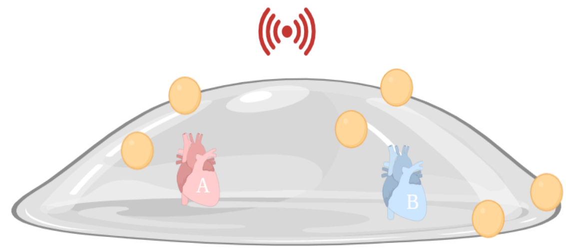

Figure 1. Gel phantom model with the speakers in the medium represented as the hearts, and our sensor array for data collection.

Fetal Heartbeat Data Generation

Gel Phantom Data Generation

The fetal heartbeat generator was constructed using an Arduino Uno and two speakers. The Arduino Uno was programmed to generate audible pulses that mimic fetal heartbeats *in utero.* This program, adapted from code by Roman Ramirez and Andrew Thede, enabled the control needed to generate distinct heartbeat signals from each speaker.

Fetal Heart Rate Data Filtering

After collecting sound data and generating synthetic data, we utilized a MATLAB algorithm for signal processing. We used a Fast Fourier Transform (FFT) to convert the time-domain data into the frequency-domain for further analysis (Figure 2). This transformation was necessary because fetal heartbeats are characterized by specific frequencies, and converting to the frequency-domain allowed us to validate the generated signals. Bandpass filters were then applied to focus on the highest peaks, isolating these signals and reducing noise for subsequent processing.

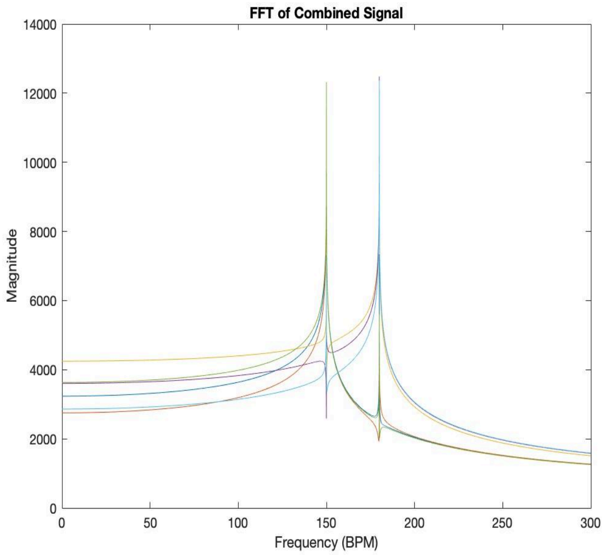

Figure 2. Frequency domain analysis for hearts A, B, and combined. An FFT and bandpass filter were applied to isolate frequencies and determine the BPM of each heart.

Triangulation Method Development

TDoA

TDoA was used to calculate the physical distances separating each sensor to the heartbeats, given the speed of sound in uterine tissue. To accomplish this, we first generated synthetic heartbeat signals using the method outlined above. The sensor array was configured in six three-dimensional locations, with sensors 16 cm apart. They were strategically placed to encompass both the abdominal and lateral aspects of the subject. Each sensor's signal was calculated using the Euclidean distance between each sensor and the fetal heart source (Heart A and Heart B). For a sensor at position s_i and a source at p_A or p_B, the distance d_{iA} or d_{iB} is given by (1).

$$d_{iA} = ||p_A - s_i|| , d_{iB} = ||p_B - s_i|| \quad (1)$$

Then, the time delay for the signals due to the propagation of sound through uterine tissue, with a speed of sound c (e.g. 1458.85 m/s)[10] was calculated using (2).

$$\tau_{iA} = \frac{d_{iA}}{c} , \tau_{iB} = \frac{d_{iB}}{c} \quad (2)$$

These time delays were used to shift the synthetic heart rate signals, which were modeled as sinusoidal waves modulated by the heart rate frequency, attenuated by the inverse of time. The signal from Heart A and B received at sensor i can be described by (3, 4).

$$x_{iA}(t) = (\frac{a}{t - \tau_{iA}}) \cdot sin(2\pi f_A (t - \tau_{iA})) \quad (3)$$

$$x_{iB}(t) = (\frac{a}{t - \tau_{iB}}) \cdot sin(2\pi f_B (t - \tau_{iB})) \quad (4)$$

where f_A and f_B are the heart rate frequencies for Heart A and Heart B, respectively, and a is the attenuation factor.

The combined signals from both sources were then added together for each sensor, simulating the overlapping waveforms that would be detected in an actual monitoring scenario. These signals formed the basis for our TDoA calculations, where we measured the arrival times of signals at each sensor relative to the first sensor, which became the foundation for subsequent source triangulation.

Triangulation algorithm

In order to triangulate two fHRs *in utero*, we first used the MATLAB fminsearch function, a direct search method particularly suited for our application due to its compatibility with non-linear, non-differentiable functions. The optimization process was configured with specific options to control the end of the optimization process based on the tolerance for the function value change (*'TolFun'*). See Supplementary Equation 1.

The source locations for Heart A and B were estimated by minimizing the cost function designed to calculate the error in TDoA. The initial guess for the heart locations was set at the origin (0,0,0). The cost function, *tdoa_cost*, calculates the error between the measured TDoA and the predicted TDoA calculated for a given position x. See Supplementary Equation 2.

The *tdoa_cost* function calculates the sum of squared differences between the measured and predicted TDoA values. For a guessed position x, the predicted TDoA for each sensor is computed by the difference in distance from the guessed position to each sensor divided by the speed of sound c, normalized by the distance to the reference sensor. See Supplementary Equation 3. This approach identifies the position of the heart that will give the least amount of error, thus giving an estimate of the heart's location.

Fetal Heart Rate Determination

An array was created to store the peak frequencies that were detected by each sensor in our sensor array. Then, for each sensor's signal, an FFT was performed to convert the time-domain signal into its corresponding frequency-domain representation. The absolute values of the FFT results were taken to obtain the magnitude spectrum for each sensor. Within the magnitude spectrum, the maximum point was identified, which represented the peak frequency. This peak is indicative of the most dominant frequency component within the signal, or the fHR. The search for this maximum value was restricted to the first half of the frequency range (up to the Nyquist frequency) to ensure that the frequency was within the range of valid human fHRs. Once the indices of these peaks were located, they were used to reference back to the original frequency array to determine the frequencies corresponding to the peaks. These frequencies represent the estimated heart rates of the fetuses.

Results

Data Filtering

Time-delayed voltage data simulating the fetal heartbeats were generated for each of the six synthetic sensors across ten trials (Figure 3).

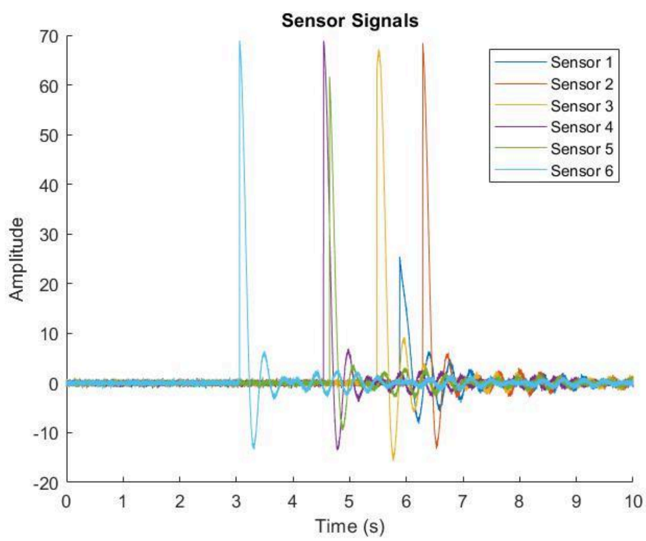

Figure 3. The generated time series over 60 seconds for the six sensors each with an error applied to the TDoA.

The time-series data from each trial was transformed into the frequency domain using FFT, resulting in spectral data (Figure 4). A MATLAB band-pass filter was applied within the range of 145 bpm to 185 bpm to remove unwanted low and high-frequency noise from the spectral data.

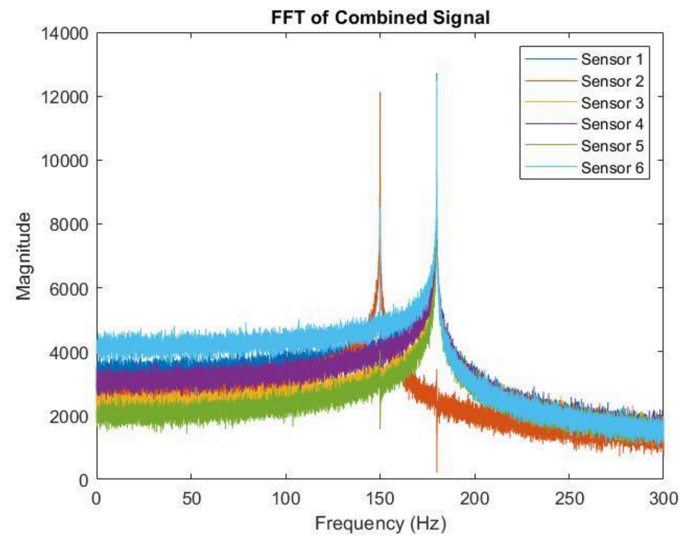

Figure 4. The Fast Fourier transformed data from the 6 synthetic sensors generated data. Shows clear peaks at 150 and 180 bpm.

Triangulation of Fetal Heartbeats

The triangulation of the fetal hearts A and B was performed using the optimization algorithm described in the methods section. This process was applied across each of the ten trials to ensure consistency in our findings. Fetus A was modeled to originate from the coordinates (1, -1.5, -1.5), with a Gaussian distributed noise applied to the TDoA measurements. This approach resulted in percent errors of 4.14%, 0.02% and 0.75% in the x, y, and z-coordinates, respectively. Similarly, the heartbeat signal for Fetus B was designed to originate from the coordinates (-3, 0, -4). The percent errors for the triangulation of this signal were 14.65% and 1.62% for the x and z-coordinates. In our analysis of the y-coordinate measurements for Fetus B, we utilized the standard error of the mean (SEM) to assess the precision of our algorithm's estimates. The SEM was calculated to be 0.17 cm. This approach was chosen to address challenges associated with calculating percent error, particularly to avoid problems arising from division by zero when the expected coordinate value is zero (Figure 5).

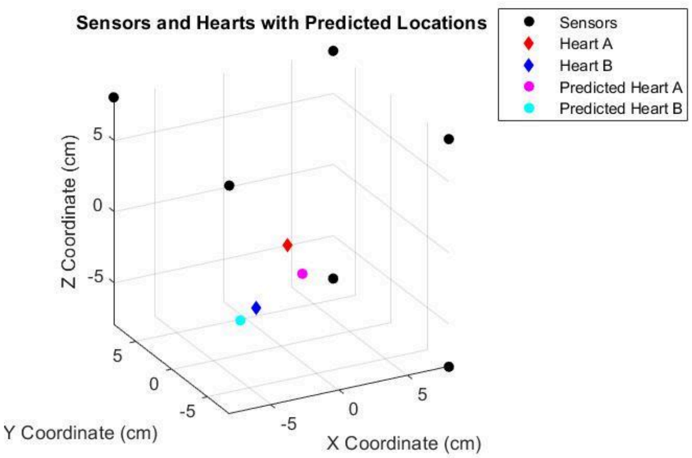

Figure 5. Location of sensors in relation to the designated locations of the fetal hearts A and B (red and blue diamonds), relative to the predicted locations for hearts A and B (magenta and cyan circles).

Discussion

Limitations

Many of the limitations we faced during this project were a result of time constraints. A significant portion of our efforts was dedicated to developing the triangulation code, which necessitated deprioritizing other objectives, specifically our original Aim 2. This aim involved developing a new prototype that accounts for maternal comfort and that does not interfere with epidural placement. Typically, fetal monitoring is disrupted when an epidural is administered, as the mother must change position, causing the handheld Doppler device to lose track of the fetal heartbeats. While we succeeded in improving the sensor array to better capture heart signals, Aim 2 remains a task for future work.

Additionally, we encountered technical difficulties with the gel phantom model. The melting point of the gel and the temperature tolerance of the speakers posed challenges, as it was hard to integrate the speakers without compromising the gel's integrity (i.e. avoid the creation of noise and speaker-air interference that resulted from the incisions in the gel, even with a sharp knife).

Furthermore, the focus of our project shifted predominantly towards enhancing signal triangulation, so we prioritized data generation through MATLAB over data collection from our gel phantom model. This shift allowed us to generate and combine signals, detect their frequencies, and calculate the TDoA for each.

Future Work

Triangulation Algorithm Refinement

Although we successfully detected two distinct fHRs in three-dimensional space, future work should focus on testing various heart locations in three-dimensional space at different distances apart. These tests would enable us to further refine our triangulation algorithm, potentially extending its application to more than two heart rates while maintaining (and eventually increasing) accuracy.

Once the algorithm is further optimized for more effective data collection and processing, we would also conduct clinical trials. These trials would compare the performance of our algorithm against the Doppler US method. The insights gained from these trials would inform additional refinements to our algorithm and enhance its clinical applicability.

Physical Model Development

Additionally, future work would involve working with the gel phantom model to a greater extent. This would involve collecting data directly from speakers and transducers within the gel. By doing so, we would be able to obtain accurate measurements of heart frequencies, taking into account the attenuation and noise influenced by the acoustic impedances of the gel, which closely mimic those of the uterus.

Optimal Maternal Comfort Redesign

One of the primary aims of this project was to redesign the Doppler US device to minimize interference with epidural placement in the lower back, while maintaining its ability to capture ultrasound data from multiple sources within an insulated environment. While we successfully optimized the placement of the transducer array to collect heart signals, the development of the physical device to improve maternal comfort did not advance as planned. Future efforts will include prototyping different configurations of the device. These designs will be clinically tested on pregnant mothers to determine which design offers the most comfort without compromising functionality.

End Matter

Author Contributions and Notes

The authors declare no conflict of interest.

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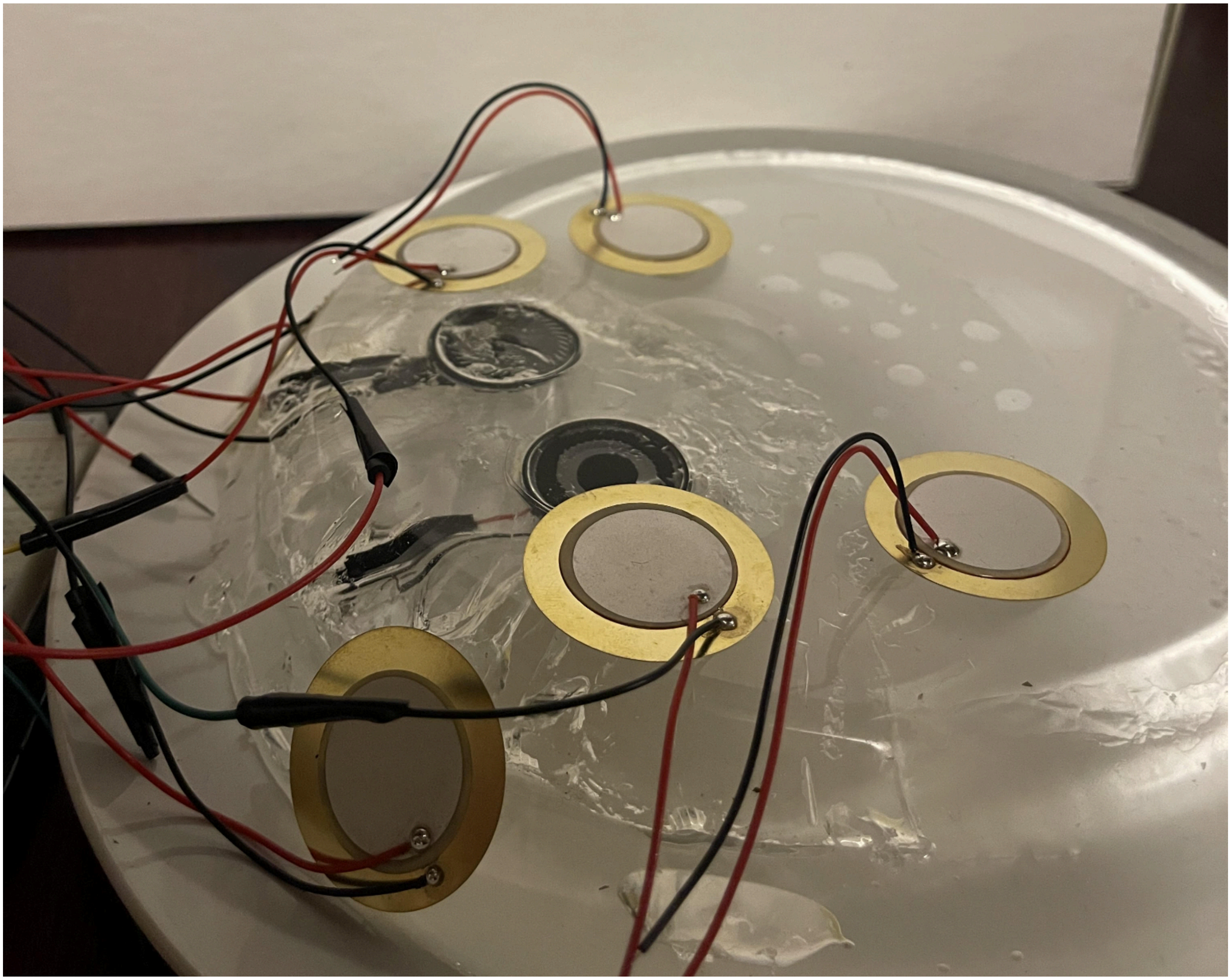
Supplementary Material

Supplementary Figure 1. Image of the gel phantom model



Supplementary Equation 1.

$$options = optimset('TolFun', 1 \times 10^{-6}$$

Supplementary Equation 2.

$$[source\_estimate\_A,\ fvalA] = fminsearch(tdoa\_cost, initial\_guess\_A, options)$$
$$[source\_estimate\_B,\ fvalB] = fminsearch(tdoa\_cost, initial\_guess\_B, options)$$

Supplementary Equation 3.

$$cost(x,\ sensors,\ TDoA,\ c) = \sum_{i=1}^{length(TDoA)} (\frac{||x - sensors[i,:]|| - ||x - sensors[1,:]||}{c} - TDoA[i])^2$$