Vibration Isolation for Seismocardiogram Measurement in the OpenMRI-Guided Operating Theater*

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The purpose of this study is to establish a method of measuring precisely the seismocardiogram (SCG) of a patient who lying in an open magnetic resonance imaging (openMRI) machine for myocardial ischemia monitoring during surgery. Vibration isolation was examined by analyzing the gantry vibration during MRI scanning and the SCG of a healthy volunteer. The MRI gantry vibration had maximum amplitude of 2.5 m/s^2 , which are several peaks more than 100 Hz up to 500 Hz. Up to 94% reduction in amplitude was observed in the patient bed vibration under both T1-weighted and T2-weighted sequences. The power spectrum center of the patient bed vibration was more than 30 Hz. The maximum amplitude of SCG was 0.92 m/s^2 and a FFT analysis revealed that the SCG was not higher than 25 Hz. The signal-to-noise ratio between the SCG and the patient bed vibration was calculated to be from 4 to 7. These results demonstrate that the peak acceleration of the SCG can be monitored during openMRI scanning. In conclusion, vibration analysis showed the feasibility of using the piezoelectric acceleration sensor for seismocardiogram measurement in the openMRI-guided operating theater.

Key Words: Vibration Isolation, Damping, Measurement, Seismocardiogram, Open-MRI

1. Introduction

In the case of brain tumor removal, a total removal is not possible until a residual tumor is visualized during craniotomy. The authors installed an open magnetic resonance imaging (openMRI) machine in the operating theater to measure the brain shift resulting from the craniotomy and to keep a precise track of the residual tumor to be resected⁽¹⁾. Thus far, we have conducted 165 neurosurgeries in this operating theater since March 2000. All of the cases were free of coronary stenosis, so that the risk of myocardial ischemia and cardiac infarction during

surgery was low. According to Skidmore and London⁽²⁾, the incidence of perioperative myocardial ischemia was extremely high in patients with coronary artery disease (6% in nonvascular surgery and 12% in vascular surgery) compared to that in patients without the disease (0.6%). Considering that the openMRI-guided operating theater expects to become more commonly used in the near future, it is likely that it will be used during operations on patients with coronary artery disease. Generally, to monitor the intraoperative incidence of myocardial ischemia caused by a shortage of blood supply from the coronary artery, it is useful to insert a probe for echocardiography into the esophagus and monitor the motion of the heart wall. Conventional probes, however, cannot be used without modification because the magnetic field interferes with the probes and distorts the echocardiogram and the MRI. The authors focused on what is measurable by ultrasound, instead of developing a new probe for echocardiography that is compatible with the magnetic field. Using a seis-

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nocardiogram (SCG), the authors focused on the phenomenon, that the motion of the left ventricular wall is altered by myocardial ischemia, which in turn alters the chest surface vibration. SCG is a method for measuring the vibration of the beating heart. Because of the downscaling of the acceleration sensor, some reports regarding its clinical use have become available since the 1990s⁽³⁾⁻⁽⁵⁾. Wilson et al.⁽⁴⁾ compared the SCG of patients with coronary artery disease and those of healthy volunteers after an exercise tolerance test, which causes a reduction of the vibration peak that is synchronized with the opening of the mitral valve or the closing of the aortic valve. This is probably because the myocardial ischemia reduces the motion of the ventricular wall, which in turn diminishes the vibration. Jerosch-Herold et al.⁽⁵⁾ confirmed that a piezoelectric sensor does not interfere with MRI by measuring the SCG using an MRI machine. A problem that should be solved before the clinical use of MRI is how to measure precisely the SCG of a patient by reducing the MRI gantry vibration during MRI scanning. The purpose of this study is to establish such method of measuring precisely the SCG of a patient lying in the MRI machine during surgery. Vibration isolation was examined by analyzing the gantry vibration during MRI scanning and the SCG of a healthy volunteer.

In Section 2, we explain the configuration of the openMRI-guided operating theater. Experimental methods and results of vibration isolation are discussed in Sections 3 and 4. The feasibility of measuring SCG is presented in the Discussion (Section 5).

2. OpenMRI-Guided Operating Theater

2.1 Configuration

Figure 1 shows an overview of the openMRI-guided operating theater. The openMRI, patient bed, surgical microscope for neurosurgery, anesthesia machine and vital sign monitor are shown. The room

Fig. 1 OpenMRI-guided operating theater

is $5.8 \times 4.2 \text{ m}^2$ in size.

The openMRI (AIRIS II, Hitachi Medical Co. Ltd., Tokyo, Japan) used in the operating theater at the University Hospital of Tokyo Women's Medical University consists of permanent magnets for generating a vertical static magnetic field (magnitude of 0.3 Tesla). The MRI has a disk-shaped vertical gap of 43 cm and a horizontal diameter of 126 cm; this is called

(a) Anesthesia

(b) Surgery

(c) MRI scanning

Fig. 2 Patient bed layout in relation to surgical stage

Fig. 3 Positional relationship between MRI gantry and patient bed. Only the sliding table supporting the patient bed enters the gantry. Plastic rollers are in contact with the gantry surface

the MRI gantry. A patient lying on the patient bed is moved into the center of the MRI gantry.

The patient bed was developed specifically for the openMRI-guided operating theater. Doctors and nurses can move the bed freely according to the surgical stage (anesthesia, surgery and MRI scanning), as shown in Fig. 2. The sliding table installed in the bed is used during the MRI scanning. Only the sliding table with the patient enters the MRI gantry. Figure 3 shows the positional relationship between the sliding table and the MRI gantry. Two plastic rollers (each having 3 cm diameter and 2 cm width) are in contact with the MRI gantry.

2.2 MRI scanning during surgery

Before placing the patient in the MRI gantry, surgeons perform two procedures. One is the fixation of a receiver coil around the surgical field for neurosurgery⁽⁶⁾. The other is covering the patient with sterilized transparent drapes.

More than three scans (once after craniotomy, several times during tumor removal and once at the end) are conducted during one neurosurgery. Each scan requires ten minutes, consisting of a pre-scan for patient positioning, T1-enhanced imaging and T2-enhanced imaging. Figure 4 shows an example of tumor visualization. The white-enhanced tumor is removed by surgery. Surgeons can find a residual tumor such as that shown in the middle image of Fig. 4. MRI gantry vibration is measured while this clinical scanning protocol is followed.

3. Methods

3.1 Measurement setups

One sensitive piezoelectric sensor (M393B05, PCB Electronics, Buffalo, New York, USA) was used to measure the vibration of the gantry and the body surface. The frequency range was 0.6 to 450 Hz ($\pm 5\%$), sensitivity was 1 V/m/s², and sensor weight was 50 g. The sensor was connected to a signal conditioner (480C02, PCB Electronics) using a cable and the output of the acceleration signal from the signal

(a) After craniotomy

(b) At the mid-point of brain tumor removal

(c) Residual tumor removed

Fig. 4 Example of intraoperative MRI

conditioner was recorded on a PC card using a data recorder (8807, Hioki E. E. Corp. Nagano, Japan). The sampling rate was 1 600 Hz. The data recorded on the PC card were subjected to fast Fourier transform (FFT) analysis using a personal computer.

3.2 MRI scanning protocol

To simulate MRI scanning during neurosurgery a receiver coil and a phantom containing water were set at the center of the gantry. The MRI scanning proto-

Fig. 5 Definition of coordinates at the MRI gantry surface

cols were the T1-weighted sequence (TR, 27 ms; TE, 10 ms; 3 min 36 s), and the T2-weighted sequence (TR, 1 000 ms; TE, 140 ms; 4 min 10 s). TR denotes interval of the gradient magnetic field input, while TE is the duration of the input.

3.3 Gantry vibration

The coordinates defined on the gantry surface are shown in Fig. 5. The origin was set at the gantry center. A section paper was attached to the gantry. The contact position between the sliding table rollers and the MRI gantry was used for measurement. Two positions at $(x, y) = (20, 35)$ and $(20, 40)$ were measured. The roller was located at $x=20$ cm. The position of the patient's left-chest is between $y=35$ cm and $y=40$ cm. The mean distance between the head and the chest is 36.7 cm, based on Japanese body size data.

3.4 Patient bed vibration

The sliding table of the patient bed was moved into the MRI gantry after gantry surface vibration measurement. The roller of the sliding table was set at $y=35$ and $y=40$. To clarify the effect of a sponge mat covering the sliding table, patient bed vibration measurement was conducted with (mat (+)) and without (mat (-)) the mat, as shown in Fig. 6.

4. Results

4.1 Time domain

Typical gantry vibration waveforms obtained during T1-weighted and T2-weighted sequences are shown in Fig. 7. For the T1-weighted scanning, the amplitude changed. The amplitudes of each condition were measured at the beginning, middle and end of the scanning. Each vibration showed a 27-ms cycle. For the T2-weighted scanning, the waveform showed intermittent vibration.

Figure 8 shows the relationship of amplitude with vibration. The maximum amplitude on the MRI

(a) Gantry

(b) Mat (-)

(c) Mat (+)

Fig. 6 Experimental conditions for vibration measurement

gantry was 2.5 m/s^2 . Patient bed vibration was from 0.09 to 0.23 m/s^2 . A more than 85% to 94% reduction in amplitude was observed under the mat (+) condition in both T1 and T2 sequences, whereas a 76% to 89% reduction was observed under the mat (-) condition. A 20% larger amplitude was measured at $y=350$ than at $y=400$.

4.2 Frequency domain

Power spectra under T1-weighted scanning sequence are summarized in Fig. 9(a). MRI gantry

Fig. 7 Vibration waveforms during MRI scanning (gantry, $y=350$)

vibration had several peaks of more than 100 Hz up to 500 Hz. Patient bed vibration changed the power spectrum pattern. Fewer peaks over 100 Hz were observed under the mat (-) condition, while only one peak at 37 Hz remained under the mat (+) condition. The frequency was equal to $1/TR$ of the T1-weighted sequence ($TR=27$ ms).

Fig. 8 Comparison of vibration amplitudes

Figure 9(b) shows the power spectra under the T2-weighted scanning sequence. Several peaks from 100 Hz to 550 Hz were observed in measurements under both gantry and mat (-) conditions. Peaks from 20 Hz to 50 Hz were enhanced due to the reduction of peaks over 100 Hz under the mat (+) condition.

5. Discussion

5.1 Feasibility of measurement seismocardiogram (SCG)

No raw data on SCG are available in previous studies⁽³⁾⁻⁽⁵⁾, however, data from volunteers are necessary for the feasibility examination. Thus, in healthy volunteers, the same piezoelectric acceleration sensor was used to measure the SCG caused by heart beating. SCG was recorded at 1600 Hz after the sensor was fixed on the body surface using adhesive tape.

The acceleration amplitude was approximately up to 0.92 m/s² and the FFT analysis revealed that the

Fig. 9 Comparison of power spectrums of vibration

SCG was not higher than 25 Hz (Fig. 10). The broken circles in Fig. 10 indicate the acceleration generated by the aortic valve opening⁽⁴⁾. Myocardial ischemia of pig hearts decreased the value of acceleration generated by the aortic valve opening⁽⁵⁾. The signal-to-noise ratio (S/N) of the SCG to the patient bed vibration (mat (+)) was calculated to be from 4 to 7, as shown in Fig. 11. Figure 12 shows a power spectrum of the patient bed vibration ranging up to 100 Hz. The

power spectrum center was more than 30 Hz. These results demonstrate that the peak acceleration of the SCG can be monitored during the openMRI scanning.

5.2 Vibration isolation effect of the patient bed

In a typical vibration isolation study, simultaneous input and output vibrations are measured. However, such measurement could not be carried out because the sliding table covers the MRI gantry, although the table had a negligible influence on the

Fig. 10 Healthy volunteer data: (upper) seismocardiogram (SCG); (lower) power spectrum of SCG

Fig. 11 Signal (SCG)-to-noise (patient bed vibration (mat (+))) ratio

MRI gantry vibration.

The spring constant k and the coefficient of viscous damping c of the patient bed are calculated according to the vibration isolation theory. The MRI gantry and the patient bed are modeled by a one-mass system, as shown in Fig. 13. When the base (gantry) vibrates (Eq.(1)), the equation of motion is that given by Eq.(2). The amplitude ratio τ of mass (patient bed) to base (gantry) can be calculated using Eq.(3).

$$x_1 = a \cos \omega t \quad (1)$$

$$m\ddot{x} + c(\dot{x} - \dot{x}_1) + k(x - x_1) = 0 \quad (2)$$

(a) T1-weighted scanning

(b) T2-weighted scanning

Fig. 12 Power spectrum of patient bed vibration (mat (+))

Fig. 13 One-mass system for vibration isolation modeling

$$\tau = \sqrt{\frac{k^2 + (c\omega)^2}{(k - m\omega^2)^2 + (c\omega)^2}} \quad (3)$$

Experimental data are derived from Fig. 9. The beginning, middle and end of the T1-weighted scanning and the T2-weighted scanning sequences were examined. The natural frequency was approximately 40 Hz because the power spectrum under the mat (+)

Fig. 14 Comparison between experimental data and theoretical values on the vibration isolation effect of the patient bed ($y=400$, mat (+), $f_n=40$ Hz, $m=5.5$ kg)

condition showed enhanced amplitude at this frequency compared to that with the gantry vibration. The amplitude of more than 100 Hz decreased to zero under the mat (+) condition. For calculation purposes, the bed weight ($m=5.5$ kg) and the natural frequency ($\omega_n=40$ Hz) were fixed. Parameter c was adjusted to match the experimental data with the theoretical values. Figure 14 shows the result, with $k=3.0 \times 10^5$ N/m and $c=300$ N·s/m.

6. Conclusion

In conclusion, vibration analysis showed the feasibility of using the piezoelectric acceleration sensor for seismocardiogram measurement in the openMRI-guided operating theater. Vibration isolation of the patient bed from noise caused by the MRI gantry was clarified. Future work will proceed toward the clinical use of the openMRI.

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