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Focusing Sound Waves Using a Two-Dimensional Non-Linear System

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Summary

Sound can be focused through a non-linear acoustic lens to produce high-energy waves capable of a variety of applications, such as eradicating cancer cells. Our previous research focused sound using a primitive system incapable of precise and predictable targeting. We engineered and assembled an improved device for focusing longitudinal waves that consisted of a non-linear acoustic lens, a release system, and a microphone recording array for data collection. During experimental trials the non-linear acoustic lens had a force applied to each of the 11 chains depending on the chain number from the desired focal point. Central trials focused sound waves to a calculated focal point to the center of the lens, while right side trials focused sound waves to the right side of the lens. The relative sound amplitude was recorded using a microphone array, analyzed, and averaged using sound analysis software. The average relative amplitudes of the control data compared to the experimental data at the predicted focal points were examined using a two-tailed t-test and were significantly different. This research was considered a success because the non-linear acoustic lens produced an evident increase in relative amplitude at a specific focal point in both sets of experimental trials.

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Introduction

Sound is logarithmic by nature and when focused is capable of creating images by non-invasively contacting an object, such as an unborn baby or underwater ruins (1). Another use for focused sound waves is sonic and ultrasonic weapons. This application is useful to stop riots, control crowds, and disperse people from an area (2,3). The behavior of sound waves is nearly the same throughout almost all mediums; one main difference in different mediums is the speed at which they travel (4). When the density of a medium is increased, the speed at which waves move through is also increased (5). This property is the basic principal of a non-linear acoustic lens (**Figure 1**).

The non-linear system works on the principal of higher density material causing waves to have increased velocity. In Young's modules of elasticity:

Equation 1:

$$E \equiv \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{F L_0}{A_0 \Delta L}$$

where E is the Young's modulus (modulus of elasticity), F is the force exerted on an object under tension, A_0 is the original cross-sectional area through which the force is applied, ΔL is the amount of length the item changes, and L_0 is the original length of the object. It measures the elasticity of a material. In Poisson's ratio:

Equation 2:

$$\nu = -\frac{d\varepsilon_{\mathrm{trans}}}{d\varepsilon_{\mathrm{axial}}} = -\frac{d\varepsilon_{\mathrm{y}}}{d\varepsilon_{\mathrm{x}}} = -\frac{d\varepsilon_{\mathrm{z}}}{d\varepsilon_{\mathrm{x}}}$$

where ν is Poisson's ratio, $d\varepsilon_{trans}$ is transverse stress, and

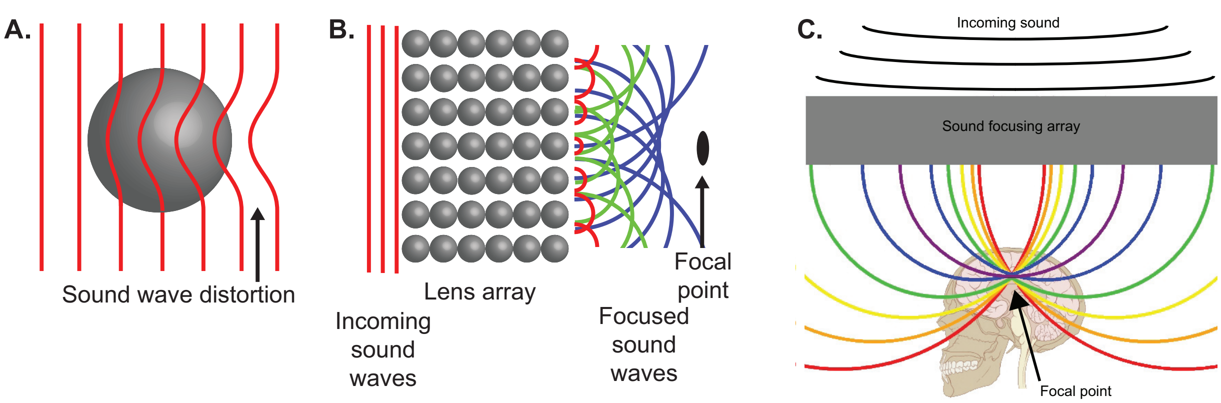

Figure 1: Practical Application. One of many practical applications of focusing sound through an acoustic lens; the user would change precompression on each chain (**A**) to vary the focus point (**B**) to noninvasively eradicate dangerous cells (**C**).

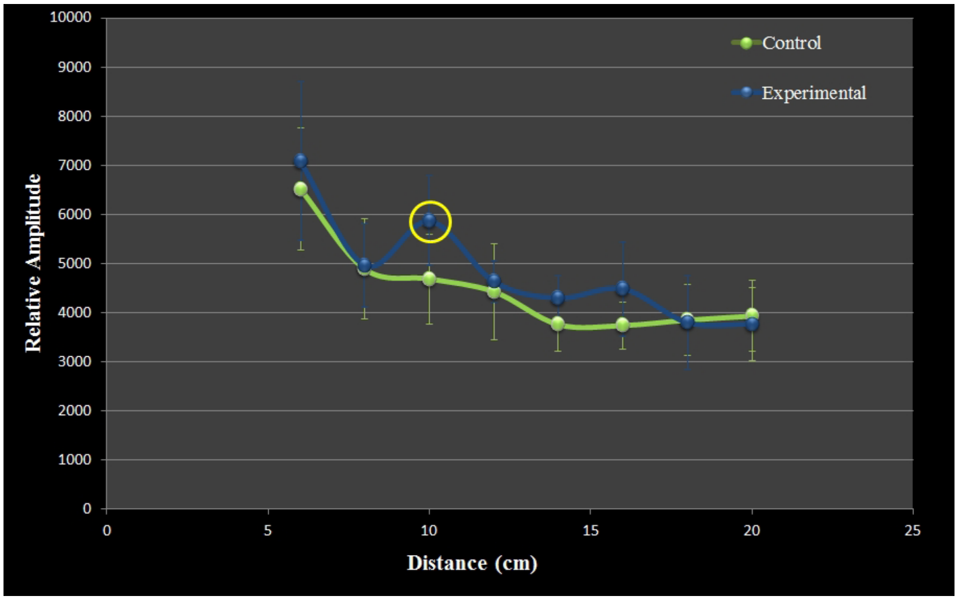

Figure 2: Central Control and Experimental. The control data and experimental data from the center trials with standard deviation. At 10 cm, the control data had average relative amplitude of 4,683 while the experimental data had average relative amplitude of 5,864 (hypothesized focus point shown circled in yellow).

$d\varepsilon_{axial}$ is axial stress (positive for axial tension, negative for axial compression). Axial stress is the change in length divided by the original length (for stainless steel, axial stress is 0.30). Using these two equations and other aspects of the lens like the particle's material density, the amount of force applied on each chain of spheres for the lens could be determined by the next equation and is explained in the materials and methods.

Equation 3:

$$c^2(t_0 - \Delta t_n)^2 = (x_f - x_n)^2 + (y_f - y_n)^2$$

This equation is used to calculate the time delay (Δt_n) necessary to focus energy at the desired location (x_f,y_f), where t_o is the travel time of the wave from the furthest source, c is the speed of sound in the medium, and (x_n,y_n) represents the location of the n^{th} source of energy (6).

The purpose of this research was to engineer chains of spheres creating a non-linear acoustic lens. Specific chains would be precompressed compared to other chains so that an acoustic signal traveling through them had different amounts of delay through certain chains. The waves traveling through each chain should meet at a specific point and form an increased relative amplitude; at the point where all the waves meet, they would form a focal point (7). The focal point should form at different distances from the acoustic lens by applying different amounts of compression to the spheres (8,9). If the acoustic lens is not precompressed (control data), there should not be an increase in amplitude at a specific focal point. If the acoustic lens is precompressed (experimental data), there should be an increase in amplitude at a specific focal point. Central trials were conducted to ensure the system was focusing sound, where the right side trials were conducted to find if the focal point could be changed.

Results

Center Trials

The data for the control group during the center trials were measured using relative amplitude. The control group had an average relative amplitude of 4,470 with a high of 8,008 and a low of 2,862 (N = 30 for each distance tested, **Figure 2**, green). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the non-linear acoustic lens (R^2 = 0.826, **Figure 2**). The experimental group had an average relative amplitude of 4,856 with a high of 10,566 and a low of 2,485 (N = 30 for each distance tested, **Figure 2**, blue). Placing the data within a logarithmic curve revealed a similar correlation between the relative amplitude and the distance the microphone array was from the end of the non-linear acoustic lens (R^2 = 0.818, **Figure 2**).

Right Side Trials

Right side trials were conducted in order to ensure the system could be focused to multiple desired focal points. The data for the control group during the right side trials were measured using relative amplitude. The control group had average relative amplitude of 1,668,723 with a high of 3,386,844 and a low of 590,762 (N = 18 for each dsitance tested, **Figure 3**). Placing the data within a logarithmic curve revealed a significant correlation between the relative amplitude and the distance the microphone array was from the end of the non-linear acoustic lens (R^2 = 0.984, **Figure 3**). The data for the experimental group during the right side trials were measured using relative amplitude as well.

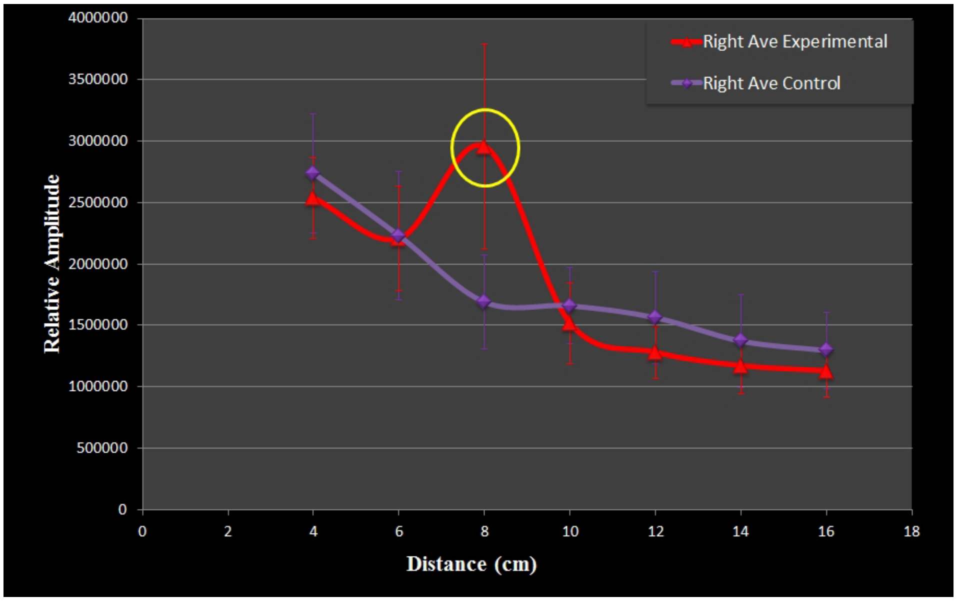

Figure 3: Right Side Control and Experimental. The control data and experimental data from the right side trials shown simultaneously in a graph with standard deviation. The red triangle line is the average relative amplitude for the right microphone in the experimental trials per distance. The purple diamond line is the average relative amplitude for the right microphone in the control trials per distance. At 8 cm, the experimental data was 2,958,398 (hypothesized focus point shown circled in yellow) while the control data was 1,690,273.

The experimental data had average relative amplitude of 1,474,835 with a high of 3,826,445 and a low of 581,378 (N = 18 for each distance tested, **Figure 3**). Placing the data within a logarithmic curve revealed a similar correlation between the relative amplitude and the distance the microphone array was from the end of the non-linear acoustic lens ($R^2 = 0.889$, **Figure 3**).

Discussion

The engineering goal was to engineer chains of spheres creating a non-linear acoustic lens, and for the waves traveling through each chain to meet at a specific point and form increased relative amplitude. The focal point would form at different distances from the acoustic lens by changing the force (or pressure) on the spheres. The engineering goal was fulfilled because the non-linear acoustic lens was engineered, and it created an increase in amplitude at a specific focal point that could be changed by adding more force as shown by the center trials and right side trials having different focal points.

During the center trials, the average relative amplitude of the control data compared to the experimental data at the projected focal point of 10 cm were analyzed using a two-tailed t-test and found to be different at the 95% confidence level (t-value = ± 2.00; df = 58; $p > 0.05$). The control data had an R^2 value of 0.826 when compared to a logarithmic trend line, while the experimental data was found to have an R^2 value of 0.818 when compared to a logarithmic trend line. It is thought that the experimental has a lower R^2 value because of the lens focusing sound at a specific distance and thus not conforming to the normal trend line that non-focused sound follows. It was uncertain why the values for relative amplitude were lower for the experimental condition compared with the control condition for most data points, but it was thought to be from the acoustic lens not being focused at all the points besides 10 cm, so this might lower amplitude (**Figure 2**).

During right side trials, the experimental average relative amplitude was almost twice as large as the control average relative amplitude at 8 cm from the lens (Figure 6). The average relative amplitude of the control data compared to the experimental data at the projected focal point of 8 cm was analyzed using a two-tailed t-test and found to be different at the 90% confidence level (t-value = ±2.73; df = 34; $p > 0.01$). The control data had an R^2 value of 0.984 when compared to a logarithmic trend line, while the experimental data was found to have an R^2 value of 0.889 when compared to a logarithmic trend line. It is thought that the experimental R^2 value was lower because of the lens focusing sound and not conforming to the normal trend line that sound follows. This supports the idea that the lens was in fact making a difference to the amplitude of the waves coming out between control and experimental data (**Figure 3**). Regarding Equation 3 from Daraio's research (6), it is unclear if these data points agree with Daraio's theoretical values. Using a ratio from Daraio's research to calculate applied forces, a focal point was formed at the same 10 cm distance, but it is unclear if this supports the equation.

Future testing will include trials in different mediums such as water or solids, such as bone, to see if the lens would continue to focus through these materials. In theory this should be possible, since each sound wave would have the same effect in traveling though different materials, and in theory would still focus regardless of

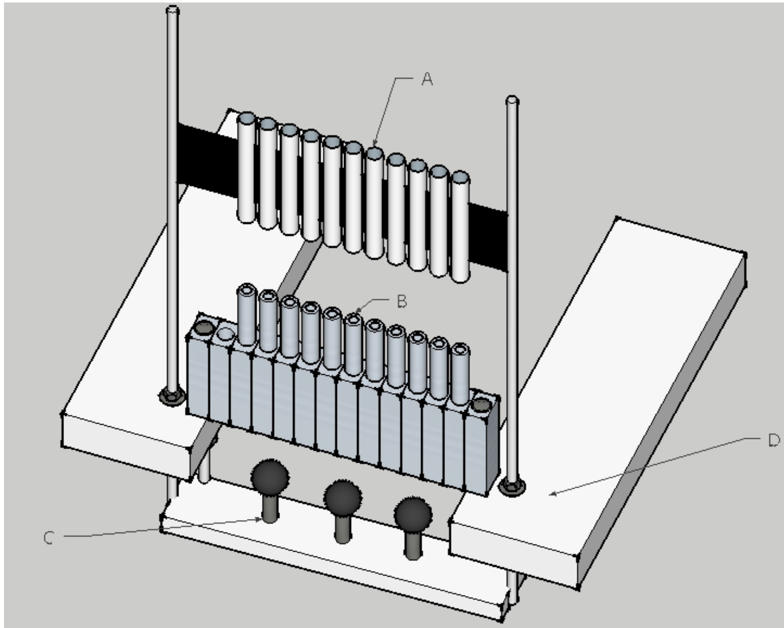

Figure 4: Lens Design. The entire engineered structure includes (A) the release system, (B) the non-linear acoustic lens with force applied, (C) the microphone array, and (D) the table stabilizer.

the composition as long as the material was uniform. If the non-linear acoustic lens were to target tumors non-invasively, trials through materials such as bone or other biological tissues would be needed.

Future improvements for this project are to make a more consistent striking system. The release system was effective but was slow to reload and not practical for creating many sound bullets rapidly. A better method could be to use a large metal rod with arms attached to the side of it with spheres on the end of each. Then, it could be turned so that the arms will land on the top spheres of each chain. This way all of the arms would hit at the same time and it could be cocked and triggered rapidly. Another way could be to have many solenoids attached to spheres that would then be hooked up to a computer that would tell them all to strike at the same time with whatever force was needed.

Another important consideration is the energy input and output of the lens, and to possibly reduce the energy lost through the lens. The lens is making many sound waves focus into one large increase in amplitude, but it is unknown whether this increase is due simply to the addition of each wave or something more complex. The amount of energy produced would need to be increased to do any physical damage to biological tissues such as tumors, or eliminating a target through a solid object. By increasing the impacting force, this increased energy output could be achieved. This theory would need to be optimized before practical applications of the system could be applied in the medical field.

In conclusion, the engineering of the non-linear acoustic lens, impactor, and analyzing system was accomplished. It was predicted that this increase in amplitude could be considerably higher than any other data point at a specific distance from the acoustic lens. The data supports a focusing effect, and with minor adjustments it should produce an increase in amplitude at any specific focal point.

Methods

A device for focusing stress waves was engineered and assembled. It consisted of a release system, a non-linear acoustic lens, a microphone recording array for data collection, and a table stabilizer to keep the lens raised and to hold the release system (**Figure 4**).

The release system was created from 11 pipes measuring 18.7 cm long with an inner diameter of 1.54 cm with horizontal slots (**Figure 5**). A solenoid was attached to a piece of plastic (55.5 cm x 6.4 cm) fitted through the horizontal slot in the pipes. Each pipe had one steel sphere resting on the plastic plate inserted through the horizontal slot. When the solenoid was activated it pulled the plastic plate out, allowing the spheres to fall down the pipes and hit the top of each ball in the acoustic lens simultaneously.

The acoustic lens consisted of 11 ASM 2024 aluminum pipes measuring 10.4 cm long, with an outer diameter of 1.905 cm each (**Figure 6**, top). This number was chosen because having an odd number of chains would produce the compression ratio for each chain because an odd number would allow for a central chain to focus towards to whereas an even number would produce two waves having to focus between the sources of each. Each chain was made from one pipe and a corresponding hole in an aluminum block. The block was 43.2 cm long by 5.1 cm wide by 12.7 cm tall. Each pipe was paired to a hole in the block and filled accumulatively with 15 ASTM A29 steel spheres grade 1010, 1.3 cm in diameter. The spheres

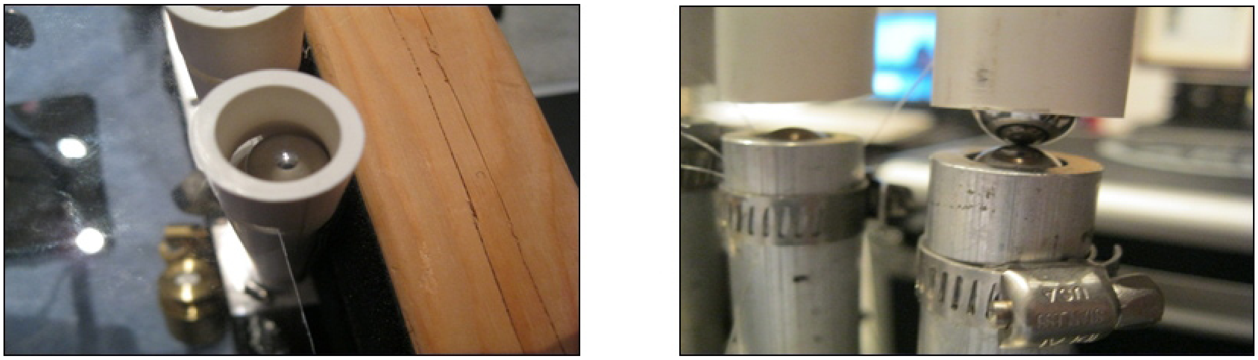

Figure 5: Release System. The release system top (left) with a sphere loaded in and the bottom (right) where the sphere hits the chain when released. Slot used to release spheres can be found at the top of each PVC tube.

protruded out each end of the chains (**Figure 6,** Bottom). The pipe in each chain was sunk into the aluminum block by 2.6 cm to ensure stability and minimize wobble from the pipe segments. When released, the spheres from the release system would impact the top sphere in each chain.

Two sets of data were collected during experimentation. The first set, or center trials, tested the lens with a proposed focal point in the middle, or center, of the lens. The second set, or right side trials, tested the lens with a proposed focal point to the side of the lens. During the center trials, a small clamp attached to fishing line to hold the weight on the chains was used. However, an improved metal plate system with hooks that fit onto each chain to hold the weight was engineered during the right side trials. A higher ratio of weights comparing each chain to another was used for the right side trials because it was thought to have made the focusing effect more prominent and thus verified the capabilities of the lens.

The applied force onto each chain was calculated using a ratio from research done by scientists Spadoni and Daraio at Caltech (6). This ratio was used to find the needed pressure on the spheres in each chain, creating the acoustic lens effect. They calculated the force using this equation:

Equation 4:

$$c_0 = \sqrt{\frac{E}{\rho_p}}\left[\sqrt{\frac{81F_0}{\pi E}}\frac{1}{\pi D(1-\nu^2)}\right]^{1/3}$$

where c_0 is the speed of sound in the chain, E is Young's modulus (Equation 1), ν is Poisson's ratio of the material (Equation 2), D is the sphere diameter, ρ_p is the particle's material density, and F_0 is the force applied to said chain.

When collecting the control data for both center and right side trials, the chains in the non-linear acoustic lens were not precompressed with any force (except the natural force of the weight of the spheres and aluminum tubes with weight holders). The release system was set up with 11 spheres and dropped simultaneously.

During the center trials, the microphone array consisted of three Audio-Technica PRO-44 cardioid condenser boundary microphones placed in the center (directly below the center chain). The sound was recorded from a distance of 6 cm away from the lens to 20 cm away from the lens at 2 cm increments for a total of 420 individual points of data for both control and experimental data combined. During the experimental portion of the center trials, the non-linear acoustic lens had a force applied to each chain depending on the chain number from the desired focal point. The chains had applied forces (starting from the left-most chain and going to the right) of: 9.800 N, 4.900 N, 1.960 N, 0.392 N, 0.098 N, 0 N, 0.098 N, 0.392 N, 1.960 N, 4.900 N, and 9.800 N. Forces were applied using weights attached to each chain.

During the right side trials, the microphone array (three Sennheiser e825s) consisted of one on the left (directly below the left most chain), one on the center (directly below the center chain), and one on the right (directly below the right most chain). The microphones recorded from a distance of 4 cm away from the lens to 16 cm away at 2 cm increments for a total of 252 individual data points for both the control and experimental data combined. During the experimental data collection in the right side trials, the chains had applied forces (going from the left most chain and going to the right) of: 29.0 N, 22.0 N, 17.0 N, 12.4 N, 8.6 N, 6.0 N, 4.2 N, 2.7 N, 2.0 N, 1.9 N, and 1.8 N.

Once the force was applied to all chains for both center and right side trials, the release system spheres were set up and released using the solenoid. Each individual microphone recording was then analyzed using Sigview Ver-2.6.0 signal analysis software to find the exact focal point of the sound waves. The average relative amplitude of the control data compared to the experimental data at the projected focal points for both the center trials and the right side trials were analyzed using a two-tailed t-test. Relative amplitude is a measuring system for sound based on arbitrary values for amplitude but maintaining the ratio between data points.

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Figure 6: Lens. (Top) A picture of the pipe segments with the aluminum block to stabilize them. Each chain contained 15 steel spheres from the top of each pipe to the bottom of the block. (Bottom) The bottom of the lens showing the spheres protruding from the aluminum block.

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