A Passive Noise Attenuation Earplug Designed to Minimise Unwanted Air Turbine Driven High-Speed Dental Drill Noise

Keywords

Additive Manufacturing
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ABSTRACT

Introduction: Air turbine dental drill noise contains high-frequency components that are of concern for patients and dental staff. Meanwhile, verbal communication between the dentist and patient is essential. Conventional active noise-cancelling headphones are ineffective for dental drill noise and simply suppress all sound and hinder communication. Method: A compact passive earplug device was designed specifically to attenuate broadband high-frequency noise ranges from 5 to 8 kHz employing an array of quarter wavelength (QW) resonators. This device was 3D printed and tested against white noise to enhance the objectivity of analysis, using a calibrated ear and cheek simulator to effectively measure its performance. Results: The results showed that the resonators produced an average reduction of 27 dB across the targeted frequency range. When compared with two proprietary passive earplugs, this developed passive device prototype was able to attenuate an average of 9 dB more across the target frequency range whilst delivering louder speech signals of 14 dB more. The results also show that using an array of resonators exhibits an accumulated effect of individual resonator performance. Conclusions: This low-cost passive device could have a place in the dental clinic to reduce unwanted drill noise equivalent to the white noise high frequency spectra tested.

INTRODUCTION

Dental drill (also known as a dental handpiece) noise can be a concern for patients and harmful to the dental team due to its high-frequency characteristic. Fear of the drill noise is a common phenomenon that causes distress to patients when they undergo dental treatment. Dental drill noise has scored highest on the Modified Dental Anxiety Scale (MDAS).[1] A study conducted in Hong Kong[2] has shown that more than 76% of the participants, even for those who come from a dental practice background, would prefer a lower volume of dental drill noise. Dental handpiece noise is frequently cited by patients as an unpleasant and anxiety-inducing noise and can result in patients avoiding treatment for oral disease leading to further pathology and increased disease and cost of treatment.

Some literature also suggests that hearing loss could be induced by prolonged exposure to a dentistry environment, for example, dentists who constantly use high-speed dental equipment.[3,4] These findings highlight the need for reducing high-frequency dental drill noise to improve the comfort of both patient and dentist, whilst maintaining the essential verbal communication from the dentist and dental nurse to the patient.

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Dental drill noise is essentially generated by high speed rotating mechanical components. Electric motor driven and air turbine driven drills are the two main types of dental drill widely used in dentistry. The air turbine driven dental drill is the focus of this study as it is widely used throughout the world and generates the well-known and disliked high frequency noise associated with dental treatment. As shown in Figure 1, a typical air turbine drill uses a pressurised air supply to propel an impeller that drives a bur (cutting tool) shaft. The rotating impeller and bur shaft normally operate at a speed ranges from 200,000 to 450,000 revolution per minute (RPM) for cutting purposes, which means that significant noise peaks caused by resonance can be generated between 3.3 and 7.5 kHz. This is supported by the research undertaken by Poole *et al.*[5] and Altinoz *et al.*[6] in which the frequency characteristic of air turbine driven dental drills studied mainly varied within the range of 3 to 8 kHz.

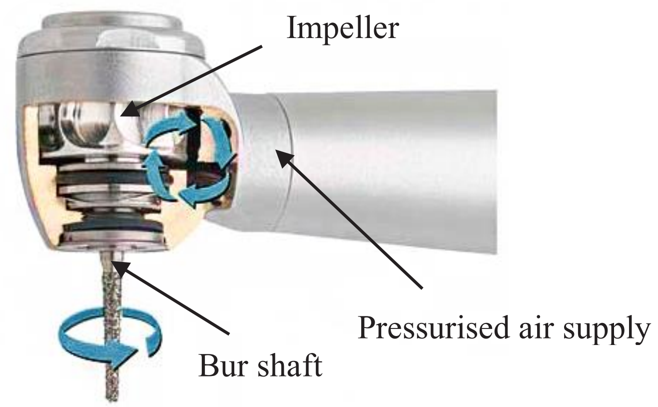

Figure 1: Air turbine driven dental drill illustration (Reproduced from Dentaltix[7]).

Dental drill noise is normally transmitted via two paths: the acoustic pathway through the vibration of air from the drill to the patient's eardrum; and through bone conduction of vibration from the teeth via jaw/skull to the eardrum and cochlear.[8] The intensity of bone conduction has been found to be relatively weak compared to the acoustic pathway partly as the drill is not in contact with the tooth at all times and the tooth is not rigidly attached in the bone.[9] Furthermore, despite much research reported in the literature, the bone conduction pathway is still considered "complex, not well understood, not completely resolved, and challenging. (Yehezkely *et al.* 2019)"[10] In addition, the ISO international standard [ISO 389-3:2016][11] reference equivalent threshold vibratory force levels for pure tones and bone vibrators is a minimum of 4.5N, whereas studies on dental drill force reveal that it is smooth and its magnitude is typically around 2N.[12] It is understood by the authors that patient anxiety caused by the dental drill is often developed prior to actual drilling treatment, for example, hearing the drill whilst in the waiting room, and so any relief that can be achieved before drilling begins will bring benefit. Therefore, bone conduction is not considered in this paper.

Active Noise Cancelling (ANC) technologies are also available for noise attenuation but they are mainly designed to suppress low frequency (e.g. <1 kHz) noises such as street sound, traffic and engine noise.[13] As a result, ANC will not be further discussed and we will focus on the passive attenuation of noise without the aid of electronics. Noise isolation is a general approach to accomplishing passive noise attenuation by physically blocking the pathway from a noise source to the ear canal.[14] Safety ear defenders are a typical example of a passive headwear solution. They tend to clamp much tighter on the user's head than normal headphones to achieve good sealing and so are uncomfortable to wear, which is unacceptable for a dental environment. They are also bulky and so can inhibit access and as they remove verbal communication to the patient, which makes them unsuitable for dental clinics.

Directly in-the-ear earplugs are also available, however, they normally operate similarly by blocking the acoustic pathway to a patient's ears and hence are not desirable, as verbal communication between the patient and dentist is important to enable successful treatment.[15-17] Some dentists employ a radio or have music playing in the background in order to mask or distract their patients from hearing the drill noise.[18,19] Patients sometimes bring their own music players such as a smartphone to mask the drill noise but doing so again affects the communication between the patient and the dentist and has only a limited effect in drowning out the high frequency drill noise.

Further development of a patented passive noise attenuation device[20] is proposed in this paper. The device aims to attenuate unwanted high frequency components of noise that are likely to be generated by air turbine driven drills whilst maintaining verbal communication between patients and dentists without the aid of electronics. The earplug contains an array of quarter wavelength (QW) resonator branches configured in a way that attenuates high-frequency noise (e.g. 5 to 8 kHz) while keeping speech frequencies (e.g. < 5 kHz) as original as possible. The next section provides brief background information with respect to speech and air turbine driven dental drill noise characteristics and the analysis techniques used in this study. Then essential principles of acoustic resonators are presented with a focus on the QW resonator and its performance estimation. Detail development of the Passive Device prototype in the form of an Earplug (referred to herewith as PDE for abbreviation) is described next, followed by a series of experiments. The outcome of the study is then discussed before concluding remarks.

SPEECH AND DENTAL DRILL NOISE CHARACTERISTICS

Commonly used English speech phonemes feature in a banana-shaped cluster on a frequency audiogram, which is often referred to as the 'speech banana', shown in Figure 2. The majority of phonemes are within the frequency range of 250 Hz to 5 kHz and therefore it is desirable to maintain the delivery of these frequencies as much as possible to allow effective verbal communication during noise attenuation. For convenience, this frequency range is referred to as the speech region for the remainder of this paper. Frequency domain techniques are widely applied to perform audio signal analysis as they are able to analyse individual frequency components of a signal, amongst which Welch method is used in this study due to its popularity.[21] Welch's power spectrum density (PSD) analysis is enabled by the MATLAB Signal Process ToolBox with an example PSD plot for an air turbine drill and human speech recordings shown in Figure 3. Both digitised audio recordings were 24-bit audio, with a sampling rate of 48 kHz and a duration of 10 s. A window size of 2048 and 1024 overlapped samples were used to produce the PSD plot. The frequency spectrum for the PSD plot was selected to be 16 kHz as above this the threshold of human hearing starts to increase rapidly.[22] The power of the signal at specific frequencies as indicated by the vertical axis, is a relative measure as commonly used in the Welch method,

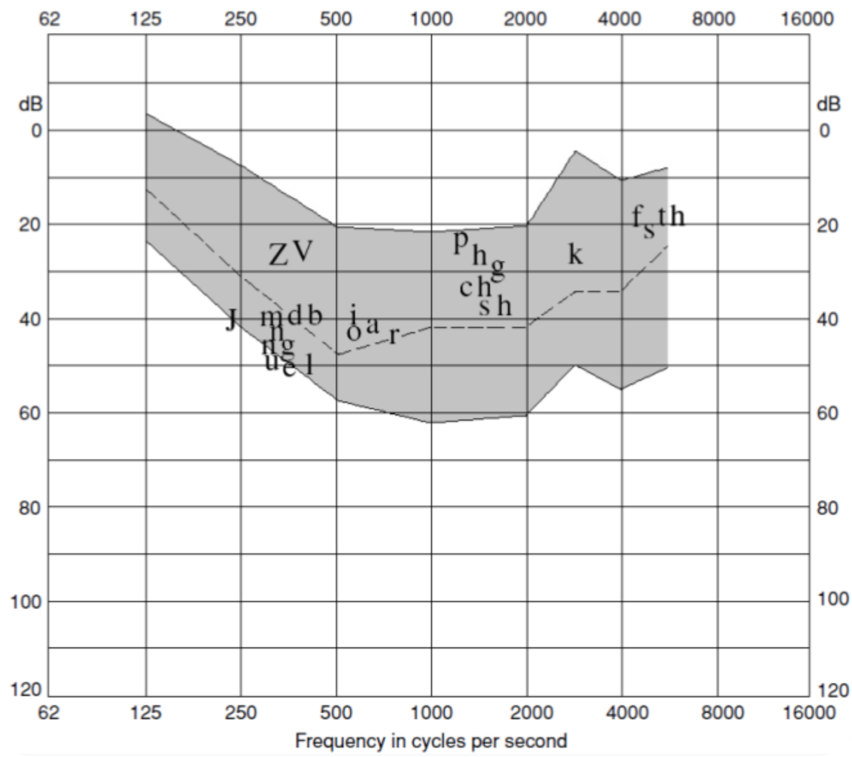

Figure 2: The "speech banana" audiogram (Adapted from Klingpornkun *et. al*[23])

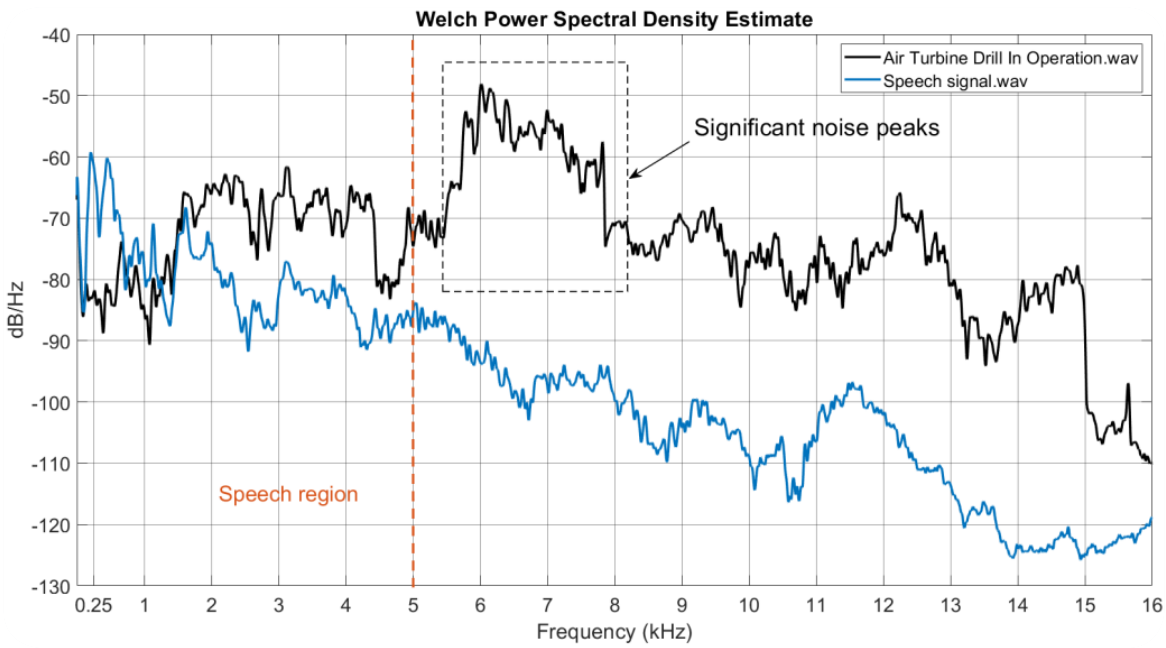

Figure 3: PSD plot of an example air turbine drill under normal load and human speech. The black line indicates drill noise and the blue line indicate speech.

where a higher value indicates a more powerful noise. When the drill is under its normal load, a range of noise peaks are captured indicating constant contact between the rotating burr and tooth. For ease of visualisation, the speech region is outlined by orange in Figure 3. It can be seen clearly that the speech signal tends to be more powerful than drill noise at lower frequencies, e.g. from 250 Hz to 1 kHz. Drill noise becomes dominant after 5 kHz beyond the speech region. This suggests that drill noise components above 5 kHz can be targeted for greatest reduction whilst maintaining the clarity of speech components within the speech region. Therefore, in this paper we show how developing a passive noise reduction device that targets noise above 5 kHz can be reasonably expected toreduce the significant drill noise peaks identified in Figure 3.

ACOUSTIC RESONATORS

Research on acoustic filters in hearing protection started to emerge after the Second World War as an alternative to conventional ear defenders.[24] Acoustic filters for hearing protection normally exist in the form of in-the-ear earplugs and are acceptably comfortable. Acoustic filters normally contain cavity resonators to amplify or absorb sound at specific frequencies.[25] The body of some musical instruments, e.g. guitars and violins, can amplify certain frequencies while car exhaust silencers/mufflers are used to dampen certain frequencies. Acoustic cavity resonators can be configured to be frequency-specific and are particularly well suited to attenuation of noise with constant frequencies such as generated by constant speed machines and hence are suitable for application to dental drill noise. Helmholtz and quarter wavelength (QW) resonators are the most used cavity resonators, and simple representations of both resonators are shown in Figure 4.

The Helmholtz resonator is a well-known device for creating the Helmholtz resonance phenomenon that is widely used in reducing noise with narrowband frequencies.[26] The Helmholtz resonator consists of a volume of air contained in a chamber that is connected through a narrow neck to the main inlet-outlet vent that carries the sound to be attenuated. Alternatively, it could be a thru-chamber along with the main vent. The dynamics of Helmholtz resonators can be understood using a mass-spring analogy. The air inside the neck behaves as a discrete mass and the compressibility of the volume of air inside the cavity behaves as a spring.[27] The characteristics of a Helmholtz resonator largely depend on its chamber volume *V*, neck length *L* and neck area $1/4\pi d^2$. The resonant frequency of a Helmholtz resonator can be identified using Equation (1).

$$f = \frac{c}{2\pi}\sqrt{\frac{\pi d^2}{4VL}} \quad (1)$$

Where *c* is the speed of sound, *d* is the neck diameter, *V* is the volume of the cavity and *L* is the neck length.

A quarter wavelength (QW) resonator is another type of acoustic resonator, which has been studied for decades in the application of sound attenuation.[28] In a QW resonator, a tube-shaped branch is used, and the branch is closed at the furthest end from the vent connection. The core working principle of a QW resonator is that it generates a resonant anti-wave with a frequency having a quarter wavelength equal to the branch length. In other words, sound reduction takes place at this resonant frequency because it is cancelled by the reflection of itself in the tube. Compared to a Helmholtz resonator, a QW resonator has a higher efficiency regarding acoustic energy collection for a given volume.[29] Consequently, a QW resonator was selected as the noise reduction means in the earplug design. The resonant frequency of a QW resonator can be determined by Equation (2), where *c* is the speed of sound and L_{eff} is the effective length of the resonator. Due to inlet effects, the effective length of the branch tube (resonator) will be slightly longer than its physical length L_0.[30] The length increment L_c can be determined using Equation (3) proposed by Rayleigh and Lindsay[31] where *r* is the QW resonator radius. Therefore, the effective length of a QW resonator L_{eff} can be determined by adding its physical length L_0 and increment L_c, shown in Equation (4).

$$f_{QW} = \frac{c}{4L_{eff}} \quad (2)$$

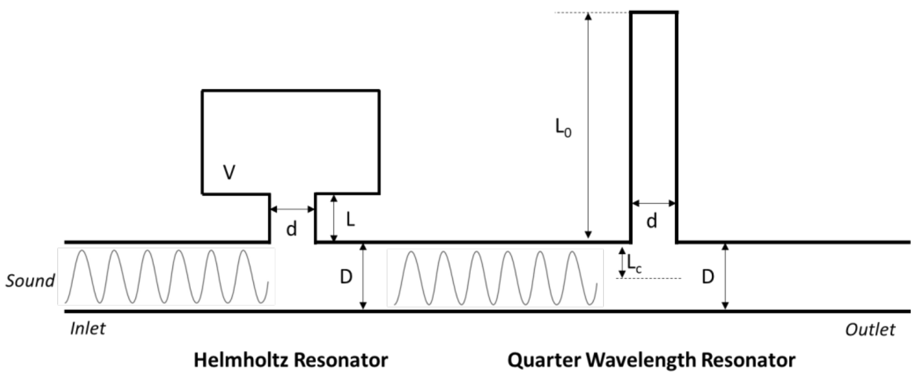

Figure 4: Schematic illustration of Helmholtz resonator and QW resonator.

$$L_c = \frac{8r}{3\pi} \quad (3)$$

$$L_{eff} = L_0 + L_c \quad (4)$$

METHODS

DEVELOPMENT OF THE PASSIVE DEVICE IN THE FORM OF AN EARPLUG (PDE)

According to the air turbine driven dental drill characteristics stated above the target frequency range of drill noise is identified to be 5 to 8 kHz, referred to as the QW resonator region from now on and therefore the QW resonators to be incorporated in the PDE are designed accordingly. When configuring the main vent size D and resonator diameter d, an occlusion effect is taken into consideration referring to studies carried out by Kuk *et al*.[32,33] The occlusion effect is a commonly seen phenomenon in hearing aid designs where reduction of low-frequency components (e.g. <1 kHz) is often observed due to the use of small vent diameters. As a result, a 5 mm main vent with 4 mm QW resonator diameter is used in the PDE development to minimise this effect. Subsequently, referring to Equation (2) to (4), QW resonator branch lengths required for target frequencies are identified. For instance, a branch with 15.4 mm in length is required to attenuate noise at 5 kHz based upon a sound speed of 343 m/s at room temperature. Performance of a QW resonator can be evaluated using transmission loss (TL), insertion loss (IL) and pressure loss (PL).[34,35] Transmission loss (TL) is used here due to its broad application in measuring the acoustical performance of sound in a duct.[26,36] In addition, TL is simple to calculate numerically compared to the other performance measures.[37] It indicates the difference between the incident sound power at the inlet and the transmitted sound power at the outlet. It can be calculated using Equation (5) where R is the ratio between the QW resonator section area and main vent section area. L_{eff} is the QW resonator effective length and λ is the wavelength of sound.[38]

$$TL = 10\log_{10}[1 + \frac{1}{4}(R \times \tan\frac{2\pi L_{eff}}{\lambda})^2] \quad (5)$$

Multiple QW resonators at different lengths connecting to one main vent are assumed to have an accumulated effect on noise reduction and therefore produce a broadband frequency coverage. To investigate this, Table 1 summarises a detailed design of four QW resonator branches to be accommodated in the PDE and their target resonant frequencies. 1 kHz increment of target frequencies for each resonator branch is chosen, corresponding to approximately 5 kHz, 6 kHz, 7 kHz and 8 kHz. D represents the main vent diameter, d is QW branch diameter, L_0 is the branch physical length, L_c is the length increment, L_{eff} is the effective QW branch length and F_{QW} is the target resonant frequency. Figure 5 presents an estimation of noise reduction using TL for the four resonators configured in Table 1 with a step increment of 20 Hz for each signal. Estimated accumulated effect is highlighted in blue thick line. The broadband noise reduction performance across the frequency range of interest, i.e. 5 to 8 kHz was estimated by obtaining the average of combined TL (the blue thick line) within this region, which corresponds to 27.8 dB.

Table 1. Four QW resonator dimensions employed the PDE design.

	5 kHz Resonator	6 kHz Resonator	7 kHz Resonator	8 kHz Resonator
D (mm)	5	5	5	5
d (mm)	4	4	4	4
L_0 (mm)	15.4	12.6	10.5	9.0
L_c (mm)	1.7	1.7	1.7	1.7
L_{eff} (mm)	17.1	14.3	12.2	10.7
f_{QW} (Hz)	5015	5997	7030	8016

For the purpose of investigating the effect of each individual resonator and their joint effect, six prototypes were developed, and 3D printed using Nylon using a layer thickness of 100 µm (see *Figure 6*). Prototypes from left to right contain: 0 resonator prototype for reference purpose; one 5 kHz resonator only; one 6 kHz resonator only; one 7 kHz resonator only; one 8 kHz resonator only and an array of four resonators covering 5 to 8 kHz. From the figure, it can be seen that the resonator length gets shorter when the target frequency increases. The reason for creating open-end QW branches is to ensure support material and residual build material formed during 3D printing can be removed easily. Pressure-sensitive adhesive putty (e.g. Blu tack™) was used to seal these openings during tests. In order to create a reliable seal, a small portion of putty was forced into the resonator branch from the open ends resulting in a reduced resonator length. From Equation (2) it can be envisaged that a small change in resonator length can lead to a greater shift in target frequencies. Therefore, an additional 2.5 mm was added on top of the effective length when designing the prototypes in CAD to compensate for the length occupied by the putty. QW resonator prototypes developed and shown in Figure 6 adopted straight branch designs with the aim of easy manufacture and testing. The developed and printed PDE, accommodating the same array of QW resonators as the 5-8 kHz prototype, is shown in Figure 7. The nozzle is designed to fit rubber or foam ear tips. Curving the QW resonators for space-saving was implemented.

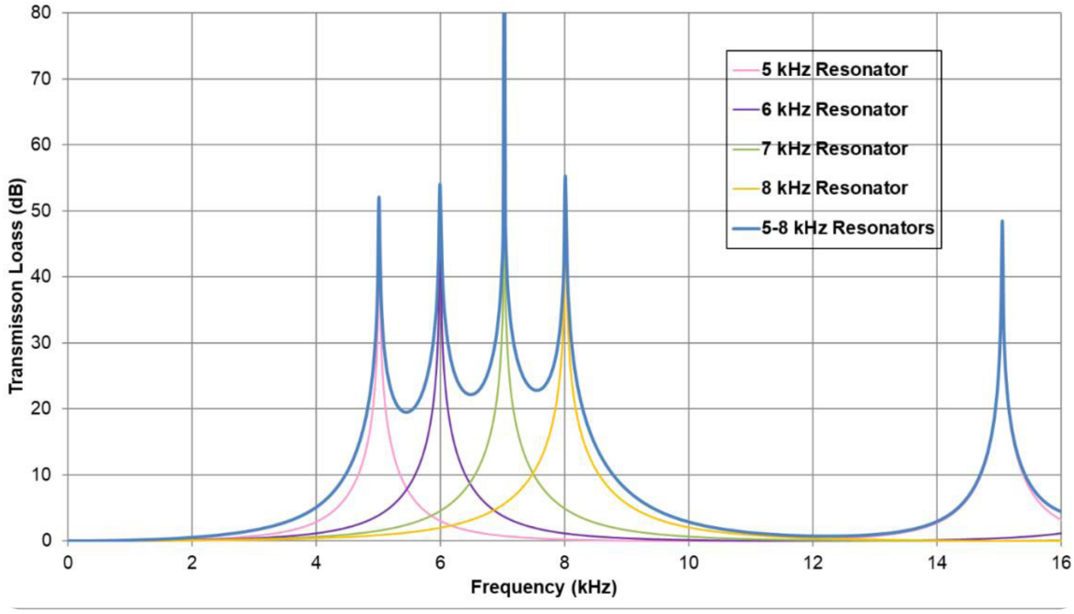

Figure 5: Noise reduction estimation using TL for the four resonators configured, the joint effect is indicated by the blue thick line.

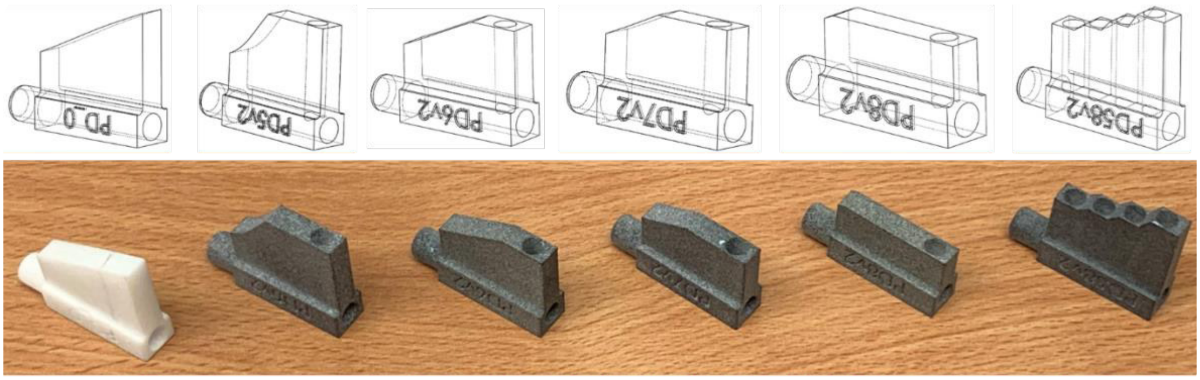

Figure 6: QW resonator designs (Top) and 3D printed prototypes (Bottom).

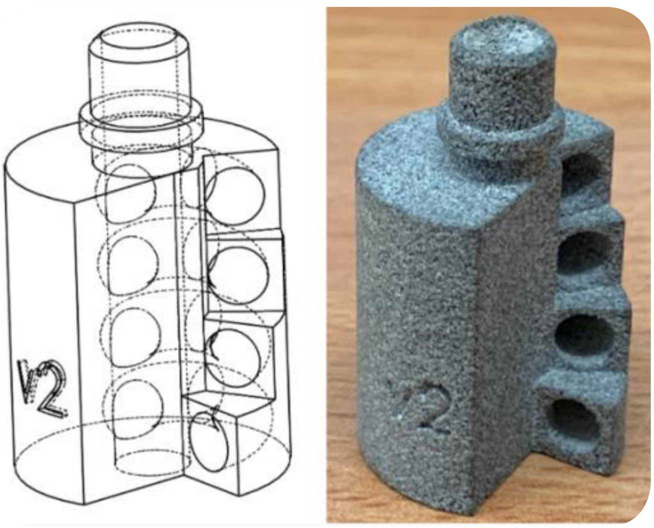

Figure 7: PDE design (Left) and 3D printed prototype (Right).

RESULTS

EXPERIMENT DESCRIPTION

A calibrated GRAS 43AG-1 Ear & Cheek Simulator (ECS)[39] was used to mimic a section of a human head and ear canal for representing the acoustic characteristics of an actual ear. It contains GRAS RA0045, an externally polarised ear simulator according to IEC 60318-4, which works effectively below 10 kHz.[40] The ECS uses a GRAS 40AG 1/2” externally polarised pressure microphone[41] according to IEC 61094-4, suitable up to 20 kHz. A GRAS KB0065 Large Right KEMAR Pinna[42] is also used later on in the experiment when two proprietary passive earplugs are tested. The experiment setup is shown in Figure 8. The ECS is powered by GRAS 12AD which is also the hardware interface between the ECS and a PC. A high-performance Behringer MS16 16-Watt monitor speaker was used at a constant volume setting to playback sound recordings representing the sound source. The speaker has a frequency response of 80 Hz to 20 kHz range[43] that is again suitable for this study.

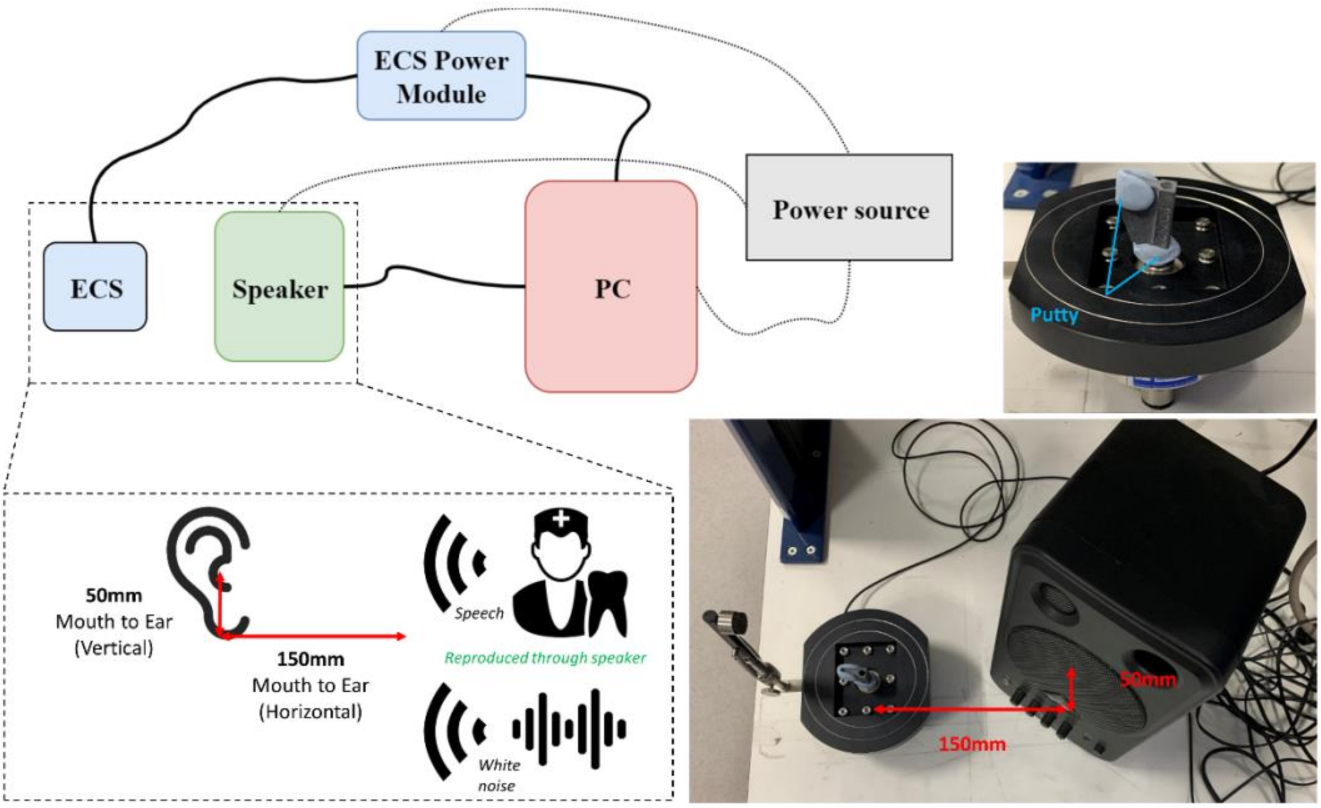

Figure 8: Experiment equipment and layout. The thick lines represent connection cable and thin lines represent power cable. The dimensions used in the experiment were selected to mimic the actual distance in a dental setting.

A Windows PC was used to capture the sound data transmitted through the ECS. MATLAB applications were developed to enable data recording and analysis.

White noise was used in the experiments for objectivity of analysis in the evaluation of QW resonator performance. The primary reason for not using drill noise recordings here is that drill noise PSD (e.g. see *Figure 3*) is considered too complex to effectively visualise the noise reduction resulting from the application of QW resonators. As the passive device does not rely on any electronics its noise attenuation effect should be identical regardless of what sound is used. During the experiments two sound recordings, white noise and human speech, were played simultaneously to reproduce the sound environment of a dental surgery. The nominal distance from the ear to the dental drill and the dentist is estimated as 150 mm horizontally and 50 mm vertically. During the test of printed resonator prototypes, pressure-sensitive adhesive putty was used to secure the prototypes onto the ECS and seal it properly to prevent any sound leakage. Pressure-sensitive adhesive putty was also used to seal the QW resonator opening as described earlier in the paper (see *Figure 6*).

Results presented in this section are categorised into two groups. The first group of results focuses on investigating the individual and accumulated effect of QW resonators on noise reduction using white noise. The second group of results focuses on the comparison between the developed PDE prototype and two different proprietary passive earplugs with a GRAS KB0065 Large Right KEMAR Pinna installed onto the ECS.

During the experiment, each prototype (device) was tested five times to confirm the repeatability of results. Figure 9 shows the PSD plot of white noise captured five times in the range of 0 to 16 kHz without pinna, indicated by red dashed lines. It is worth noticing that the power spectrum of white noise captured by the ECS does not exhibit constant signal power across the entire spectra, as it represents how a human ear modifies sound. Similar forms of white noise PSD can also be found in the literature.[44,45] The outcome for the 0 resonator prototype (see *Figure 6* left), without pinna, secured and sealed using putty, is also shown in the figure. From the figure, it is obvious that five tests for both cases are almost identical indicating the repeatability of the results. For easy visualisation, only the result for the first test was used for the remaining figures unless specified otherwise.

For the 0 resonator prototype result, compared to the raw white noise without pinna, the signal below 1 kHz was maintained successfully without any attenuation, indicating that the occlusion effect in this region has been eliminated. However, an obvious reduction between 2 kHz to 5 kHz in the speech region is observed instead. A slight reduction in the QW resonator region (5 to 8 kHz) can also be observed. This suggests that having just a 5 mm main vent in between the ECS and sound source has an attenuation effect before any resonators are added. However, because the rest of the devices are built off the main vent, it is necessary to use the response obtained from the 0 resonator prototype as the benchmark when evaluating the sole effect of QW resonators.

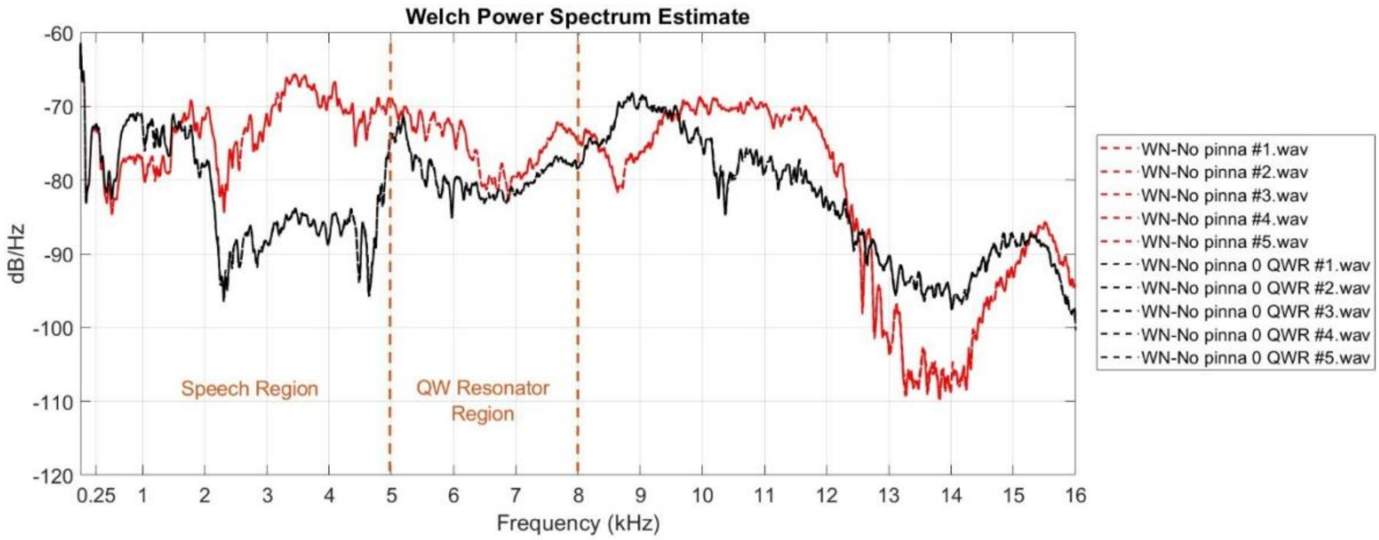

Figure 9: PSD plot for raw white noise recorded without pinna and using the 0 resonator prototype. All five tests are shown. Red dashed line represents raw white noise, Black dotted line represents the outcome of 0 resonator prototype.

Figure 10 shows the effects of frequency-specific white noise reduction when individual QW resonators are applied with reference to the sound data of the 0 resonator prototype. Designs of each QW resonator can be referred back to Figure 6 and Table 1. From the group of figures shown, the effect of a single QW resonator is apparent, indicated by a 'V' shaped descent (negative peak) centred around the designed frequencies, representing significant signal power decreases. The 5 kHz resonator does not perform as well as others but noticeable attenuation is still obtained. Signal profiles that are lower than 3 kHz are almost identical to the 0 resonator prototype (reference profile) for all cases. Power of sound components adjacent to and slightly lower than the target frequencies of each QW resonators appear to be amplified, for example, in the case of using an 8 kHz resonator, components range from 6 to 7 kHz are increased. A similar effect is obtained by all prototypes. Sound components beyond the region of interest (>8 kHz) are similar for all designs apart from the reduction due to the third harmonic resonance for the 5 kHz resonator around 15 kHz. There are slight deviations of the negative peaks from the designed frequencies for the 5, 6 and 7 kHz resonator prototypes.

Figure 11 shows the noise reduction result when the 5-8 kHz resonator (refer to *Figure 6*) is employed and can be compared to the 0 resonator prototype. PSD plots of each individual QW resonator from Figure 10 are added to the plot for comparison. The speech region (250 Hz – 5 kHz) and QW resonator region (5 kHz – 8 kHz) are highlighted for easy visualisation. A clear broadband reduction compared to the white noise signal captured through the 0 resonator prototype can be observed in the QW resonator region. Similar signal amplification behaviour is also found between 2 to 4 kHz for the 5-8 kHz resonator. An accumulated effect of individual resonators is observed when they were arranged together in an array.

Figure 12, in which the vertical axis for the transmission loss (TL) for the QW resonators estimated in Figure 5, is inverted for easy comparison. Similar accumulated effects are observed in both figures. Noise attenuation performance for the 5-8 kHz resonator across the QW resonator region is obtained by averaging the reduction from the 0 resonator prototype for each frequency using MATLAB. Thus a broadband reduction of 27.53 dB is obtained. The broadband reduction performance estimated using TL is obtained in a similar way by averaging the reduction for every frequency calculated. This results in a 27.8 dB reduction performance, indicating an almost identical performance.

The developed PDE (see *Figure 7*), employing four curved QW resonators of the same lengths as the 5-8 kHz resonator (see *Figure 6*), was tested against white noise by using putty to secure it onto the ECS without pinna. Five tests were performed, the same as the 5-8 kHz resonator. A comparison between the PDE and the 5-8 kHz resonator against white noise captured using the 0 resonator prototype (reference profile), is shown in Figure 13. Results from the five tests for both devices are shown in the figure. Very small differences for the repeated tests indicate the repeatability of results. In terms of noise attenuation, the two devices behaved almost identically within the speech region, with an observable difference in the QW resonator region. If evaluated using broadband reduction, the PDE yields an average of 26.54 dB reduction for all five tests compared to the averaged 27.53 dB reduction for the 5-8 kHz resonator prototype. This suggests that a virtually identical broadband reduction performance for high-frequency applications can be achieved even with the QW resonator branches curved.

For the second group of results, two proprietary passive noise attenuation earplugs, the Alpine WorkSafe[46] and the Ety ER20XS[47] were tested and compared with the PDE prototype. In this series of tests, the GRAS KB0065 Large Right KEMAR Pinna was used in order to accommodate the two proprietary earplugs. A foam tip was attached to the PDE and then inserted into the pinna, as depicted in the photo image at the top of

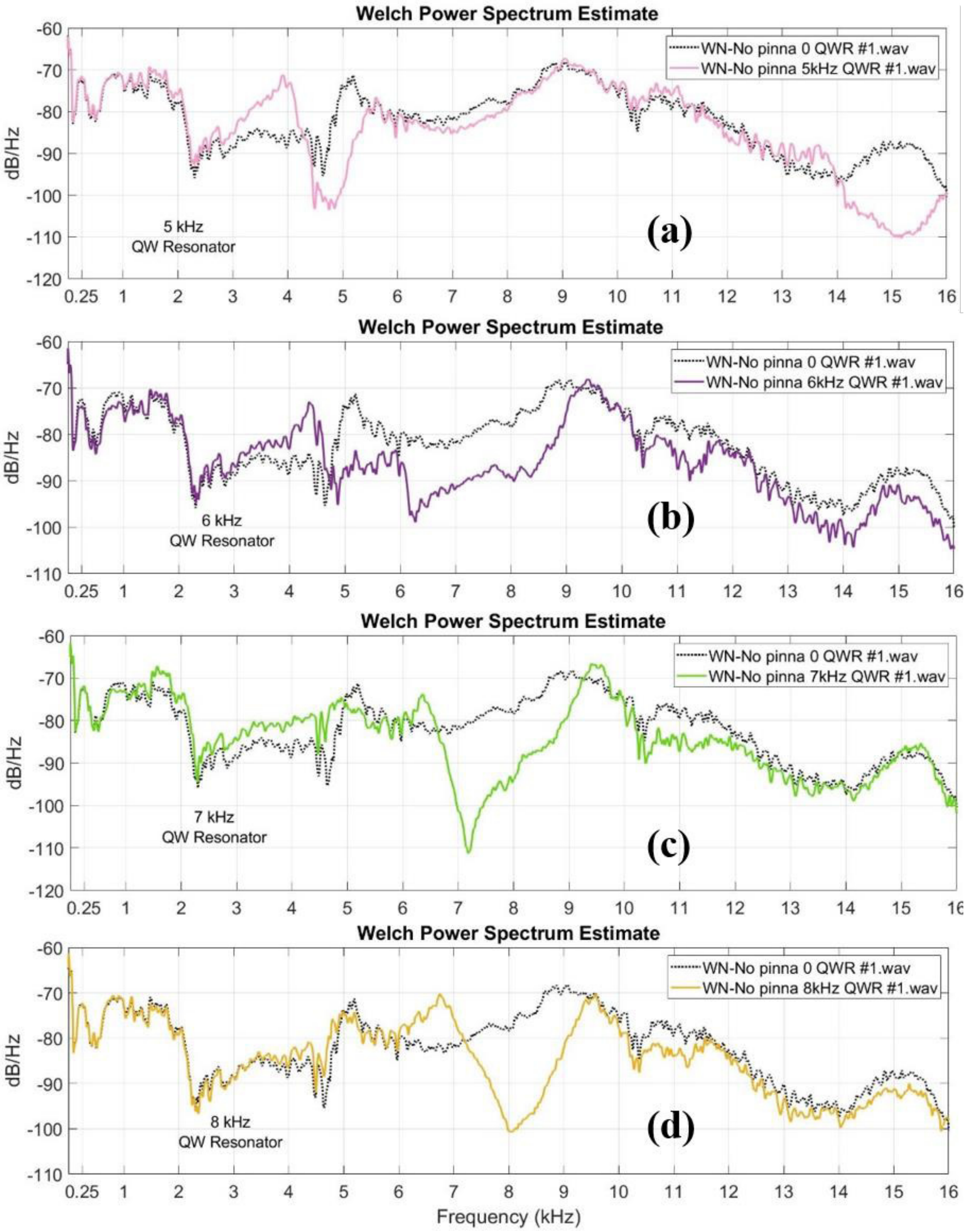

Figure 10: White noise reduction effect of individual QW resonators. From (a) to (d): 5 kHz, 6 kHz, 7 kHz and 8 kHz QW resonator. The outcome of the 0 resonator prototype is shown in black dotted lines.

Figure 14. Based on Alpine and Etymotic, both proprietary earplugs claim to provide a uniform of 20 dB noise reduction across the hearing range and are relatively comfortable to wear due to their small size. Deep insertion was performed for all three devices during the experiments for the best possible performance. Noise reduction performance comparison of these three devices is shown in Figure 14, with reference to white noise captured when the pinna is attached to the ECS. Again, it can be seen that the power spectrum is not constant compared to a theoretical white noise PSD due to the effect of simulating the behaviour of a human ear. This response was used as benchmark for evaluating performance of the three devices.

The result shows that both Alpine and Ety devices managed to achieve an almost uniform reduction that is across the entire PSD plot range, with near 20 dB average reduction in the speech region and QW resonator region (see Table 4 under column Noise Reduction). A better reduction performance in the QW resonator region is accomplished by the PDE. Moreover, the PDE achieves a considerably better performance in the speech region indicated by the more powerful sound components delivered. For higher frequency ranges, e.g. beyond 8 kHz the PDE is able to deliver a more powerful sound to the receiving end creating a more natural hearing experience.

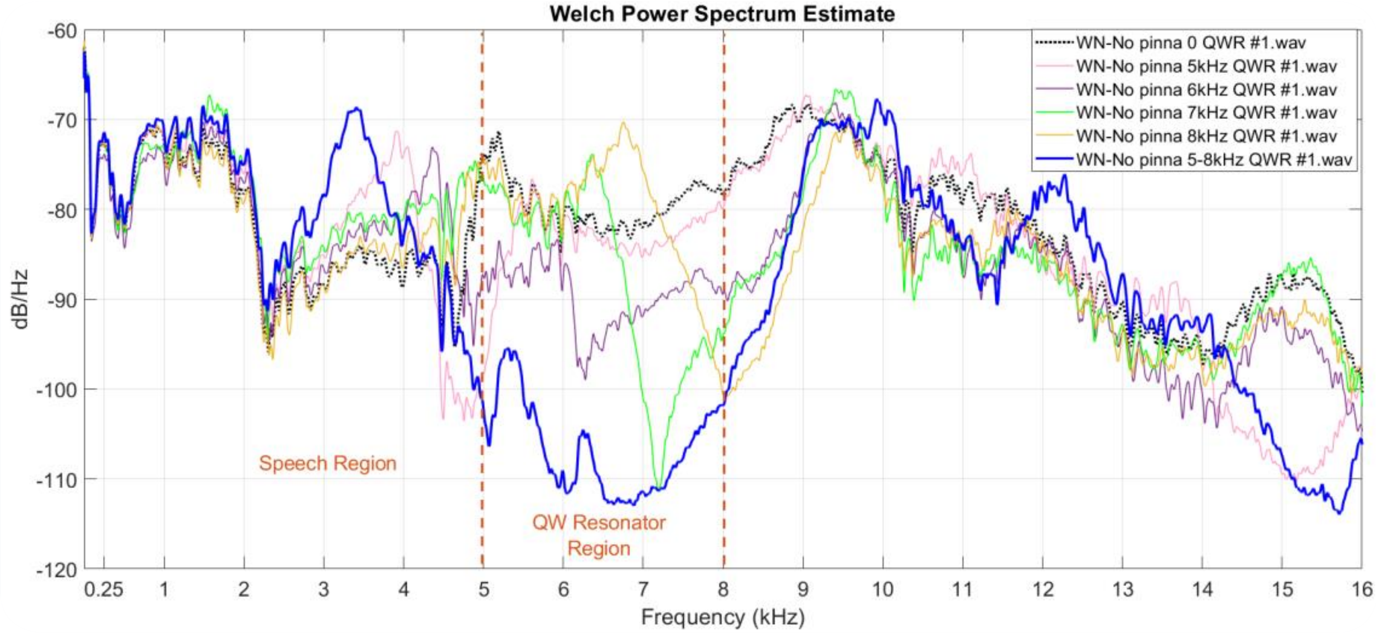

Figure 11: Noise reduction effect using the 5-8 kHz resonator with speech region and QW resonator region highlighted. Reference data of the 0 resonator prototype is shown by the black dotted line and the result obtained using 5-8 kHz resonator is shown in the thick blue line. Effects of individual resonators are shown in pink, purple, lime and yellow respectively.

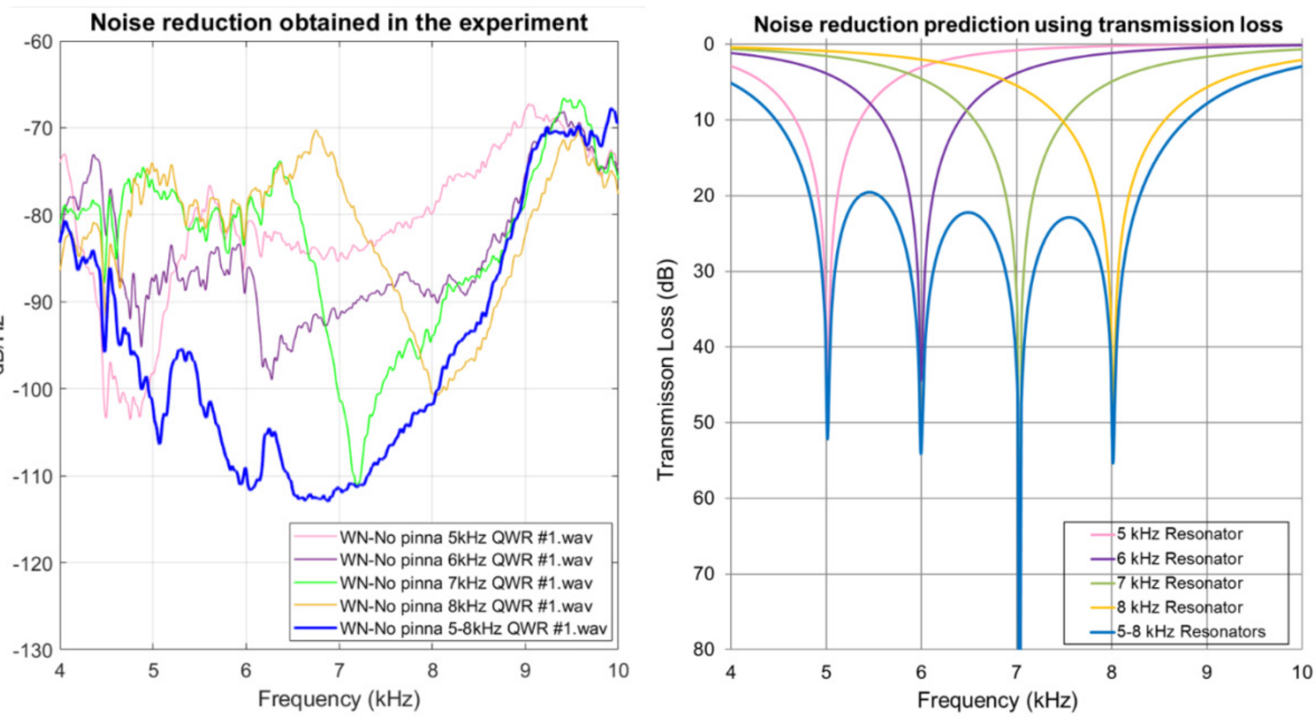

Figure 12: Comparison of noise reduction performance in the QW region between the experiment outcome (Left) and estimation using transmission loss (Right).

As mentioned above, every test on the devices was performed five times to confirm the repeatability of noise reduction results. In addition to some PSD plots that already have shown the repeated tests, e.g. Figure 9 and Figure 13, a summary of average signal power obtained across the two regions of interest for all the repeated tests is shown in Table 2. Average signal power across the two frequency regions of interest obtained from the repeated tests for each device, plus white noise without and with pinna attached.. Mean of results obtained in those five tests is used to calculate the nominal performance for each device.

Using the nominal average signal power calculated in Table 2, an analysis of the 5-8 kHz resonator and the PDE with respect to white noise and white noise with the 0 resonator prototype attached is shown in Table 3. Two performance measures are established, derived from Jiang & Atherton,[48] namely Speech

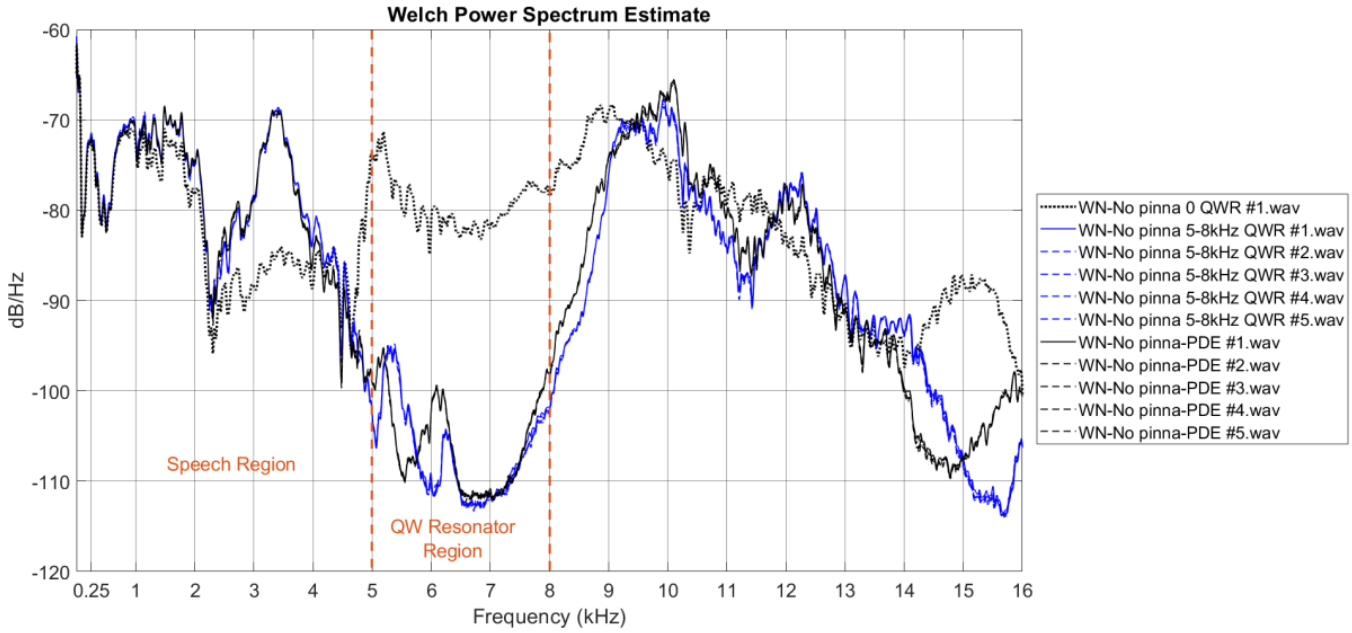

Figure 13: Comparison of broadband reduction performance between the 5-8 kHz resonator prototype (blue) and the proposed PDE prototype (black).

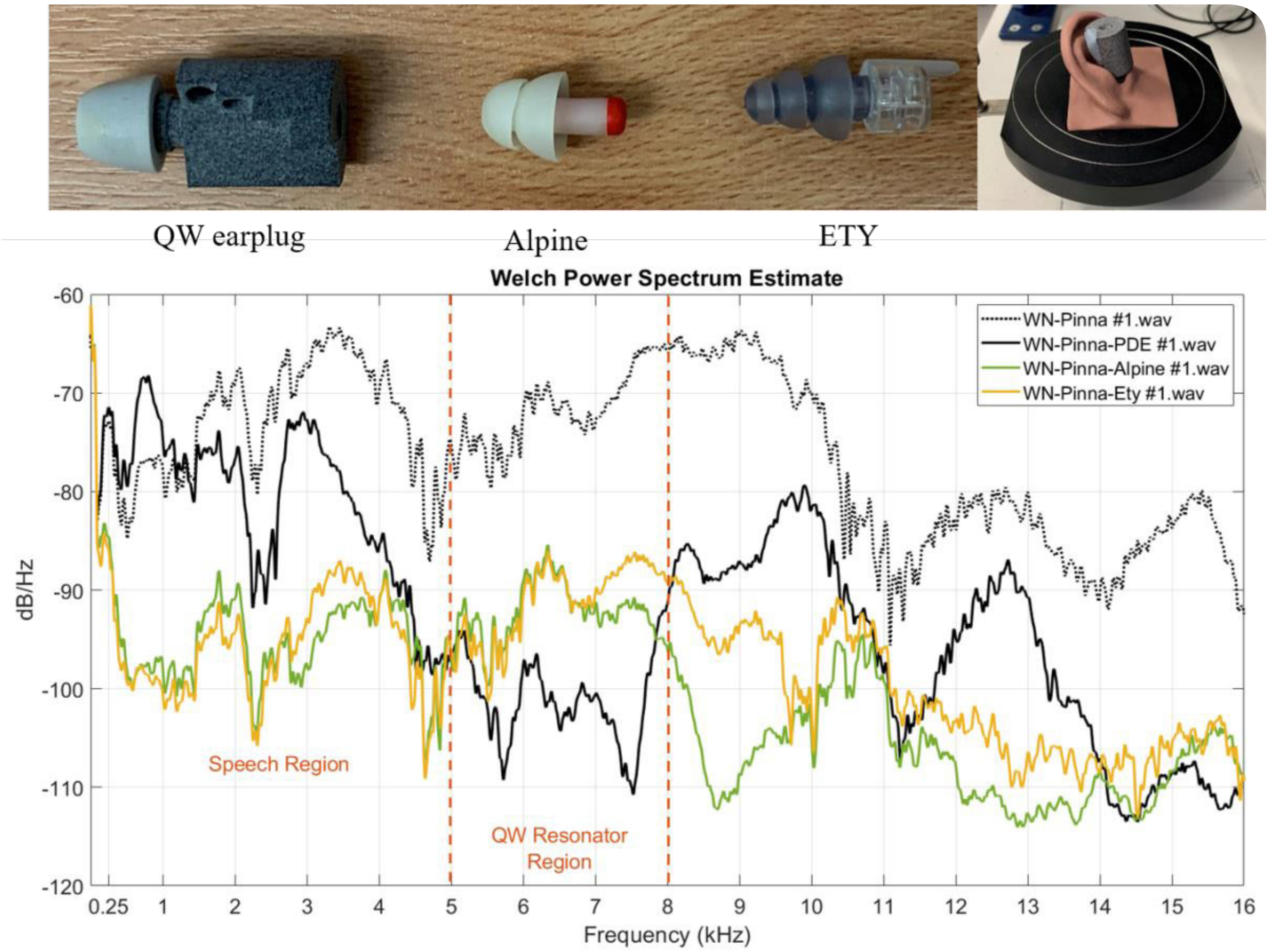

Figure 14: Comparison of broadband reduction performance in the QW resonator region and delivery of sound components in the speech region using PDE, Alpine WorkSafe and Ety ER20XS. Black dotted line indicates white noise captured with pinna attached, the black line represents PDE, green indicates Alpine WorkSafe and orange indicates Ety ER20XS.

Table 2. Average signal power across the two frequency regions of interest obtained from the repeated tests for each device, plus white noise without and with pinna attached.

	Test 1	Test 2	Test 3	Test 4	Test 5	Mean	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
White Noise - No Pinna	-73.35	-73.32	-73.34	-73.36	-73.39	-73.35	-75.24	-75.19	-75.15	-75.23	-75.25	-75.21
White Noise - No Pinna 0 Resonator	-82.32	-73.32	-82.33	-82.30	-82.27	-80.51	-79.40	-79.44	-79.43	-79.39	-79.38	-79.41
White Noise - No Pinna 5 kHz Resonator	-81.10	-73.32	-81.15	-81.17	-81.19	-79.59	-83.21	-83.20	-83.20	-83.22	-83.20	-83.20
White Noise - No Pinna 6 kHz Resonator	-80.85	-73.32	-80.64	-80.59	-80.54	-79.19	-89.42	-89.27	-89.27	-89.18	-89.13	-89.26
White Noise - No Pinna 7 kHz Resonator	-78.80	-73.32	-78.80	-78.79	-78.80	-77.70	-87.62	-87.59	-87.63	-87.66	-87.66	-87.64
White Noise - No Pinna 8 kHz Resonator	-81.66	-73.32	-81.59	-81.53	-81.50	-79.92	-80.12	-80.12	-80.10	-80.08	-80.09	-80.10
5-8 kHz Resonator No Pinna with putty	-79.04	-73.32	-79.10	-79.14	-79.18	-77.95	-106.77	-106.94	-106.96	-107.00	-107.03	-106.94
PDE No Pinna with putty	-79.39	-73.32	-79.43	-79.43	-79.47	-78.21	-105.92	-105.93	-105.94	-105.97	-105.96	-105.94
White Noise - With Pinna	-72.81	-72.77	-72.75	-72.70	-72.67	-72.74	-71.82	-71.78	-71.77	-71.75	-71.69	-71.76
PDE With Pinna & Foam tip	-81.05	-81.14	-81.13	-81.15	-81.15	-81.12	-101.18	-100.85	-100.84	-100.82	-100.80	-100.90
Alpine WorkSafe With Pinna	-95.43	-95.56	-95.58	-95.66	-95.63	-95.57	-92.24	-92.02	-91.97	-92.04	-92.02	-92.06
ETY ER20XS With Pinna	-95.77	-95.85	-95.84	-95.87	-95.90	-95.85	-91.17	-91.31	-91.29	-91.31	-91.34	-91.28

Clarity and Noise Reduction. The former is referred to by an inverse measure, shown as Inverse Speech Clarity in the tables, is obtained by calculating the difference in average power between signals within the speech region. As a result, the smaller the value of this inverse measure, the better the speech clarity achieved by the device, i.e.. Inverse Speech Clarity is smaller-the-better (STB). Noise Reduction is obtained by taking the average power drop in the QW resonator region between signals, i.e.. larger-the-better (LTB). Results highlighted in the table correspond to the PSD plots shown in Figure 13.

Table 3. Comparison of Speech Clarity (with Inverse Speech Clarity value shown) and Noise Reduction between the 5-8 kHz resonator and PDE.

	Speech region (0.25 - 5 kHz)	QW resonator region (5 - 8 kHz)	White Noise - No Pinna		White Noise - No Pinna 0 Resonator	
			Inverse Speech Clarity (STB)	Noise Reduction (LTB)	Inverse Speech Clarity (STB)	Noise Reduction (LTB)
White Noise - No Pinna	-73.35	-75.21				
White Noise - No Pinna 0 Resonator	-82.31	-79.41				
5-8 kHz Resonator No Pinna with putty	-79.11	-106.94	5.76	31.73	-3.20	***27.53***
PDE No Pinna with putty	-79.42	-105.94	6.07	30.73	-2.88	***26.54***

Table 4 shows a cross-comparison between the PDE, Alpine and Ety earplugs with respect to white noise captured with pinna installed. Results highlighted in the table correspond to the PSD plots shown in Figure 14. Looking at the highlighted area in the table, it is obvious that the PDE manages to achieve a much better Speech Clarity indicated by a significantly smaller Inverse Speech Clarity value of 8.38 dB. The PDE also exhibits a better Noise Reduction performance of approx. 10 dB than the two proprietary devices.

Table 4. Cross-comparison of Speech Clarity (with Inverse Speech Clarity value shown) and Noise Reduction between the PDE, Alpine and Ety devices.

	Speech region (0.25 - 5 kHz)	QW resonator region (5 - 8 kHz)	Inverse Speech Clarity (STB)	Noise Reduction (LTB)
White Noise - With Pinna	-72.74	-71.76		
PDE With Pinna & Foam tip	-81.12	-100.90	8.38	29.14
Alpine WorkSafe With Pinna	-95.57	-92.06	22.83	20.30
Ety ER20XS With Pinna	-95.85	-91.28	23.11	19.52

DISCUSSION

There has been extensive work on applying large-size scale QW resonators for low-frequency noise attenuation such as engine noise[30,49,50] and building ventilation noise.[28,35] It appears that little research has focused on small-size scale QW resonator for high frequencies. The outcomes of the experiment results presented have demonstrated the effectiveness of applying small size scale QW resonators to attenuate high-frequency noise. A single QW resonator is able to suppress noise at a target frequency whilst an array of resonators is capable of accomplishing broadband noise attenuation and exhibits an accumulated effect of all the QW resonators incorporated. White noise was used throughout all the experiments instead of actual drill noise, as the complexity of a drill noise PSD plot could overshadow the actual effect of noise reduction when using QW resonators. White noise is better suited to visualising noise reduction effect when using QW resonators and other passive devices.

As mentioned before, the actual white noise captured by the ECS is slightly different than ideal white noise. However, this dissimilarity is not an issue as it is only the relative difference, i.e. portions of signal being either kept or attenuated passively, that are of key interest when comparing the devices. The response for the 0 resonator prototype with white noise suggests that having a vent alone between the noise source and the microphone causes significant attenuations within the speech region and only slight attenuations within the QW resonator region. A substantial reason could be that, as explained by Kuk, Keenan and Lau,[32,33] transmission loss will be enhanced by the vent effect at high frequencies. The use of vents has been researched extensively (e.g. Winkler *et al.*[51]) in the field of hearing aid design with the purpose of minimising the occlusion effect. The design of PDE demonstrated in this study is similar to hearing aid design in the sense that vents have a significant influence on the real-ear perception of sound. However, as addressed by Kuk *et al.*[32,33] there are compromises to be made when choosing vent sizes as smaller vent induces occlusion effect whilst larger vents affect audibility at high frequencies. In this study, the minimisation of the occlusion effect was prioritised by employing a 5 mm vent diameter. Furthermore, with the purpose of excluding the vent effect from the analysis, the output of the 0 resonator prototype was used as a reference to examine the noise reduction effect of QW resonators.

Experiment results in Figure 10 to Figure 12 have indicated a clear correlation between transmission loss and actual noise reduction performance. As predicted, individual QW resonators manage to attenuate noise at targeted frequencies without affecting the rest of the signal too much. Slight shifts in resultant frequency reductions (negative peaks) from the target resonant frequencies observed in Figure 10 are likely to be caused by the amount of putty entering into the resonator. Although 2.5 mm was added to the original resonator length the actual working length during experiments can vary slightly. The array of four QW resonators configured with 1 kHz increments in target frequencies (5 kHz to 8 kHz) appears to have promising performance in terms of accomplishing a broadband noise reduction. The resultant reduction obtained from the experiment appears to have an accumulated effect of four individual resonators investigated. This again aligns with the estimation using transmission loss indicating that noise reduction performance of an array of QW resonators can be predicted using aggregated transmission loss of each resonator with reasonable accuracy. In this study, four resonators were used considering ergonomics of an earplug design. It can be envisaged that with additional resonator branches of different lengths a broader attenuation performance might be achieved. Too many QW resonators can lead to a larger earplug design which may be uncomfortable to wear. For high-speed air turbine driven dental drills, 5 to 8 kHz seems to be appropriate. However, for electric motor driven drills which is the main alternative drill type, normally operating at a maximum speed of 200,000 RPM (approx. 3.3 kHz), hence a much longer resonator will be required. Furthermore, the speech components around this frequency might get attenuated altogether. Bearing in mind that unlike active systems relying on intelligent algorithms to distinguish drill noises from speech, passive devices intend to suppress all sound within the target frequencies.

Bending a QW resonator as a general space-saving approach has already been researched at larger size scales[34] suggesting a similar performance with a slight shift (around 1-2%) in target resonant frequencies. In the context of drill noise attenuation, this can be neglected as the noise generated tends to vary within a broad range. Curved resonators, together with the error introduced by using the putty when sealing the open ends, contributes to the difference obtained between straight 5-8 kHz resonator prototype and the passive earplug prototype (see *Figure 13*). The benefits are evident when testing the prototype against two proprietary passive devices. The 5 mm vent exposed to the sound source contributes to the maintenance of signals within the speech region. Four QW resonators connected to the main vent achieve a broadband reduction within the QW resonator region, 5-8 kHz in this case.

The increased size for the PDE compares to the other two earplugs will make it less comfortable to wear. One potential improvement is to reduce the vent and resonator diameter which can result in a smaller earplug size. However, as discussed earlier in this section, a smaller vent size can increase the occlusion effect therefore rational decisions need to be made to find the optimal vent and resonator diameters and hence earplug size.

Results obtained in this study imply that effective passive noise attenuation devices employing QW resonator principles for specific applications where verbal communication is essential can be developed as long as target noise frequencies are known. The device can exist in the form of an earplug, like the PDE prototype shown in this study or more complex shapes as over-the-ear devices. Conventional over-the-ear protection devices tend to block noise using tight seals and/or sound absorbing materials to attenuate all frequencies altogether but they have the potential to use QW resonators instead. The larger size of an over-the-ear device means more resonators can be incorporated hence allowing verbal communication plus good noise attenuation performance.

CONCLUSION

In this study a novel passive earplug, designed for attenuating high-speed air turbine driven dental drill noise was developed and tested using white noise. White noise was used instead of actual drill noise to enhance the objectivity of performance analysis. The earplug employs quarter wavelength (QW) resonator principle to accomplish a broadband noise attenuation of target frequencies ranges. Experiment results indicate that the aggregated effect of noise filtering when multiple QW resonators are employed and can result in a significant broadband frequency reduction up to 27 dB. The results have also shown that transmission loss (TL) can be used to estimate the noise reduction performance of an array of multiple QW resonators. Comparative experiments were performed to demonstrate the advantage of the proposed passive device in the form of an earplug (PDE) over two proprietary passive devices in the perspective of maintaining speech clarity whilst achieving noticeably better noise reduction performance. The results suggest that that this type of device may have a place in dentistry to reduce drill noise. Broader application of this earplug concept to machine noise with identified target frequencies is possible.

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DATA AVAILABILITY

All sound recordings used to support the findings of this study are available from the corresponding author upon request.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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