VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2025.2.17
Vibrations in Physical Systems, 2025, 36(2), 2025217

Noise in MRI diagnostic rooms

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Abstract The paper presents an acoustic analysis of noise levels in Magnetic Resonance Imaging (MRI) diagnostic rooms, including both mobile and portable laboratory configurations. Measurements were conducted to assess noise exposure to patients and medical staff during different MRI signal sequences: Diffusion-Weighted Imaging (DWI), Diffusion-Weighted Imaging with oscillating gradient (DWI-og), and Diffusion-Weighted Imaging Turbo Spin Echo (DWI-TSE). Results demonstrate that noise levels during MRI examinations often exceed occupational safety limits, with A-weighted equivalent levels (LAeq) reaching up to 94 dB. The study identifies the main sources of acoustic emissions and discusses implications for hearing protection and room design.

Keywords: MRI, acoustic noise, gradient coils, mobile diagnostic units, sound pressure levels.

1. Introduction

Magnetic Resonance Imaging (MRI) scanners are among the most important devices in modern medical imaging diagnostics. MRI is a non-invasive examination that allows obtaining images of a cross-section of the human body without the use of ionizing radiation. Typical MRI examinations can generate A-weighted Sound Pressure Levels (SPLs) between 90 and 130 dB, occasionally exceeding recommended occupational exposure limits without hearing protection [1-5]. They are used to create high-quality, detailed images of organs and tissues inside the body [6-8]. MRI diagnostic laboratories are located stationary in hospital buildings, but mobile laboratories are also produced: on car platforms and portable modular MRI laboratories.

In medical diagnostics, the accuracy and precision of the image of the body's interior are crucial for the effective treatment of patients. Magnetic resonance imaging uses the phenomenon of nuclear magnetic resonance, characteristic of the nuclei of elements with an odd number of protons or neutrons, and thanks to this, having angular momentum (spin) and a magnetic moment [9-13]. The magnetic resonance phenomenon in medical applications consists in the absorption of electromagnetic wave energy of radio frequency f by a proton (hydrogen nucleus, which is characterized by non-zero magnetic spin). Then, after switching off the radio transmitter (RF); the absorbed energy is radiated (as a result of relaxation processes) by protons, inducing a radio signal of the same frequency in the receiving coil. The most commonly used element is the hydrogen atom, which is related to its common occurrence in living organisms [6].

MRI diagnostics require simultaneous exposure of the patient to a magnetostatic field and a variable magnetic field [13-15]. The magnetic field used usually has a value from 0.5 to 12.0 Tesla [16-20]. In Poland, magnetic resonances in a field of 1.5 T are most commonly used in medical examinations. Many medical facilities in Germany use MRI systems with magnetic fields of 7 or 9.4 Tesla [9]. Undesirable acoustic noise occurs during magnetic resonance examination. At relatively low sound levels, it can cause irritation, disrupt verbal communication between staff and patients, and cause increased anxiety in patients. Acoustic noise levels of up to 133 dB have been recorded and several reports have noted noise levels in the range of 120–130 dB [19-21].

2. Noise sources in MRI rooms

Mobile diagnostic stations are being built to make magnetic resonance imaging scanners more widely available. These can be laboratories on truck chassis wheels, as well as portable diagnostic laboratories. Acoustic studies in MRI rooms were conducted in two types of modular diagnostic imaging laboratories: mobile (Figs. 1 a, b) and portable (Figs. 1 c, d): [22]. The schematic of noise measurements plan in MRI rooms is shown in Fig. 2.

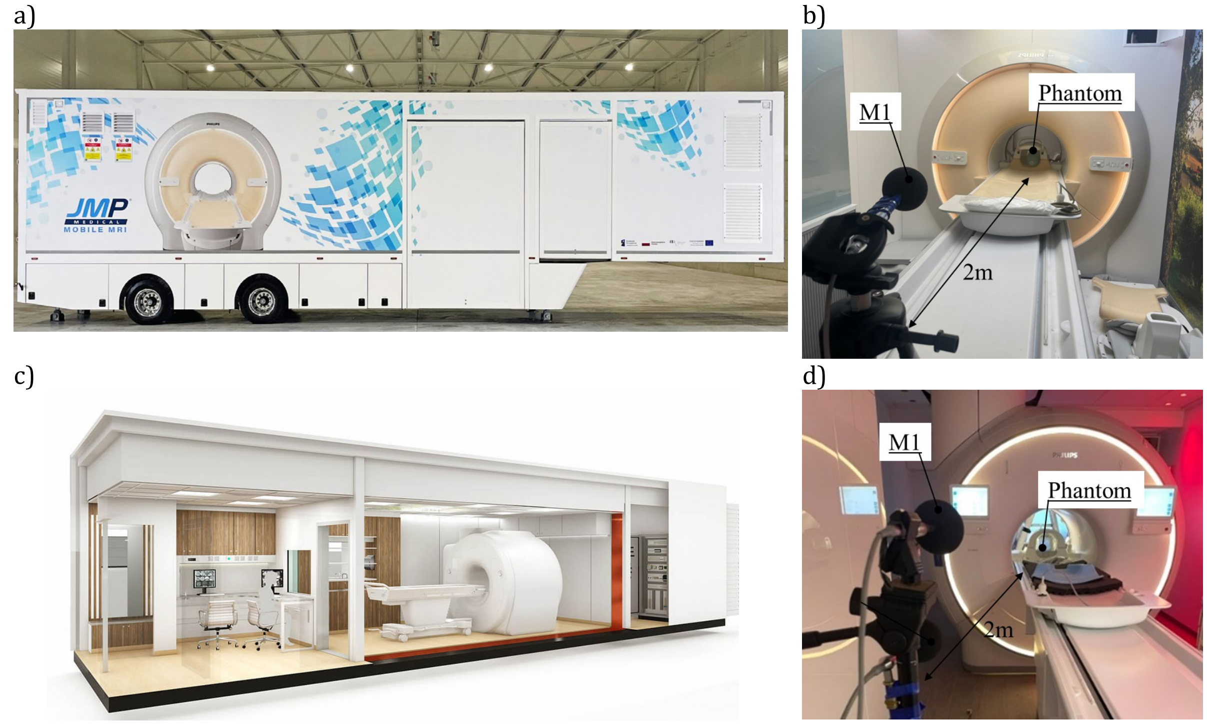

Figure 1. a) Mobile diagnostic imaging laboratory [22] and b) measurement setup in examination room, c) Portable diagnostic imaging laboratory [22] and d) measurement setup in examination room.

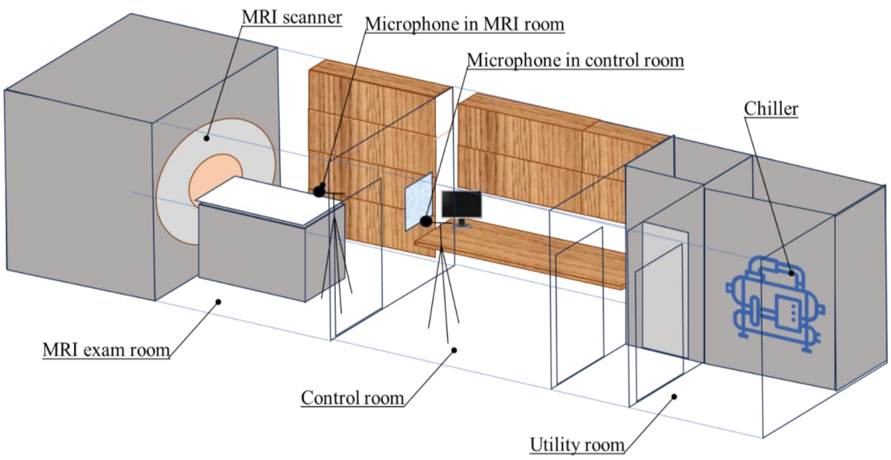

Figure 2. Measuring path diagram in a mobile MRI lab.

The following sources of noise related to the operation of the MRI scanner occur in magnetic resonance diagnostic rooms (Fig. 2):

- MRI scanner, especially gradient coils operating during the MRI scanner examination (source active only during the examination of the patient),
- air conditioning and ventilation system ensuring cooling of the superconducting magnet and constant air temperature in the scanner cabin (chiller and helium pump) (operating continuously),
- computer devices controlling the scanner operation and enabling archiving and analysis of examination results (operating continuously during working hours).

Diagnostic images during the examination are obtained via a pulsed magnetic field (so-called gradient field) and a pulse-modulated magnetic field with a frequency in the range of 21–126 MHz (in the case of MRI 0.5 T – 3 T). Pulses of very strong gradient magnetic fields are generated by built-in gradient coils, in which current flows in pulses with intensity reaching thousands of amperes. The rapid, i.e. within about 0.5 ms, increase or decrease of the pulse current intensity in the gradient coils causes thermoplastic processes associated with the generation of pulse noise. The noise is often described as a series of loud knocking, tapping or thumping sounds that can be disturbing to patients.

In this study, the mobile MRI system and portable MRI system were evaluated using their standard clinical protocols. The scanning signal sequences routine and implementation were different on both the systems because of difference in hardware, software, and workflow variations. The signal sequences employed for examination in a mobile MRI system include Diffusion-Weighted Imaging (DWI), Diffusion-Weighted Imaging with oscillating gradient (DWI-og), and Diffusion-Weighted Imaging-Turbo Spin Echo (DWI-TSE), while the portable diagnostic laboratory was analysed for scanning sequences of Echo Planar Imaging-Spin Echo (EPI-SE) and Turbo Spin Echo (TSE). Each of these sequences is characterized by a specific spectrum and generated noise level in the diagnostic laboratory, examination room, and operator's room. The configuration parameters for individual signal sequences are presented in Table 1. In MRI, standard scanning sequences are composed of various electrical pulses, including slice selection, phase encoding, and frequency readout, each applied to the corresponding gradient coils within the MRI system. The characteristics of these input pulses depend upon the method of scan, leading to varying scan duration for different scanning sequences as observed in Table 1.

Table 1. Configuration for individual signal sequences.

Parameter	Scanning sequence				
	Mobile MRI system			Portable MRI system	
	DWI	DWI TSE	DWI-og	EPI-SE	TSE
Static field strength B_0 [T]	1.5	1.5	1.5	1.5	1.5
Repetition time TR [ms]	2623	3329	2957	500	1500
Echo time [ms]	83	72	85	40	100
Duration [s]	36	261	36	30.5	49.5

The most commonly used cylindrical magnetic resonance imaging (MRI) scanner in research has three gradient coils that generate three orthogonal magnetic linear fields to spatially encode the scanned object. During the imaging sequence, currents flowing through the gradients are rapidly switched on and off to perform the imaging procedure. As a result of the rapid current switching inside these coils, in the environment of a strong static magnetic field B_0, the gradient coils experience rapidly changing Lorentz forces, which causes significant vibrations and thus produces loud acoustic noise. The entire vibrating structure is surrounded by air, in which the sound wave propagates and is perceived by humans as noise [12, 13]. The frequency spectrum of such noise has significant components in the audio frequency range. The unpleasantness and even pain of this noise is a long-standing problem [1, 2], which is exacerbated by both higher field strengths and faster imaging methods. While MRI acoustic noise problems start with severe patient discomfort (earplugs are usually used), patients tend to jump every time a new gradient sequence is started, and this movement is detrimental to obtaining high-quality imaging. In the case of brain MRI, this movement is particularly detrimental, given the small signal that is being extracted from brain activity. In the case of auditory system studies, acoustic noise generated during MRI can interfere with medical evaluation of this system by introducing uncontrolled extraneous sounds [2].

3. Noise tests in the rooms of the MRI diagnostic Laboratory

3.1. Examination room

In the examination room of the mobile diagnostic station, microphones were placed approximately 2 m from the scanner opening at a height of 1.5 m above the floor and at the height of the patient's bed. The source of noise was a magnetic resonance scanner, in which three types of signal sequences were induced: DWI, DWI-og, DWI TSE. Fig. 3 shows the time courses of signals measured in the examination room of the mobile MRI system.

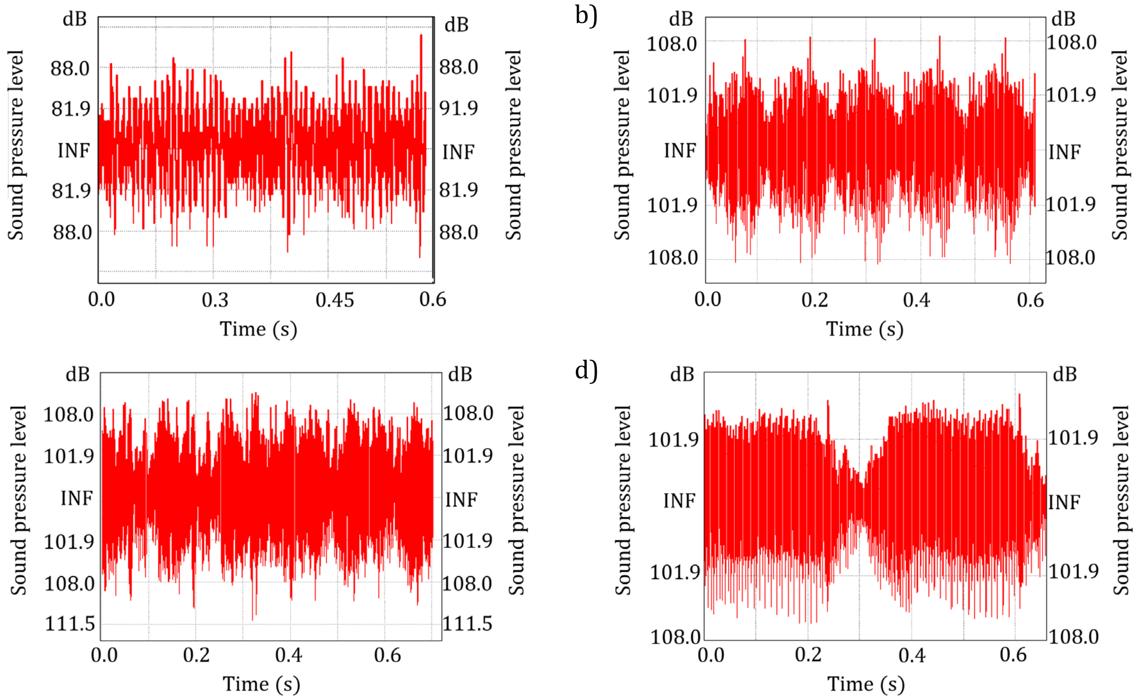

Figure 3. Sound signal recordings in a mobile MRI examination room: a) background noise, b) DWI, c) DWI-og, and d) DWI-TSE sequences.

The recorded spectral characteristics are presented for these three signals and the background noise are shown in Fig. 4, and Tab. 2 contains the values of the A-weighted sound pressure levels L_{Aeq}, L_{Apeak}, L_{A90} and C-weighted sound pressure levels L_{Cpeak}.

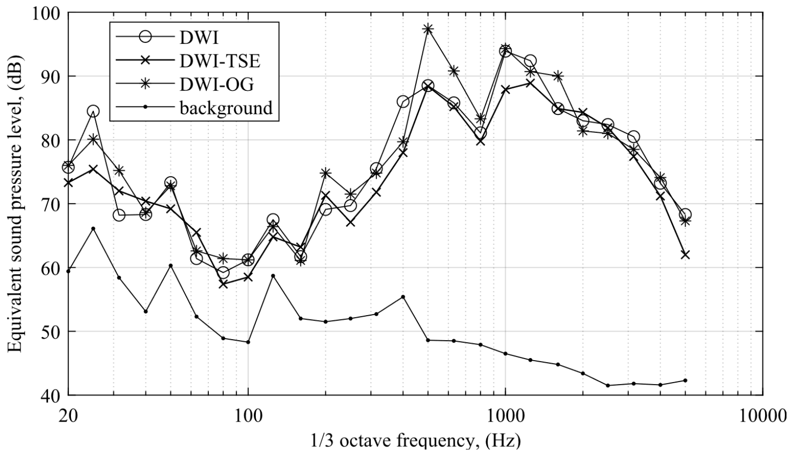

Figure 4. Noise spectra of different type of MRI signals in mobile MRI.

Table 2. The measured sound pressure level of different type of MRI signals in mobile system.

Parameter [dB]	Scanning sequence			Background noise
	DWI	DWI TSE	DWI-og	
L_{Aeq}	94	90.1	94.2	58.8
L_{Apeak}	103.9	101.5	105.9	75.6
L_{Cpeak}	104.2	101.8	105.4	81.3
L_{A90}	102.2	99.1	104	73.6

In case of portable MRI system. the microphone was placed at the height of 1.5 m from the floor and 2 m from the opening of MRI. The acoustic measurements were carried out for the operational state of MRI during scanning sequence of EPI-SE and TSE. The time domain signals in the examination room of portable

MRI system are presented in Fig. 5. The acoustic spectra of the signals are depicted in the Fig. 6. The acoustic parameters of the examination room in portable MRI are presented in Tab. 3.

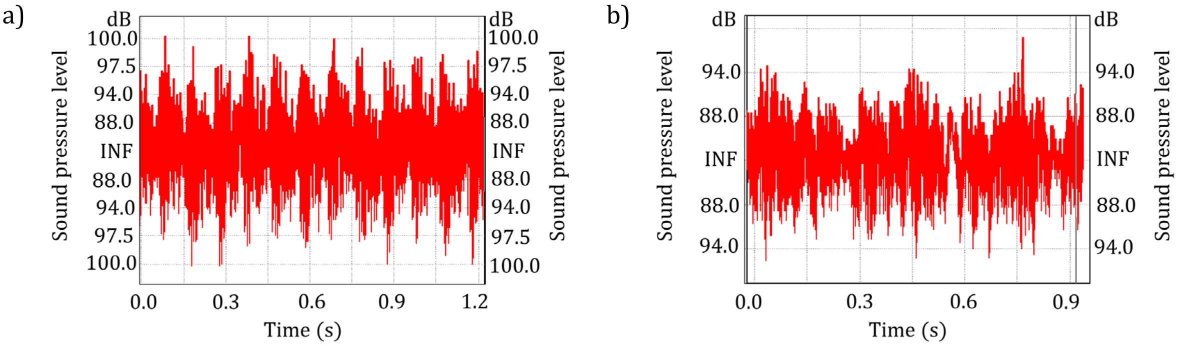

Figure 5. Sound signal recordings in a portable MRI examination room: a) EPI-SE, b) TSE sequences.

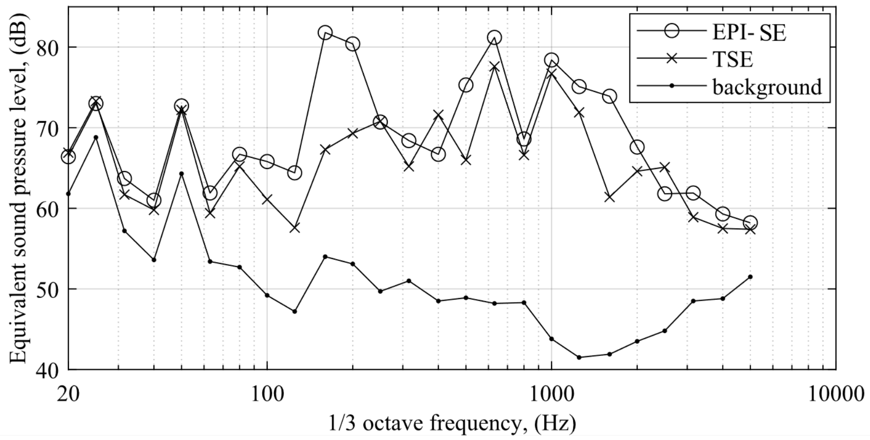

Figure 6. Noise spectra of MRI signals in portable MRI.

Table 3. The measured sound pressure level of different type of MRI signals in Portable system

Parameter	Scanning sequence		Background noise
	EPI-SE	TSE	
L_{Aeq}, [dB]	78.2	74.7	60.7
L_{Apeak} [dB]	93.9	87.8	81.1
L_{Cpeak} [dB]	95.5	90.8	83.1
L_{A90} [dB]	91.6	86.0	78.5

3.2. Operator room

The control room or operator's area lacks a distinct noise source of its own. However, it is positioned directly adjacent to the MRI examination room and the Chiller room. The predominant source of noise infiltrating this space originates from the operation of the MRI scanner. Within the control room, the noise primarily arises from the secondary excitation, which is a result of the propagated vibrations emanating from the MRI scanner. These vibrations travel to the walls, subsequently leading to structure-borne noise.

Figure 7 illustrates the acoustic and spectral properties observed within the operator room of an MRI scanner, which is utilized in both mobile and portable diagnostic systems. The data acquisition was performed while the MRI system was actively operating. Specifically, the scanning sequences employed were DWI for the mobile system and EPI-SE for the portable system.

The operator room reported the A-weighted sound pressure levels L_{Aeq} = 63.1 dB, L_{Apeak} = 75.9 dB and C-weighted sound pressure levels L_{Cpeak} = 84.1 dB during the scan process. Similarly, A weighted sound pressure levels L_{Aeq} = 54.2 dB, L_{Apeak} = 77.2 dB and C-weighted sound pressure levels L_{Cpeak} = 78.7 dB were obtained in operator room during the scan process in portable MRI system.

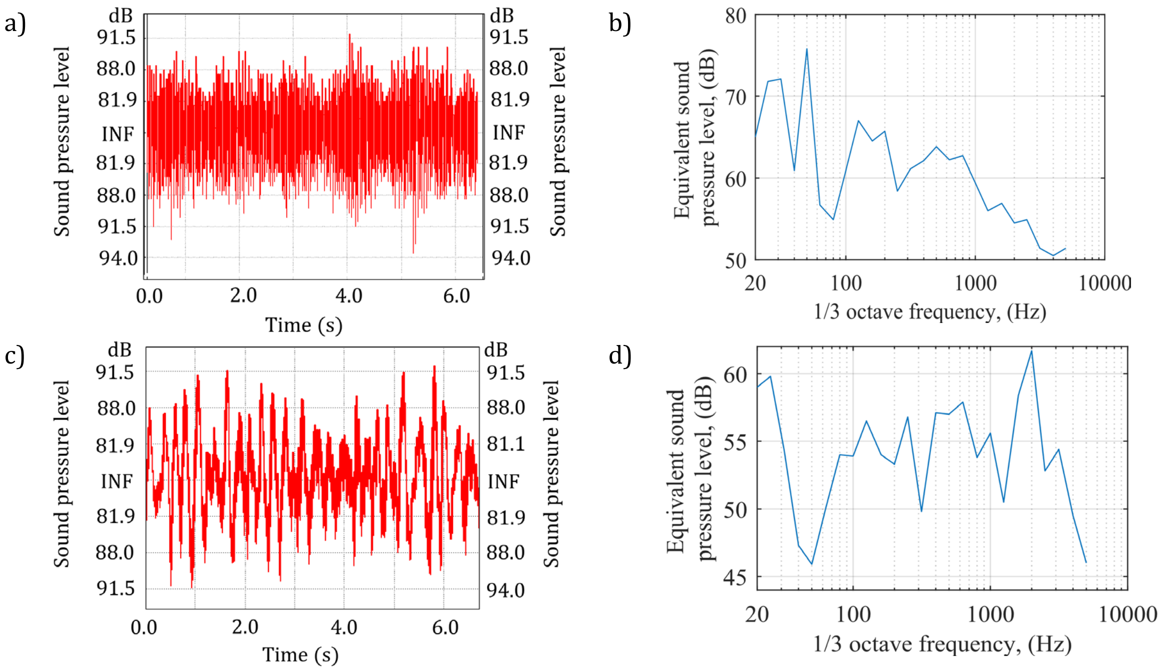

Figure 7. Operator room noise signal and spectra for mobile (a, b) and portable (c, d) MRI.

3.3. Chiller room

As mentioned earlier, most of the devices used in Poland are MRI with 1.5 T superconducting magnets [2]. Stable operation of superconducting magnets is possible thanks to the helium cooling system, which maintains the magnets in a superconducting state. The cooling system is located in a separate room. It is also an essential part of the air conditioning and ventilation system of the entire diagnostic station. The helium pump is continuously operated in order to keep the MRI system functional. Hence, significant noise is emitted into the diagnostic facility and in the external environment.

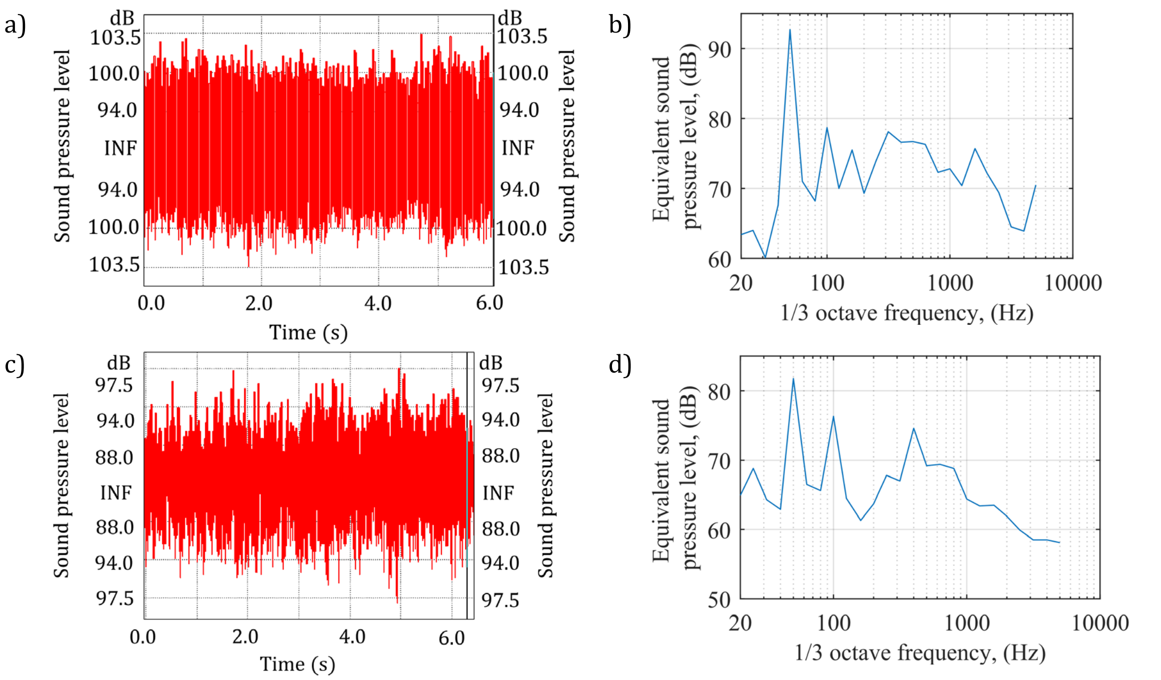

Figure 8. Noise signal and spectra in the chiller room of the mobile (a, b) and portable (a, b) MRI station.

Figure 8 depicts the time-domain signals of the sound and recording and the corresponding acoustic spectra measured in the mobile MRI system (a, b) and portable MRI system (c, d). The acoustic parameters in the chiller room are calculated from the recorded signals. The chiller room of mobile MRI system reported the A-weighted pressure sound pressure levels L_{Aeq} = 77.8 dB, L_{Apeak} = 90.4 dB and C-weighted sound pressure levels L_{Cpeak} = 95.9 dB during the scan process. Similarly, A-weighted sound pressure levels L_{Aeq} = 70.1 dB, L_{Apeak} = 85.6 dB and C-weighted sound pressure levels L_{Cpeak} = 91.8 dB was reported in the chiller room of portable MRI system.

4. Discussion

The noise accompanying the MRI examination is bothersome not only for the patient, but also for the medical staff and persons accompanying the patient. The main source of noise is physical phenomena occurring primarily in the gradient coils. Sounds reach the middle ear not only through the ear canal, but also the transmission of sound to the brain takes place directly or indirectly through body structures, i.e. the skull bones. In reality, we still experience loud sound even after putting on earplugs, because earplugs only muffle high-frequency sound noise in the audible frequency band. Noise levels can be high, including those measured in our experiment. There are no specific noise levels for magnetic resonance imaging. However, the harmfulness of the noise dose can be estimated using legal regulations related to performing work in a noisy environment. In industrial noise conditions, the permissible noise dose $L_{AEX,8h}$ cannot exceed 85 dB for an 8-hour working day. The noise exposure level $L_{EX,8h}$ is determined from the formula:

$$L_{AEX,8h} = L_{Aeq,Te} + 10log\left(\frac{T_e}{T_0}\right) \text{ [dB]}, \quad (1)$$

where $L_{Aeq,Te}$ – equivalent A-weighted sound pressure level for the exposure time T_e,[dB], T_e – effective exposure time ([h], [min] or [s]), T_0 – reference time = 8 h = 480 min = 28 800 s.
We transform the formula to determine the permissible time of staying in a room with a specific noise level:

$$T_e = 10^{0.1(85-L_{Aeq,Te}+10\log(T_0))} \text{ [s]}. \quad (2)$$

The above considerations show that the time limit is exceeded relatively quickly. If we consider the sound pressure levels A obtained in the measurements in the examination room (see Tab. 2 and 3), the calculated dwell time depending on the signal sequence is presented in Table 4.

The measured $L_{Aeq,Te}$ values correspond to the noise dose $E_{A,Te}$, that the patient or a companion will receive during time T_e in the MRI scanner room:

$$E_{A,Te} = {p_{ref}}^2 \cdot 10^{0,1 \cdot L_{Aeq,Te}} \times T_e \quad \text{[Pa}^2\text{s]}, \quad (3)$$

where, p_{ref}– reference sound pressure = 2*10^{-5} Pa, Te – duration of the scanning signals, s and $L_{Aeq,Te}$ – measured equivalent A-weighted sound pressure level for the signal sequences, dB.

Table 4 shows the noise doses received by a person in the examination room. The measurement was performed at a distance of 2 m from the scanner chamber. Minimum and maximum values are given depending on the duration of noise exposure during the examination. The shortest examination time was 20 minutes and the longest was 60 minutes

Table 4. Noise dose generated during an MRI examination.

Scanning sequence	L_{Aeq} [dB]	Calculated permissible time [min]	Noise exposure $E_{A,Te}$ [Pa²s]	
			T_e =20 [min]	T_e = 60 [min]
Diffusion-Weighted Imaging (DWI)	94.0	60.4	1204	3610
Diffusion-Weighted Imaging Turbo Spin Echo (DWI-TSE)	90.1	148.3	491	1473
Diffusion-Weighted Imaging with oscillating gradient (DWI-og)	94.2	57.7	1262	3781
Echo-Planar Imaging -Spin Echo (EPI-SE)	78.2	2297.4	31	95
Turbo Spin Echo (TSE)	74.7	5143.2	14	42

The examination of the patient usually takes quite a long time (20–60 min), and the patient is in a tight chamber, where unpleasant crackling sounds are also heard, so a contraindication may be, for example, claustrophobia or lack of cooperation of the examined person (artifacts due to movement). The acoustic parameters presented in Tab. 2 and 3 shows significantly elevated sound pressure levels in the examination room of both MRI systems. A-weighted sound pressure level L_{A90} highlights that for 90% of the scanning process the A-weighted sound pressure level exceeded 99.1 dB in mobile MRI system and 87 dB in portable MRI system, respectively. In magnetic resonance imaging in Poland, devices with magnetic field values of 1.5 T and 3 T are used. The higher the magnetic field value, the better the image, i.e. the examination can detect more details. Simultaneously, the noise level in the MRI examination room also increases with higher magnetic field systems.

An important issue is the use of partition walls between rooms. Internal walls must meet many requirements related to the applied construction solutions, such as meeting sanitary requirements corresponding to medical rooms, appropriate protection against magnetic and electromagnetic fields, as well as appropriate sound insulation.

Due to the acoustic comfort of people staying around the magnetic resonance scanner necessitates addressing the issue of noise emitted by the scanner into the examination room. It is crucial to acknowledge that the acoustic properties of the examination room play a significant role in influencing both the levels of noise and the distribution of sound pressure. Consequently, it is apparent that both the patient and any accompanying individuals are at an increased risk of exposure to elevated noise levels, potentially reaching or exceeding their daily permissible noise exposure during the scanning procedure.

5. Conclusions

Acoustic studies of mobile magnetic resonance diagnostic stations provide a lot of information on the acoustic impact of the operating system on the work environment of the personnel conducting the tests, as well as the environment in which such laboratories are located. In the measurement sessions, we performed acoustic measurements on the mobile MRI diagnostic station, in the next session on the portable MRI diagnostic station. A characteristic feature of both stations is the compactness of the architecture, i.e. all rooms are directly adjacent to each other, and have relatively small, limited geometric dimensions. External and partition walls must meet a number of requirements such as: fire protection, screening of magnetic and electromagnetic fields, as well as acoustic insulation requirements.

When assessing the hazards associated with noise generated by magnetic resonance scanners, its impulsive nature should also be taken into account. The hazard resulting from this type of noise may be more serious than would result from an assessment based solely on the quantities characterizing the noise. Pilot studies of the maximum A-weighted sound pressure level and the noise exposure level related to an 8-hour working day have shown that even short exposure can exceed the noise limits specified for pregnant women. Hence, it reflects the need for better solution to the noise problem in MRI systems.

Acknowledgments

We thank dr hab. Szymon Łoś, JMP Medical Sp. z o.o. for his gracious assistance. This work was partly supported by research subsidy of the Faculty of Mechanical Engineering and Robotics, AGH University, no. 16.16.130.942.

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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