# Design of experiments to characterize and predict polymer acoustic properties

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## Introduction

Acoustic impedance and attenuation are important material properties that impact sound propagation. Using an I-optimal design of experiments, the acoustic properties of polymers with added particles were studied with respect to multiple fabrication and characterization conditions. The resulting statistical model is used to construct sensors that are acoustically matched to materials such as human skin, wood, and water.

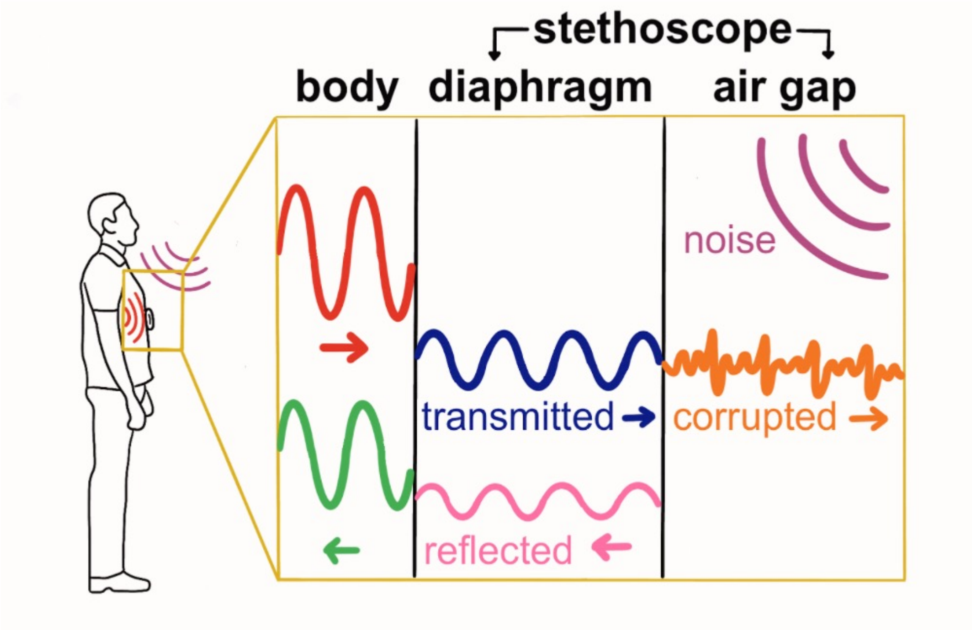


***Figure 1.*** *Diagram showing the effect of acoustic impedance on the propagation of sound from the body.*

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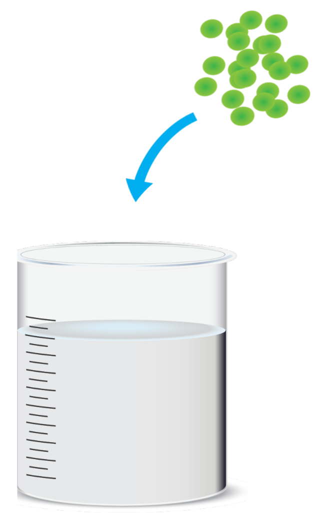
## Design of experiments setup

An optimal design was used to consider the experiment's continuous, discrete, and categorical factors with restrictions. Seven factors and four responses were studied by characterizing 98 samples.



**Factors** Polymer type, particle density, particle concentration, average particle size, sample thickness, characterization frequency, characterization temperature

**Responses** Density, speed of sound, acoustic impedance, attenuation

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***Figure 2.*** *Multiple factors were varied to assess the acoustic properties of polymers with added particles.*

## Modeling results

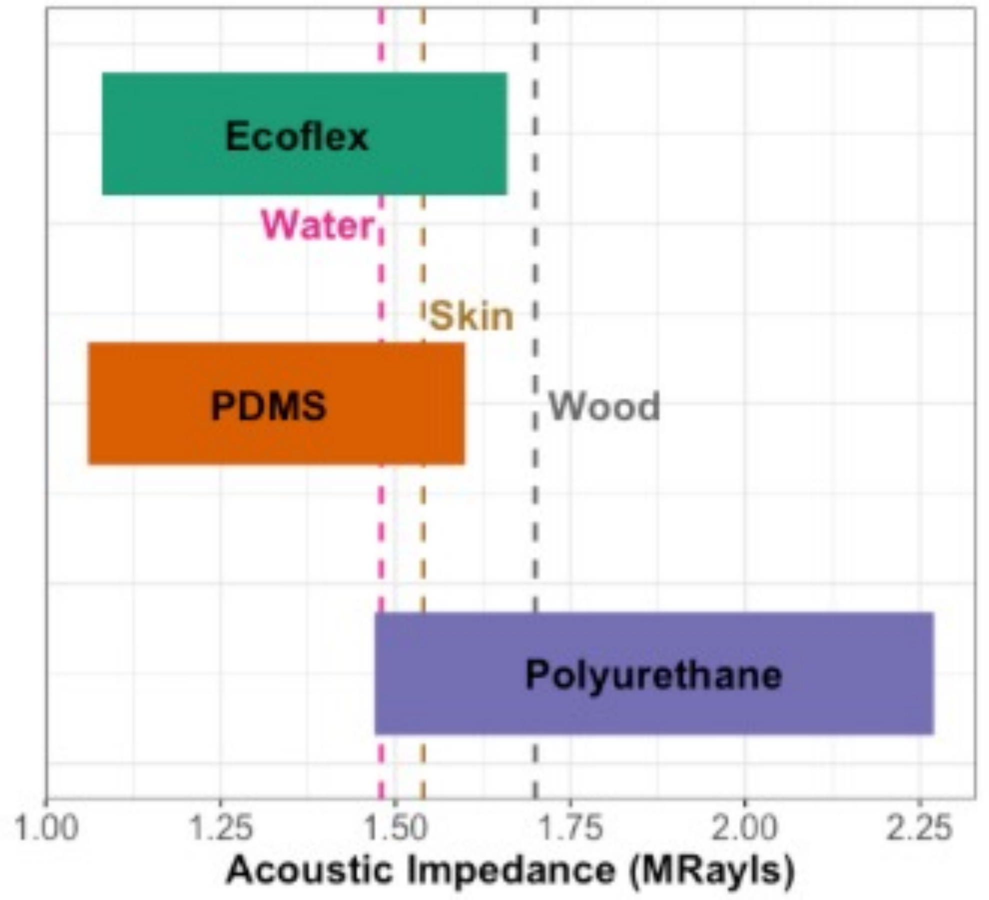
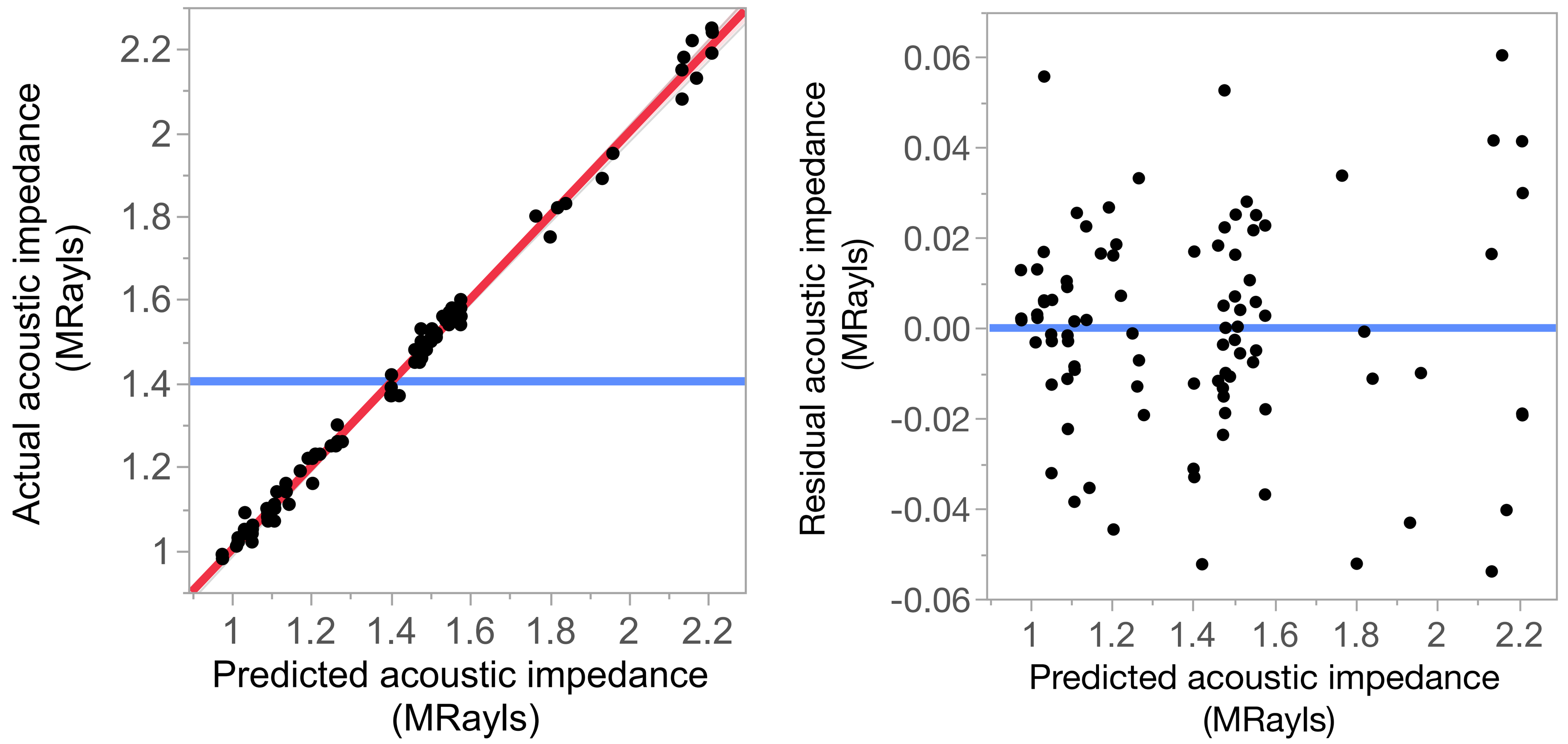



***Figure 3.*** *A range of acoustic impedances were measured and, with the proper choice of polymer and added particles, the polymers are fabricated to match water, skin, and wood.*

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Adjusted $R^2$: 0.995

Root mean square error: 0.02

***Figure 4.*** *Several results from the chosen reduced acoustic impedance model. Significant factors included polymer type, dopant concentration, and temperature. The more information section shows how the prediction profiler is used to determine the conditions to fabricate a polymer with specific acoustic properties.*

## Impedance-matched sensor (Hearo)

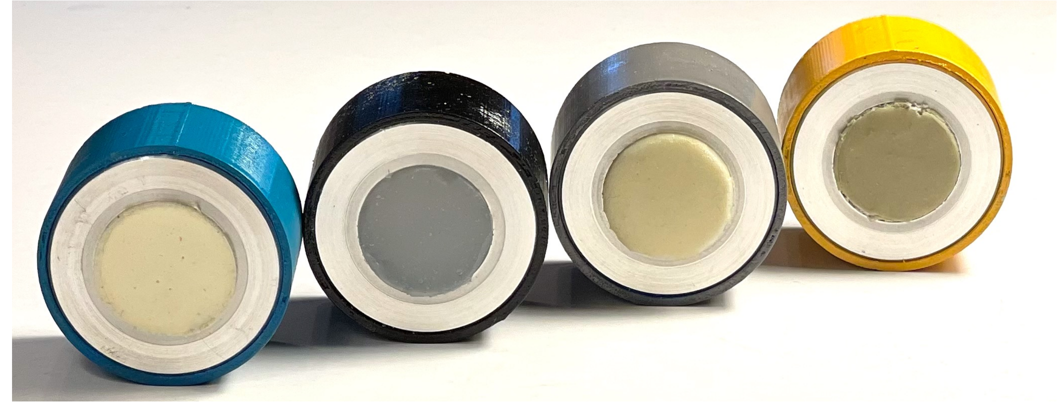

***Figure 5a.*** *Several Hearo devices with a range of acoustic impedances.*

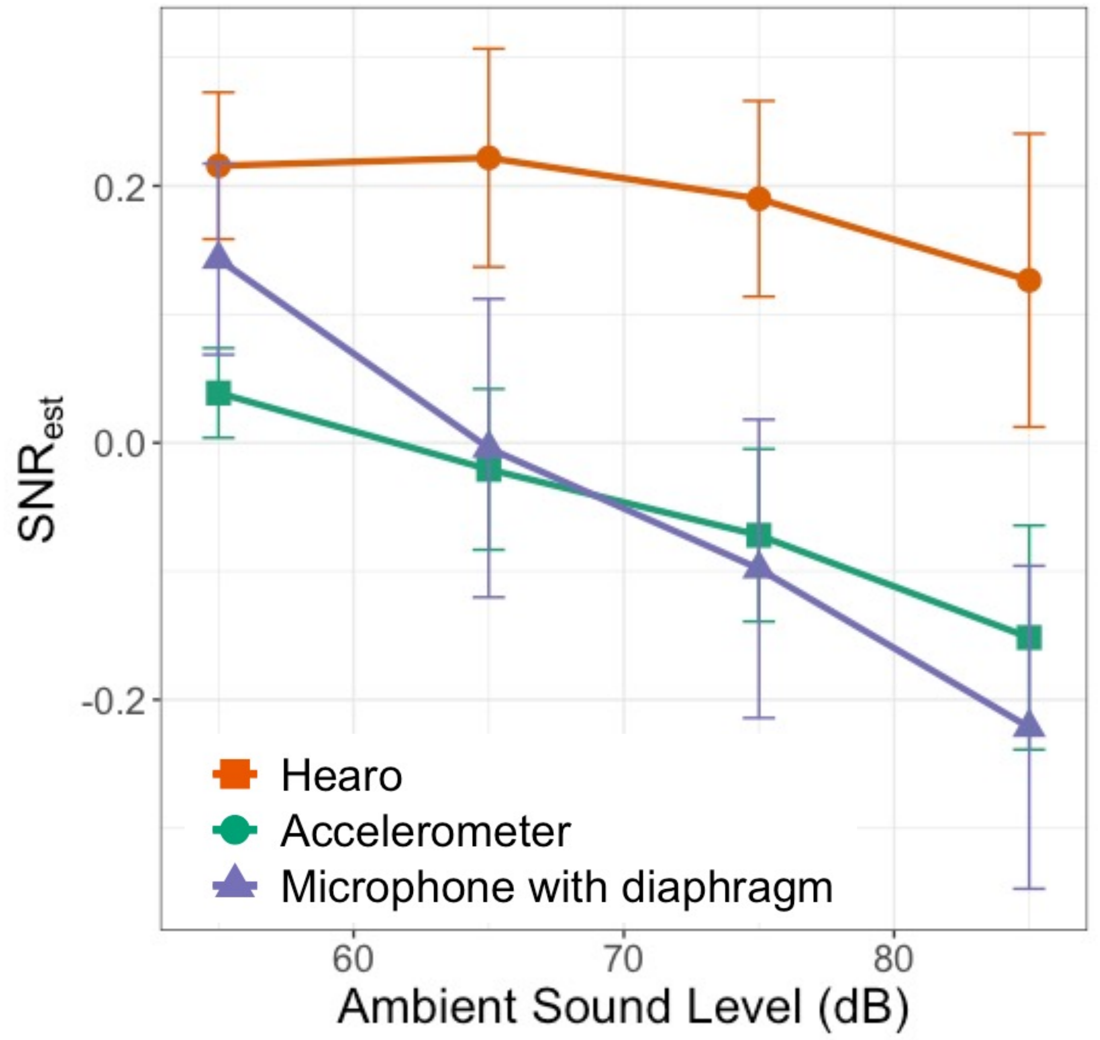


***Figure 5b.*** *SNR metrics comparing Hearo to a typical accelerometer and microphone. A higher SNR indicates greater correlation with the signal of interest and less correlation with airborne noise.*

More Info ▶

## Conclusion

A design of experiments in JMP explored the effect of seven fabrication and characterization factors on the acoustic properties of polymer samples. The resulting statistical model was used to fabricate polymers with a specific acoustic impedance and minimum attenuation. The acoustic impedance matched material is used in an acoustic sensor to improve sound capture for a variety of applications by maximizing sound transmission.

Please contact Valerie Rennoll (vrennol1@jhu.edu) for more information.

# Matching acoustic impedances maximizes sound transmission between materials.

## Figure 1. Animations showing how acoustic impedance impacts the transmission of body sounds.

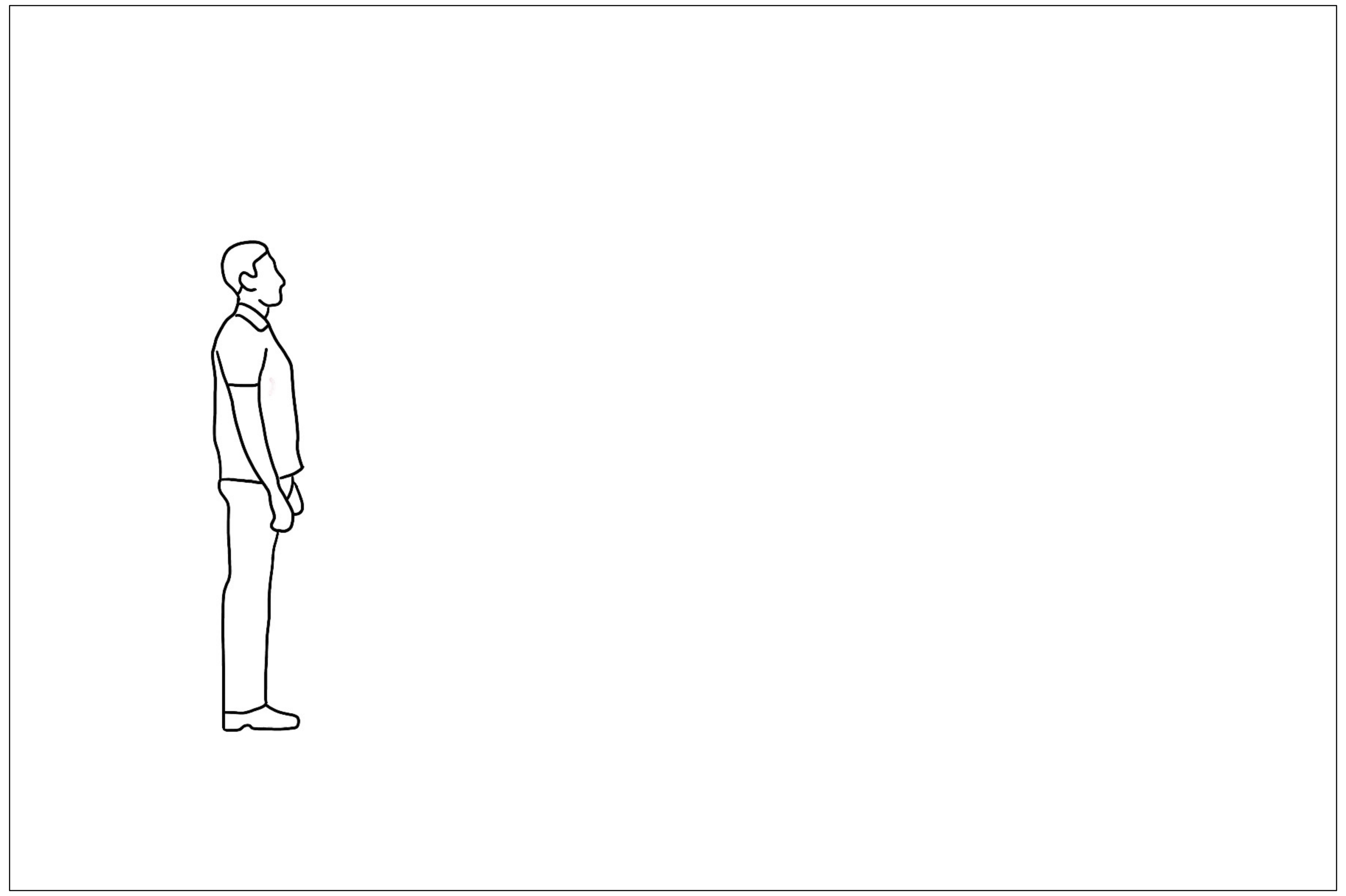

***Figure 1a.*** When your heart beats or lungs exhale, the emitted sound encounters a boundary at the interface between your skin and the air. At this interface, most sound is reflected due to the impedance mismatch between skin and air.

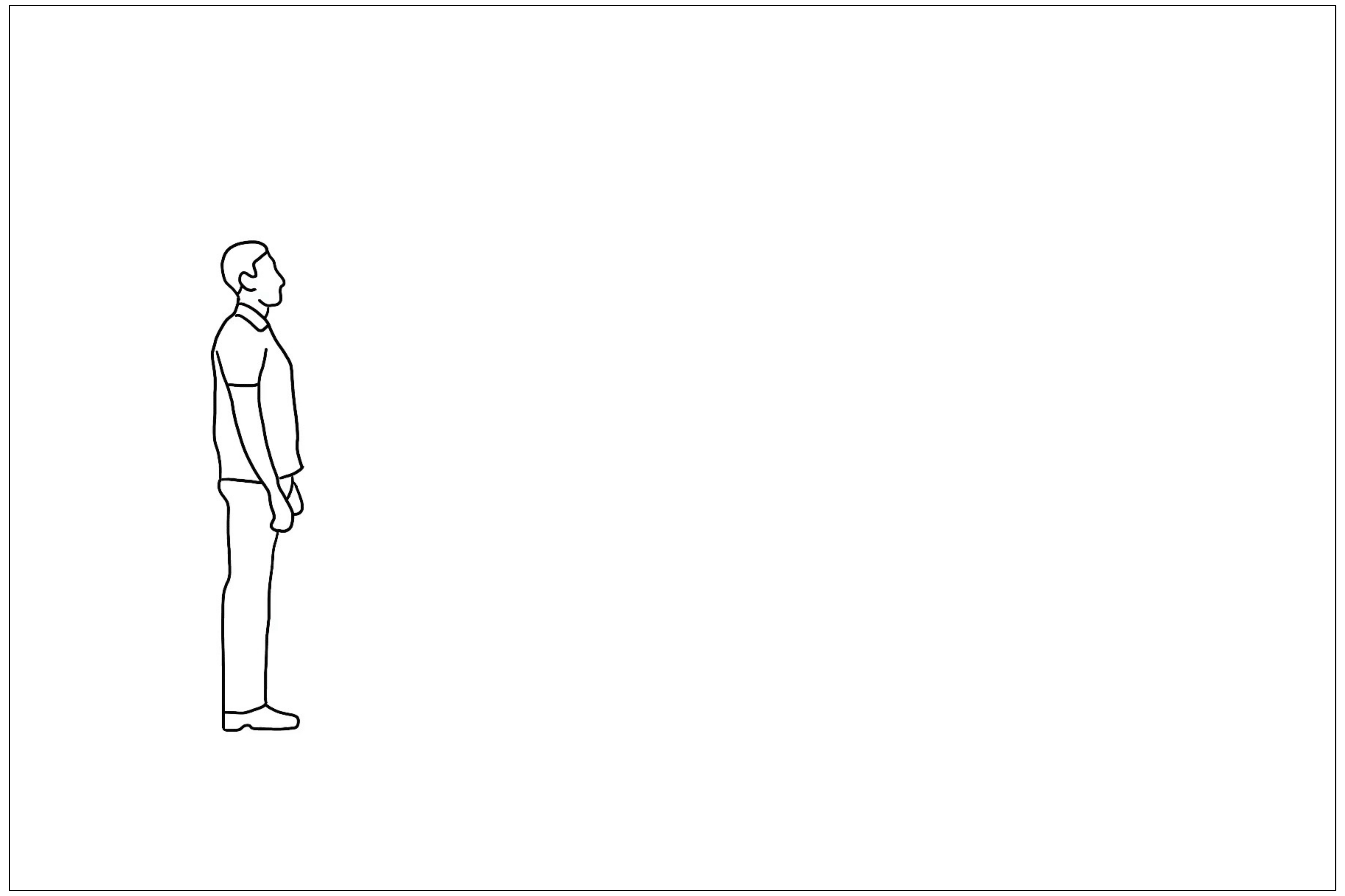

***Figure 1b.*** When a doctor listens to your body, the sound transmitted to the stethoscope encounters another interface between the diaphragm and air gap. Only a small portion of the incident energy is transmitted to the doctor's ears and a path is added where airborne noise corrupts the signal.

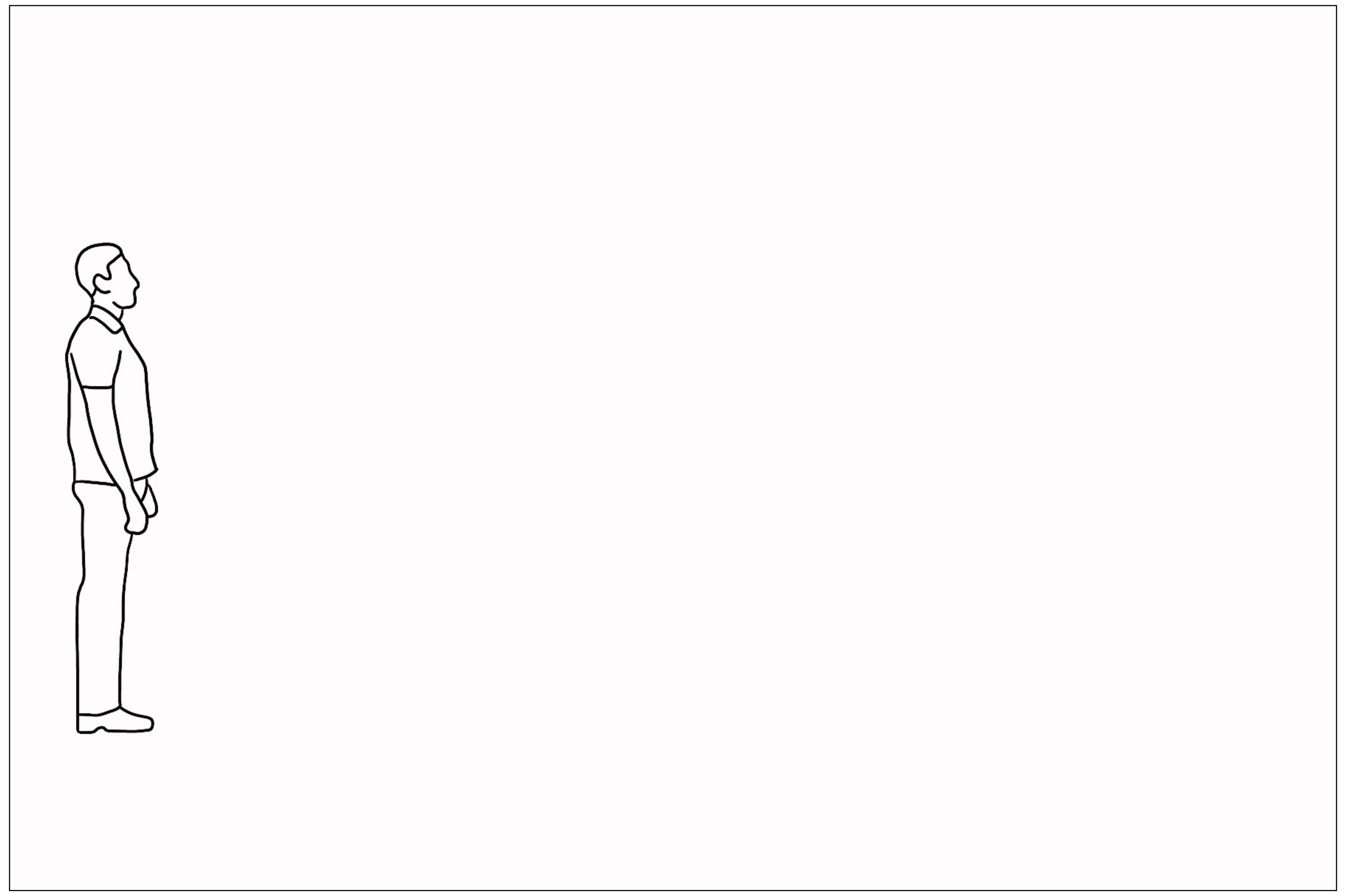

***Figure 1c.*** Using the design of experiments results, we designed a sensor (Hearo) with a material that is tuned to match the impedance of skin. The acoustic signal from the body is transmitted to the sensor with minimal reflections and no airborne noise corruption.

# An optimal design was used to explore the experimental space.

## Figure 2. Multiple factors were varied to assess the acoustic properties of polymers with added particles.

| Factor | Type | Levels |
|---|---|---|
| Polymer type | Categorical | PDMS (10:1 & 20:1), Ecoflex, Polyurethane |
| Particle density ($10^3$ kg/$m^3$) | Discrete numeric | 2.2 ($SiO_2$), 3.89 (TiO2), 6.02 ($BaTiO_3$) |
| Particle concentration (wt%) | Continuous | 0, 25, 50 |
| Average particle size (nm) | Discrete numeric | 150, 450, 1000 |
| Sample thickness (mm) | Continuous | 2, 6, 10 |
| Characterization frequency (MHz) | Discrete numeric | 0.8, 1.2, 1.6 |
| Characterization temperature (°C) | Continuous | 15, 25, 35 |

***Figure 2a.*** The various factors and levels included in the optimal design. A factor restriction with polymer type and average particle size was included for Ecoflex with 150 nm particles.

| Response | Goal |
|---|---|
| Density | None |
| Speed of sound | None |
| Acoustic impedance | Match target |
| Attenuation | Minimize |

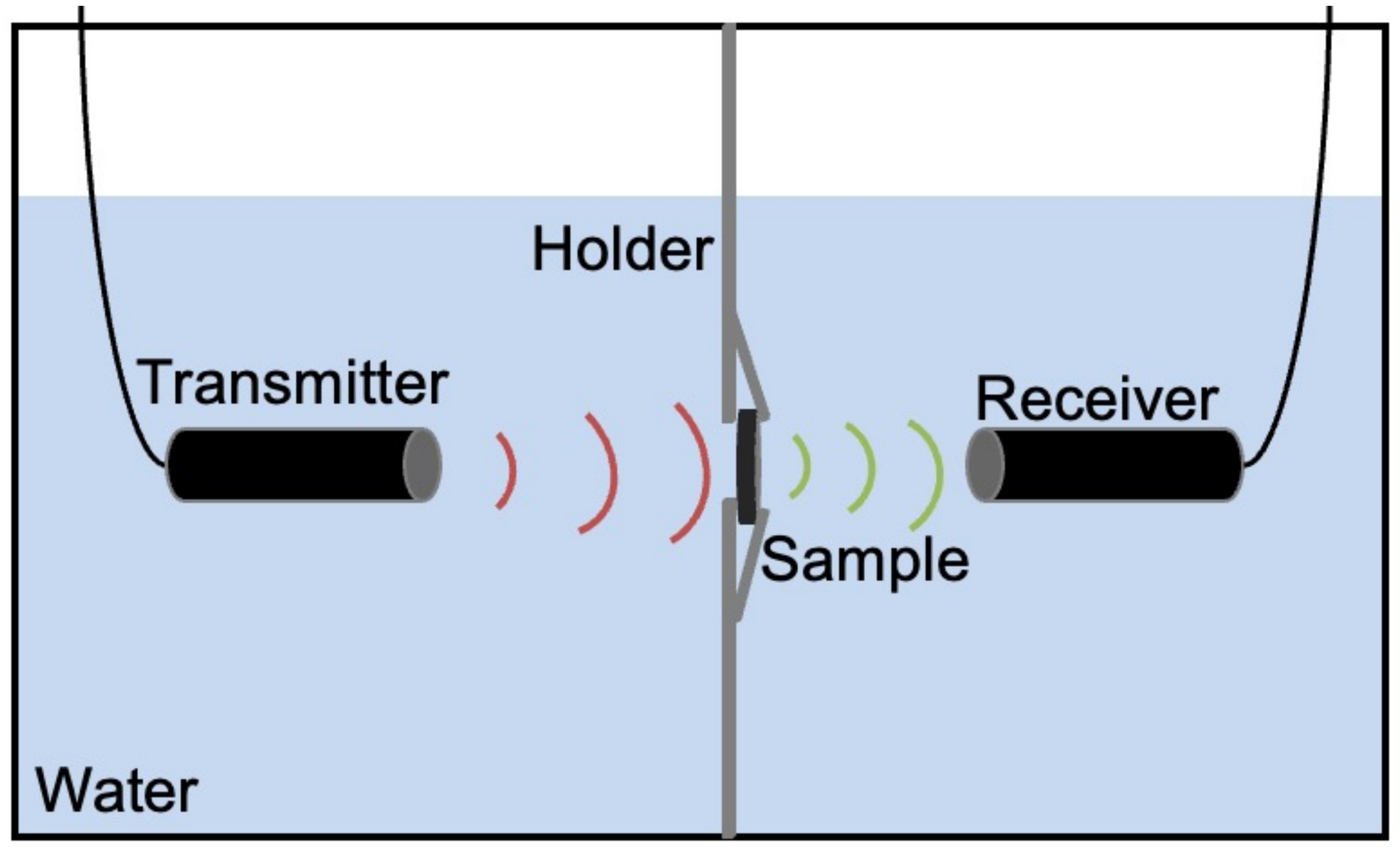


***Figure 2b.*** The responses measured from each of the 98 polymer samples and a diagram showing the through transmission setup used for acoustic characterization.

# Final models determine the factors to make a polymer with a specific acoustic impedance with high accuracy.

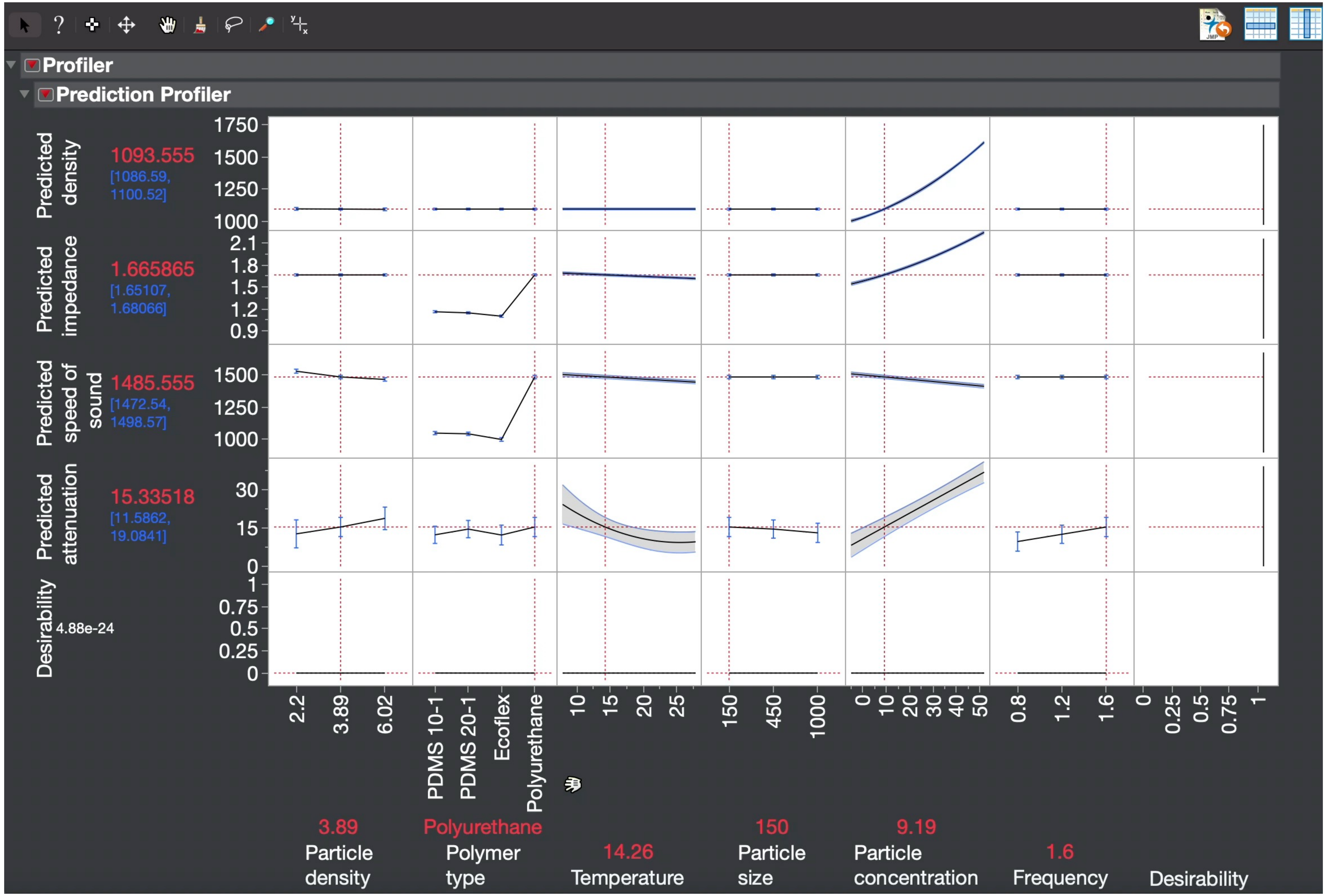


**Figure 4. The prediction profiler was used to fabricate polymers with the desired acoustic properties.**

Video showing the use of the prediction profiler to predict the conditions necessary to fabricate a polymer with an acoustic impedance of 1.3 MRayls and minimum attenuation.

The conditions from the prediction profiler were used to fabricate 9 polymer samples with targeted impedances from 1 to 2.2 MRayls with minimum and maximum attenuation. The average error between the predicted and measured acoustic impedances was 1.4%.

# Hearo demonstrates improved signal fidelity and airborne noise rejection compared to traditional acoustic sensors.

## Figure 5. Demonstrations and SNR metrics with Hearo.

***Figure 5a.*** Demonstrations showing Hearo used to record lung and heart sounds, as well as musical instruments.

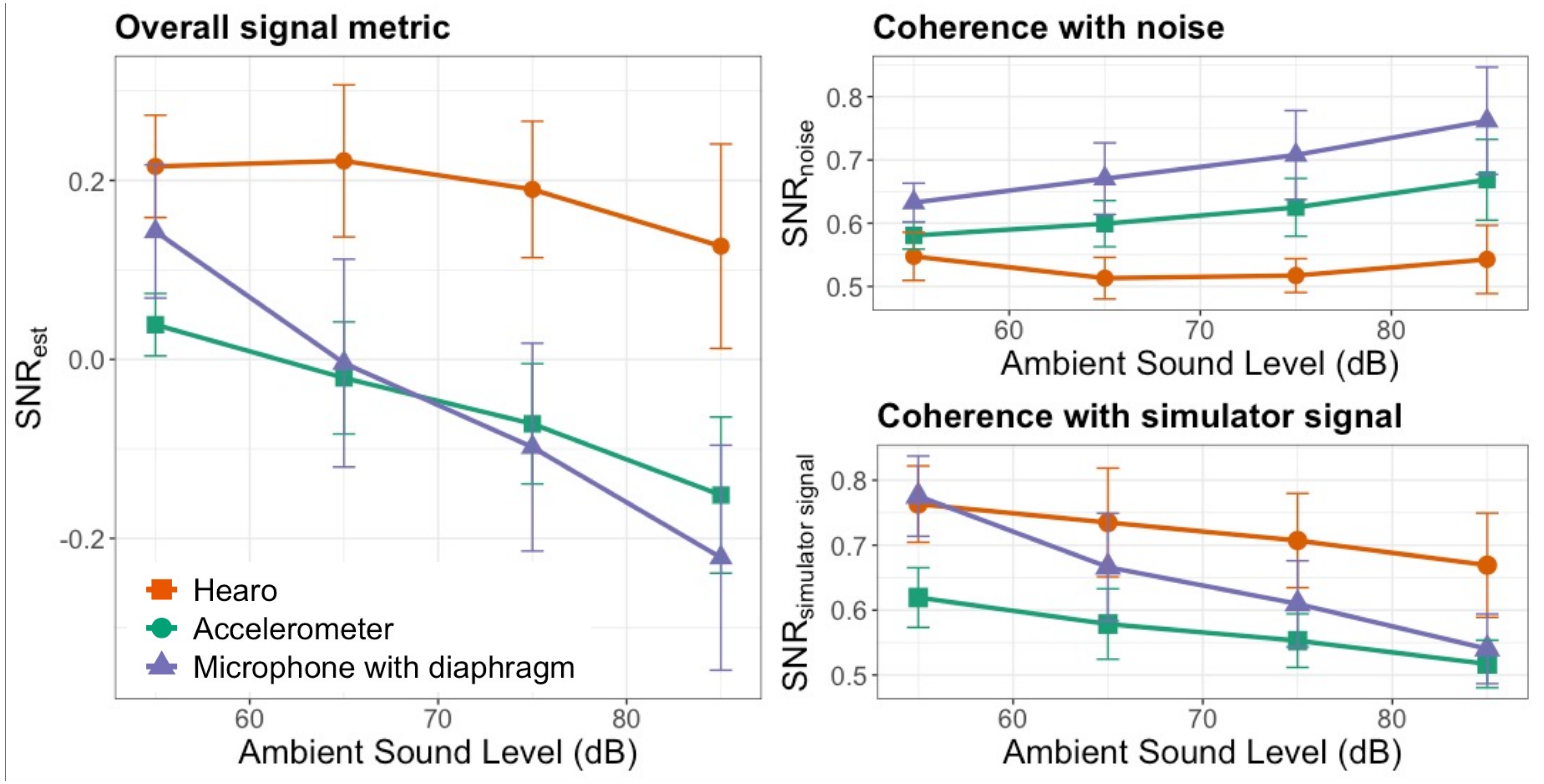


***Figure 5b.*** SNR metrics comparing Hearo to an accelerometer and microphone when characterized on a simulator designed to mimic the characteristics of the human body. Compared to the other devices, Hearo demonstrates less coherence with noise and greater coherence with the signal of interest, leading to an overall higher signal quality.