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A Quality Design of Bone Conduction Voice in Magnetic Resonance Imaging Noise

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ABSTRACT

The acoustical driving noise of a magnetic resonance imaging (MRI) device is loud. A bone conduction microphone is used to transmit the patient's voice because it works better than other microphones during an MRI examination. However, when the patient becomes unwell, the doctor cannot understand the transmitted voice of the patient because the voice is faint and the MRI acoustical noise is loud. The MRI acoustical noise generates a vibration in the patient body. The vibration propagates to the microphone and deteriorates the communication quality. Our goal is to explore the relation between the shielding area of the bone conduction microphone and the communication quality. We propose a theoretical formula for the characteristic of the vibration propagation and the ratio of the vibration acceleration to the sound pressure based on a distributed constant. The communication quality in the case of the shielding the bone conduction microphone was verified using the theoretical formula. The estimated communication quality was equal to the experimental communication quality with high accuracy. The results show that the communication quality could be improved by a shielding area, such as an earmuff, to a level where the doctor could recognize the patient's faint voice.

Keywords: Bone conduction microphone, MRI acoustical noise, Vibration
I-INCE Classification of Subjects Number(s): 36.1, 76.9

1. INTRODUCTION

Examinations by magnetic resonance imaging (MRI) are important in medical diagnostics. However, MRI devices generate loud acoustical noise, with the sound pressure levels exceeding 100 dB [1]. The MRI acoustical noise is extremely loud and interferes with the voice of the patient. If a patient becomes unwell during the MRI examination, he or she would be unable to communicate with the doctor. Even though the MRI device is equipped with a call button, it cannot be used by patients who are unable to move their hands. A bone-conduction microphone could solve this problem. Such microphones reduce the influence of acoustical noise propagating through the air [2]. However, there are several problems associated with the use of a bone-conduction microphone during an MRI examination. The voice of ill patient may be faint; in which case, the microphone produces only a weak bone-conducted voice signal from the patient. In addition, MRI acoustical noise is very loud, and generates a vibration noise in the human body. The microphone receives the vibration noise caused by the MRI acoustical noise; thus, the signal-to-noise ratio (SNR) of the bone-conducted voice decreases [3].

With regards to the transmission of a faint voices, the non-audible murmur (NAM) microphone can pick up very faint whispers [4]. However, it is unsuitable for this study because the target of the voice volume of NAM microphones is smaller than our voice volume target. With regards to vibrations, a study has reported analyzed vibrations generated in buildings and the ground during the passage of trains [5]. In addition, there has been studies on ultrasonic vibrations [6]. In these studies, very low or high frequency vibrations were analyzed; however, vibrations in the audible range have not been

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sufficiently studied. Therefore, a study on audible range vibrations is needed. With regards to protecting the hearing of MRI patient, there is a measurement result for the shielding effect of MRI acoustical noises when the patient is wearing a helmet. In this study, the measurement result is not theoretically verified.

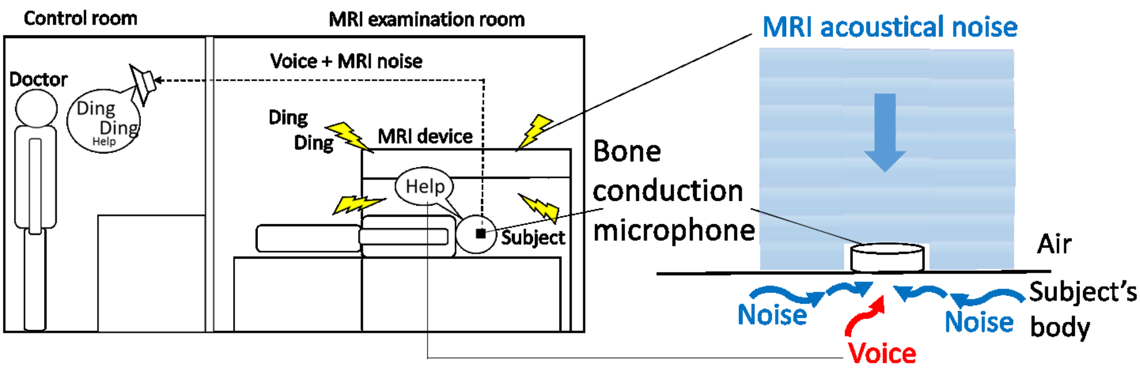
Our goal is to improve the communication quality of the faint voice of ill patient to enable successful communication with the doctor during an MRI examination. The influence of MRI acoustical noise is reduced with shielding of the bone-conduction microphone, which also reduces the vibration induced by the MRI acoustical noise. The shielding area is important to improve the SNR. The relation between the shielding area and communication quality of the bone conduction microphone is examined to calculate the effective shielding area. We propose a theoretical formula for the characteristic of the vibration propagation and the ratio of the vibration acceleration to the sound pressure based on a distributed constant. In this study, the improvement level of the communication quality in the case of shielding of bone conduction microphone is verified using a theoretical formula.

2. Calculation method for the effective shielding area

A bone-conducted voice propagates to the surface of the human body through bones and muscles as longitudinal waves. A bone-conduction microphone placed on the patient's face, only picks up vibrations traveling in the direction perpendicular to the surface of the human body. The direction of the vibration caused by the MRI noise is the same as the vibration direction of the bone-conducted voice; therefore, the vibration caused by the MRI acoustical noise interferes with the voice. Resulting in a decrease in the SNR of the bone-conducted voice. Figure 1(a) shows a communication system using bone-conduction microphone during an MRI examination.

The vibrations' influence on the bone conduction microphone depends on the surface area exposed to the MRI acoustical noise. Figure 1(b) shows the propagation flow of the sound and vibration from the air to the bone conduction microphone. The shielding reduces the surface area exposed to the MRI acoustical noise, and reduces the vibration caused by the acoustical noise.

The shielding area is important to improve the communication quality. We measured several parameters in the following elements to calculate of the effective shielding area of the bone-conduction microphone. One parameter is the ratio of the vibration acceleration to the sound pressure, $H_1(f)$, and another parameter is the characteristic of vibration propagation, $H_2(x,f)$.



(a) Communication system using a bone-conduction microphone. (b) Propagation flow.

Figure 1 – Communication system using a bone-conduction microphone.

2.1 Measurement of the ratio of the vibration acceleration to the sound pressure

2.1.1 Measurement Method

MRI acoustical noise is very loud and generates a vibration noise in the human body. The vibration caused by the MRI acoustical noise propagates to the bone-conduction microphone, and SNR of the bone-conducted voice decreases. Therefore, we measures the conversion relation between the acoustical noise and the vibration.

The bone-conduction microphone is shielded to reduce the vibration caused by the MRI acoustical noise. The shielding of the bone conduction microphone blocks the generation of the vibration by the acoustical noise. Non-shielded areas are exposed to acoustical noise, and are vibrated by the MRI noise. Therefore, the ratio of the vibration acceleration to the sound pressure, $H_1(f)$, is important when calculating the effective shielding area. The ratio of the vibration acceleration to the sound pressure, $H_1(f)$, is shown by the following equation,

$$H_1(f) = \frac{a(f)}{p(f)} . \tag{1}$$

where $p(f)$ is the sound pressure at the boundary of the human body, $a(f)$ is the vibration acceleration at the boundary of the conversion to the vibration by the human body, and f is the frequency.

2.1.2 Measurement conditions

The ratio of the vibration acceleration to the sound pressure ,$H_1(f)$, was measured under the following conditions. A phantom with a ceramic plate (thickness: 5 mm; 37860, ArTec) and silicone rubber (hardness: 20°; thickness: 5 mm; KT0049, KYOWA) representing bones and muscles, respectively, was used to prevent the risk of the hearing loss due to the loud acoustical noise. A vibration accelerometer (PV-85, RION) was placed on the center of the phantom. A loudspeaker was placed above the phantom. Figure 2 shows the position of the loudspeaker and vibration accelerometer. The ratio of the vibration acceleration to the sound pressure, $H_1(f)$, was measured in the frequency range 200-4000 Hz (i.e., the frequency band of a telephone). The output from the loudspeaker was a sine wave with sound pressure level of 65-75 dB.

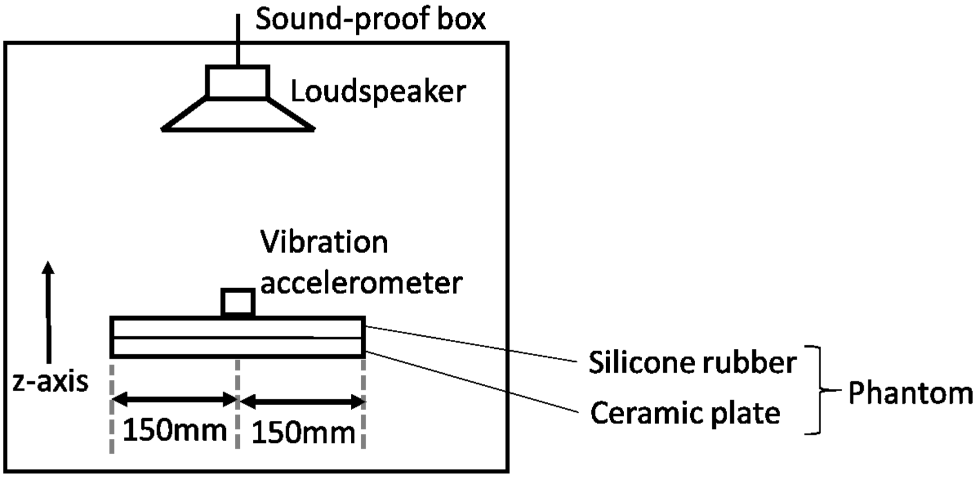


Figure 2 – Position of the loudspeaker and vibration accelerometer on the phantom.

2.1.3 Measurement result

The ratio of the vibration acceleration to the sound pressure, $H_1(f)$, was measured to examine the relation between the shielding area and communication quality. Figure 3 shows the frequency characteristics of the ratio of the vibration acceleration to the sound pressure, $H_1(f)$, in the frequency range 200-4000 Hz.

The ratio of the vibration acceleration to the sound pressure, H_1, decreased as the frequency increased. An approximation formula was calculated using the results for each frequency [7]. This result is captured by the following equation in the case of the phantom,

$$H_1(f) = 0.012e^{-0.001f} . \tag{2}$$

This section demonstrated the conversion relation of between the sound wave and the vibration over the frequency domain. The results indicate that low frequency sound waves are easily converted to vibrations. Therefore, the vibrations caused by the MRI noise greatly influence the bone-conducted voice, because the primary frequency range of the human voice is from 200 to 1000 Hz, and the primary frequency range of MRI noise is from 400 to 1000 Hz.

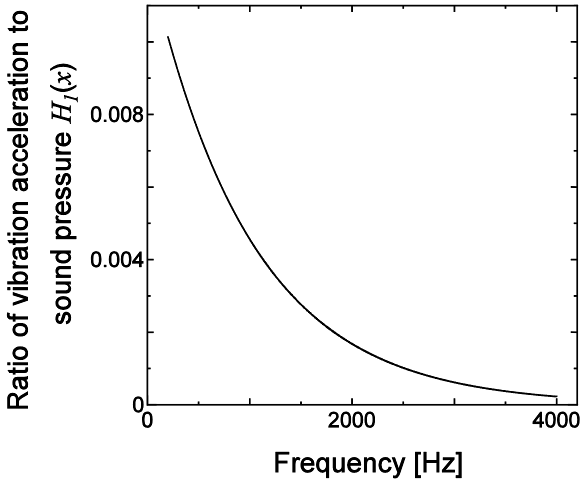


Figure 3 – Frequency characteristics of the ratio of the vibration acceleration to the sound pressure.

2.2 Measurement of the characteristic of vibration propagation

2.2.1 Measurement method

MRI acoustical noise is very loud and generates vibration noise through the human body. The vibration caused by MRI acoustical noise propagates to the bone-conduction microphone, and SNR of bone-conducted voice decreases. Therefore, we measure the characteristic of the vibration propagation.

The vibration caused by MRI acoustical noise propagates to the bone-conduction microphone through the body. Therefore, the characteristic of vibration propagation in the body, $H_2(x,f)$, is important when calculating the effective shielding area. The characteristic of vibration propagation, $H_2(x,f)$, is characterized by the vibration acceleration ratio at a distance x and frequency f, as shown by the following equation,

$$H_2(x,f) = \frac{a_2(x,f)}{a_1(f)}. \tag{3}$$

where, $a_1(f)$ is the vibration acceleration of the reference point, and $a_2(x,f)$ is the vibration acceleration at a distance x from the reference point.

2.2.2 Measurement conditions

The characteristic of vibration propagation, $H_2(x, f)$, was measured under the following conditions. The phantom contained a ceramic plate and silicon rubber, as in section 2.1. A vibrator was placed on the phantom. Two vibration accelerometers were used. One vibration accelerometer is placed on the center of the vibrator (PV-90B, RION), and the other (PV-85, RION) was placed on the phantom at a distance x (20–120 mm) from the center of the vibrator. Figure 4 shows the position of the vibrator and each vibration accelerometer on the phantom. The characteristic of vibration propagation was measured in the frequency range 200-4000 Hz (i.e., the frequency band of a telephone).

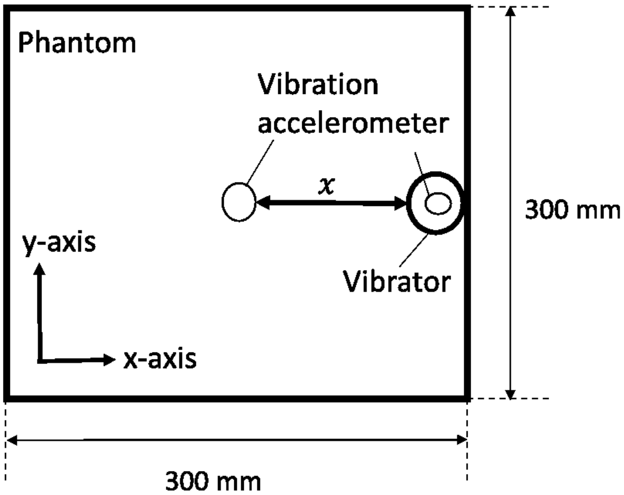


Figure 4 – Position of the vibrator and each vibration accelerometers on the phantom.

2.2.3 Measurement result

The characteristic of vibration propagation, $H_2(x, f)$, was measured to examined the relation between the shielding area and communication quality. Figure 5 shows the relation between the frequency, distance, and the characteristic of vibration propagation, $H_2(x, f)$.

The characteristic of vibration propagation, $H_2(x, f)$, decreased as the frequency increased. This shows that the characteristic of vibration propagation is inversely proportional to the distance. An approximation formula was calculated using the results for each frequency [8]. This result is captured by the following equation in the case of the phantom,

$$H_2(x, f) = \left\{(2835 - j1.399)\frac{1}{f}\frac{1}{x}\right\} . \tag{4}$$

The characteristic of vibration propagation is large for short distances and low frequencies. Therefore, we focused on a range having large ratios when estimating the shielding area.

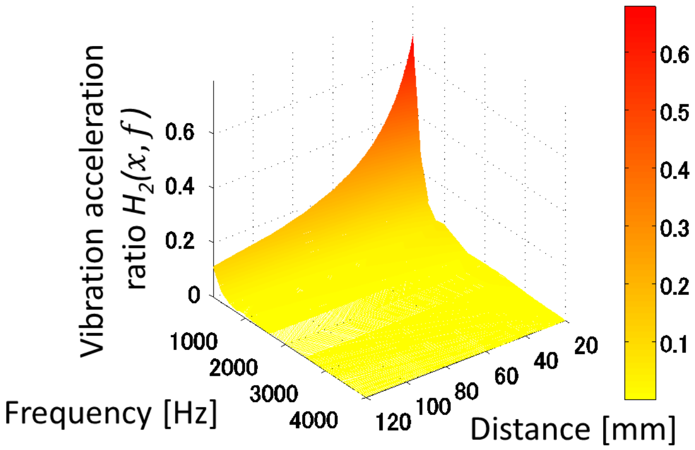


Figure 5 – Characteristic of vibration propagation $H_2(x, f)$.

3. Estimation of the communication quality improvement with shielding

3.1 Estimation method for the effective shielding area

Each element used to calculate the effective shielding area was measured in the previous section. Here, the improvement level of the communication quality is estimated using those elements and the proposed theoretical formula.

The shielding of the bone conduction microphone reduces the surface area exposed to the MRI acoustical noise and vibration caused by the acoustical noise. Figure 6 shows the propagation flow of the sound and vibration with and without shielding. The improvement level of the communication quality is affect by the shielding area. The shielding area is restricted because both the bone conduction microphone and shielding are mounted on the patient's face. Therefore, the shielding area is important to effectively improve the communication quality. The effective shielding area is calculated by the proposed formulae, where f is the frequency, t is the time, x is the distance from the bone conduction microphone to the optional point, $P\sin(2\pi ft)$ is the sound pressure of the MRI acoustical noise, S_o is the surface area of the human body exposed to MRI acoustical noise, $H_1(f)$ is the complex number of the ratio of the vibration acceleration to the sound pressure, $H_2(x,f)$ is the complex number of the characteristic of vibration propagation, the instantaneous value $a_o(f,t)$ is the vibration acceleration that propagates to the bone conduction microphone without shielding, and $a_o(f,t)$ is estimated from

$$a_o(f,t) = \int_{S_o} H_1(f) H_2(x,f) \sin(2\pi ft) dS, \tag{5}$$

where S_x is the shielding area. The instantaneous value $a_s(f,t)$ is the vibration acceleration that propagates to the bone conduction microphone with shielding, and $a_s(f,t)$ is estimated from

$$a_s(f,t) = \int_{S_o - S_x} H_1(f) H_2(x,f) \sin(2\pi ft) dS. \tag{6}$$

The improvement level, L_i, for the communication quality with shielding is defined as follows,

$$L_i = 10\log \overline{a_0{}^2(f,t)} - 10\log \overline{a_s{}^2(f,t)} \quad \text{[dB]}. \tag{7}$$

The effective shielding area is calculated by estimating the improvement level L_i in the case for each shielding area S_x.

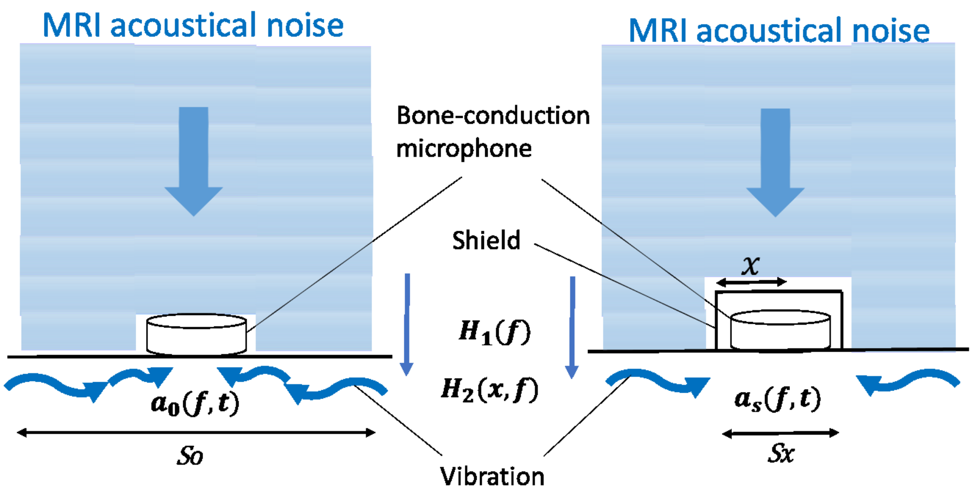


Figure 6– Method for improving the communication quality with shielding.

3.2 Measurement conditions for the signal to noise ratio

SNR of the bone-conducted voice and the improvement level with shielding by earmuff were measured to calculate the effective shielding area.

The bone-conducted voice was measured as follows. A vibration accelerometer (PV-85, RION) was placed on the cheekbone. When the outputted voice of the subject was 60 dB (re.1m), the vibration of the cheekbone was recorded. Next, a vibrator and vibration accelerometer (PV-85, RION) were placed on the phantom. The phantom comprise a ceramic plate and silicon rubber, as in section 2.1. The vibration of the recorded bone-conducted voice was outputted to the phantom, and the vibration characteristic of the bone-conducted voice in the phantom was measured.

The vibration caused by the MRI acoustical noise was measured as follows. A vibration accelerometer (PV-85, RION) was placed on the center of the phantom. A loudspeaker was placed above the phantom. When the loudspeaker outputted an MRI acoustical noise of 90 dB into the phantom, the vibration on the phantom was measured in the cases of shielding by earmuff and non-shielding.

From the results, the SNR of the bone-conducted voice and MRI noise in the phantom was calculated.

3.3 Change in the improvement level by shielding

First, SNR of bone-conducted voice and MRI noise without shielding were measured to calculate the effective shielding area. Figure 7 shows the SNR of bone-conducted voice in the MRI noise environment. The SNR of the bone-conducted voice was −8 dB without shielding.

Second, the improvement level of the communication quality in the MRI noise environment with the shielding of the bone-conduction microphone was estimated using the proposed formula to calculate the effective shielding area. Figure 8 shows the estimated improvement level of the communication quality with shielding. The estimated improvement level with shielding (7850 mm^2) was 9 dB. When the shielding area was greater than 7850 mm^2, the communication quality sufficiently improved for MRI examinations because the SNR of bone-conducted voice was −8 dB. Because the communication quality sufficiently improved by the shielding area, such as an earmuff, it is possible for the bone-conduction microphone to be combined with an earmuff.

Finally, the experimental improvement level with shielding by earmuff and the estimated improvement level were compared to determine the accuracy of the estimation result. Figure 9 shows the experimental improvement level with shielding by an earmuff (a shielding area of approximately 7850 mm^2). The experimental improvement level with an earmuff was L_i=8 dB in the experimental result. The estimated improvement level in the case of a shielding area of 7850 mm^2 was L_i= 9 dB. This estimated improvement level L_i had accuracy of 1 dB, and the estimated improvement level was equal to the experimental improvement level with high accuracy. It is thought that the error was caused by the reflection of the vibration at the edge of the phantom.

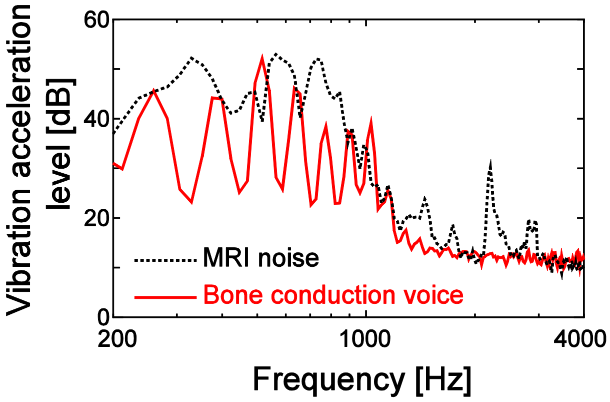


Figure 7 – The SNR of the bone-conducted voice.

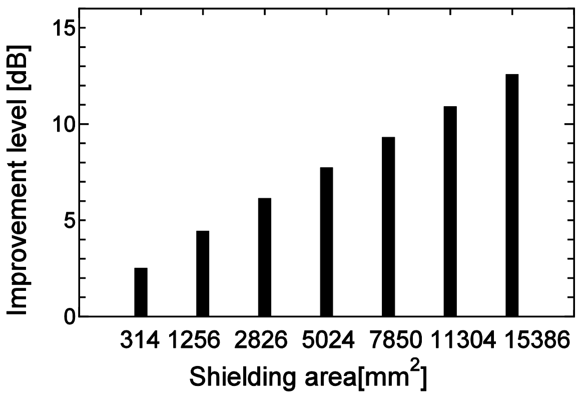


Figure 8 – The improvement level of the vibration for each shielding area.

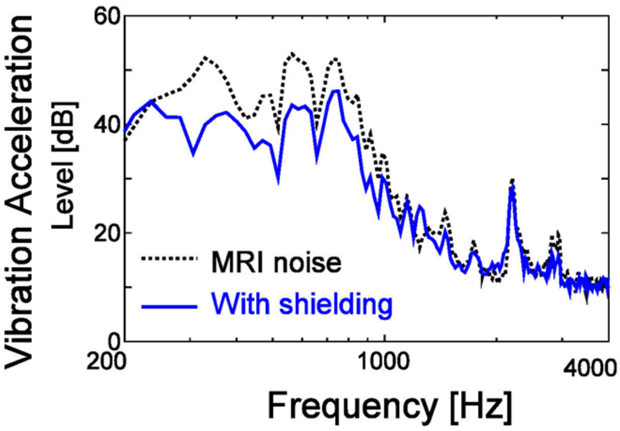


Figure 9 – The measured vibration acceleration level with and without earmuffs as shielding.

4. Conclusions

Our goal was to improve the communication quality of the faint voice of an ill patient when talking to a doctor during an MRI examination. In this study, the improvement level of the communication quality in the case with shielding of the bone conduction microphone was verified using a theoretical formula. The estimated noise reduction level was equal to the measured noise reduction level with high accuracy. The communication quality can be improved using a shielding area, such as an earmuff, to a quality where the doctor can recognize the patient's faint voice.

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