

# Exploring Air Properties for fMRI-Compatible Interaction Devices

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**Abstract.** The strong magnetic field of functional magnetic resonance imaging (fMRI) and the supine position of participants in fMRI scanners severely limit how participants can interact during fMRI experiments. This paper explores the use of air properties to design interaction-device systems that allow various interaction styles inside a fMRI scanner. Airflow and air pressure are explored to design and develop the interaction system. A series of air-based devices are introduced and discussed to demonstrate the feasibility of an air-based approach. This includes soft tactile and conventional controls (e.g., button, slider, joystick, pedal). To achieve fMRI-compatibility, all parts used inside the scanner are built from non-ferromagnetic, off-the-shelf plastic, and/or 3D printed materials. The fMRI compatibility was evaluated on a 3.0 Tesla fMRI scanner. We conclude with example applications and thoughts on future avenues of research.

## 1 Introduction

Functional magnetic resonance imaging (fMRI) [1] enables medical doctors and researchers to study correlations between brain activation and tasks performed by participants during a brain scan. In addition to the scanned brain images, participants' responses and/or behavioral data while performing the tasks are required during post-processing of brain study to improve the detection of brain activity [2]. Furthermore, in a task that requires special stimulation other than visual stimulation, additional equipment is required to deliver the stimulation (signals) to the participants, such as haptic sensations and/or fragrance [3]. However, the strong magnetic field of fMRI limits the choice of response and/or stimulation device that can be used. Devices with traditional ferromagnetic materials and actuation/sensing methods are not permitted in the fMRI environment.

Optical fiber-based sensing has been used in various fMRI applications such as force measurement [4], motor response [5], and a musical instrument [6] because of its small size, it is not affected by electromagnetic interference (EMI), and presents no electromagnetic susceptibility (EMS). Due to its popularity, there are some commercial providers that offer fMRI-compatible fiber-optic devices for recording participant' responses during fMRI scans. However, these devices are typically expensive, requiring specialized control software, limited to recording response only and cannot be used to provide stimulation to the participants. Similarly, air-based (pneumatic) devices are invulnerable to EMI and lack of EMS. Pneumatic-based devices have also been used in various fMRI

applications such as robot interaction [7-9], skin stimulation [10,11], haptic interface [12]. However, these devices are limited to one configuration and only provide stimulation to participants without sensing and/or recording participants' response information.

This paper proposes a complementary method for designing and developing fMRI-compatible devices that are able to both record participant responses and provide stimulation (such as soft tactile feedback and fragrance signal) to the participants in fMRI environment. This paper explores the use of air properties, especially air-flow and air-pressure (pneumatic) for designing and developing various interaction devices for use in the fMRI experiments (Figure 1). This paper also explores the use of the 3D printer, plastic pockets, and off-the-shelf materials to enable fast development and replication of various custom interaction devices for use in fMRI environment. We conducted informal interviews with several expert fMRI researchers who have been using fMRI to conduct experiments for more than 5 years to find out what possible interaction device functions may be required, which are currently unavailable and, which may be made possible by using the proposed air based interaction devices. We also conducted an evaluation experiment for fMRI-compatibility of the developed devices on a 3.0 Tesla fMRI scanner. The evaluation results show that air-based interaction devices are effective and that they comply with standards for the device in fMRI [13].

We envisioned that in the future these air-based devices will allow fMRI researchers to expand their choice of tools in experiments aimed at understanding human behavior using fMRI scanners. These devices could be selected from a standardized library, edited and then be

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3D printed, allowing fast and inexpensive testing in pilot studies for new brain studies instead of directly purchasing expensive commercially available devices.

## 2 Related Work

The work presented in this paper builds on fMRI-compatible devices, pneumatic-based interaction devices, and device fabrication.

### 2.1 fMRI-compatible devices

Several researchers have developed various fMRI-compatible devices using pneumatics control [7-9] and optical-fiber [4-6]. However, fiber-optic-based devices are limited to only sensing and recording response information. Although pneumatic systems are able to record responses based on changes in air pressure, no previous work utilizes this capability to develop a response device using the pneumatic system. Also, there is no prior work that explores the use of air-flow to provide interaction inside the fMRI environment.

### 2.2 Pneumatic-based interaction devices

Utilizing pneumatics to develop interactive devices have been exemplified by several researchers, e.g., jamming interface [14], visual display with dynamic button [15], inflatable mouse [16], Pneu [17], robot interaction [18]. However, these devices were developed not to be used inside the fMRI environment, because they require additional components that may contain ferromagnetic materials. Our work is focused on allowing interaction by solely using air-properties and only components that can be put inside fMRI scanners i.e., made from plastic and/or non-ferromagnetic materials, and expanding our previous work [19]. Previous researchers demonstrated the flexibility of pneumatic control devices for interaction and the need to further expand the possible applications in different research areas such as fMRI.

### 2.3 Device fabrication

Pneumatic devices can be built using several methods such as 3D printing [20-21], manual construction [17], casting or molding [22]. Vazquez et al. [21] have shown that 3D printing is a unified and flexible approach to fabrication and customization of pneumatic devices. They also showed that it is possible to do multi-material 3D printing, however, the 3D printer that is capable of print using multiple materials is costly at present (Objet Eden260V, \$19800 in 2016). Although manual construction such as plastic welding is considered cumbersome and error-prone compared to 3D printing, it is one of the fastest methods in fabricating air-pocket for using with pneumatic systems. In this paper, we explored a combination of plastic welding and 3D printing to develop various pneumatic chambers (air-pockets) to be used in our interaction devices. Fabricating using plastic welding to allow fast development which is used to

provide proof-of-concept of the developed design then refined using 3D printing.

## 3 fMRI-compatible air-flow-based system

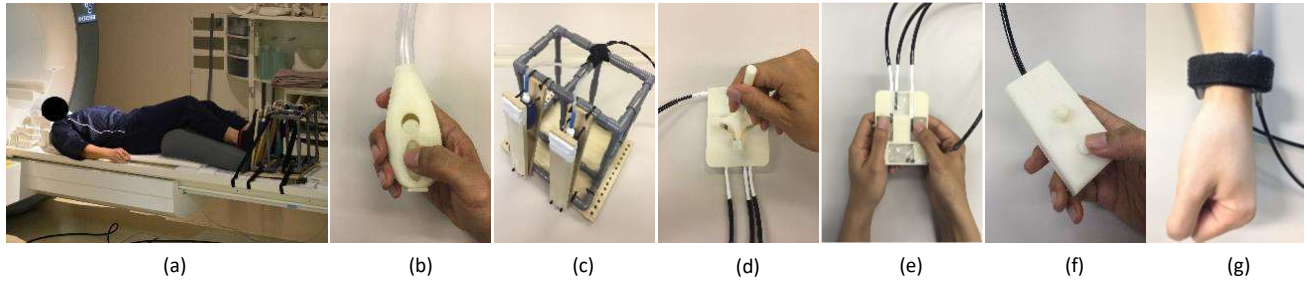
The air-flow-based system is designed to allow simple interactions with simultaneous soft air-tactile feedback to users. In this work, we used the air-flow-based system to allow users to have a soft air-flow sensation and a simple precise control over a levitated ball inside a transparent tube at the same time. Figure 2c shows a complete of the air-flow-based system. The air-flow-based system consists of a fan motor, a ball (diameter 8 mm) in a transparent tube (inner diameter of 1 cm, thickness 3 mm), an 8-meter long transparent tube (inner diameter of 1 cm, thickness 3 mm), a flow meter (range 100 mL/min to 1500 mL/min), an Arduino microcontroller and a 3D printed interaction device (Figure 1b). The Arduino controller turns on the fan-motor generating air-flow through the transparent tube to 3D the printed hand-nozzle device (Figure 3) which is held by the user. The hand-nozzle device was developed using a uPrint SE 3D printer with ivory color ABSplus material.

The strength of the air-tactile feedback is correlated with the strength of air-flow that is generated by the fan motor. Furthermore, in Figure 3, position control of the ball can be done in two different interactions, which are an on-off (open-close) interaction and a sliding interaction. Open-close interaction provides a digital-like control, while the slide interaction provides an analog-like control behavior.

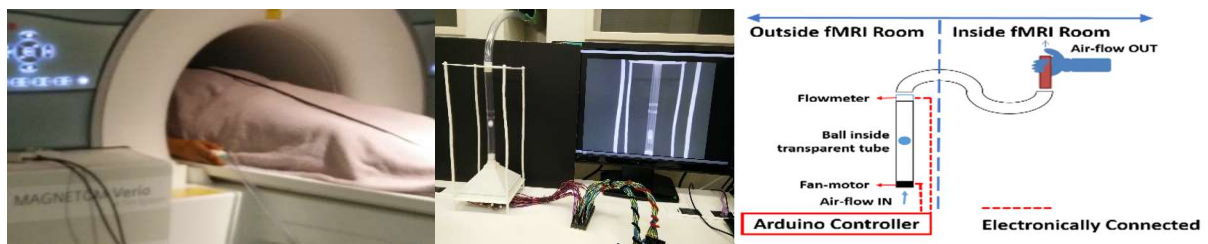
Despite its simple setup, this system allows both soft tactile feedback (with just-noticeable differences (JND) in air flow pressure) while concurrently recording user behavior when precisely controlling the ball position, which normally could not be achieved with an optical-fiber-based system. By utilizing data recorded by a flow-sensor, the interaction enabled by this system can not only control the ball position (as shown in Figure 2) but also can be used to provide a single-button-like response or an analog slider response (Figure 3c).

## 4 fMRI-compatible pneumatic-based system

The main design consideration is that all components that will be put inside fMRI need to be non-ferromagnetic and/or contain no metal/electronic circuit. Thus we focus on utilizing air only without additional component such as a potentiometer or LED to our systems. In addition, the device should be able to be operated while the participant is lying down. The pneumatic-based systems that we explored in this work rely on changes in air pressure to record user response information, to generate tactile sensation to users or to send scented air to users inside fMRI scanner.



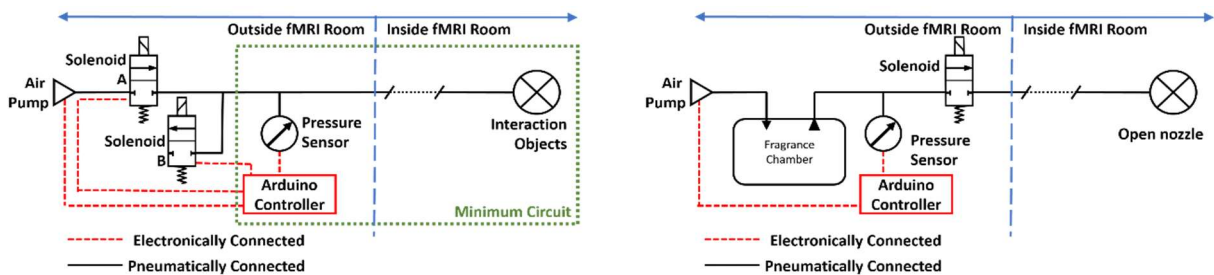
**Fig. 1.** Various air-based devices. (a) Pneumatic pedal set in fMRI scanner, (b) 3D printed air-flow based device for tap and slide interaction, (c) a pneumatic pedal device constructed from two pneumatic balls, wood, and PVC tube, (d) pneumatic joystick which can be used to manipulate x-y movements, (e) Pneumatic button with four pressure-sensitive buttons, constructed from four air pockets arranged in a 3D printed structure, (f) a two button pneumatic device, constructed using a single air pocket with 3D printed structure, (g) two 3D printed soft pneumatic button put together as wearable soft-haptic device.



**Fig. 2.** fMRI-Compatible air-flow-based system, (a) a participant uses an air-flow-based device to control the ball position located outside the fMRI room (b) from inside of the fMRI scanner, (b) air-flow-based system, consisted of a transparent tube and a ball, (c) Schematic diagram of air-flow-based system



**Fig. 3.** Interaction for fMRI-Compatible air-flow based system, (a) open interaction to lift the ball by allowing air-flow, (b) close interaction to put the ball down by stopping air flow, and (c) slide interaction for precise control of ball position by controlling the amount of air-flow.



**Fig. 4.** Pneumatic diagram for (a) general design of pneumatic-based fMRI-compatible device and (b) fragrance delivery system

## 4.1 Design

In this work, we explored three designs to serve three different purposes. The first purpose is to dynamically change air pressure to alter the physical form of air pockets while the sensor continuously reads internal air pressure of the system to allow precise closed-loop control. The second purpose is to only sense user input with pressure sensors, thus further simplify the system. The third purpose is to deliver smell from fragrance chamber outside of fMRI room to users inside the fMRI room while air pressure sensor and solenoid control the air flow to the user to have a constant pressure.

Figure 4a shows the diagram for the first pneumatic design. This first design is for general use which contains an air-pump as a pressure source, two solenoid valves, a pressure sensor, and an interaction object (e.g., air pocket or 3D printed air chamber). In the rest state, both solenoids A and B are closed (no air in or out, both solenoids are normally closed). If solenoid A is actuated and B is at rest, the pressure source (air pump) can increase air pressure in the system. If solenoid B is actuated, the system is open, releasing air and thus decreasing the air pressure inside the system.

The second design is for recording air pressure information only. This design is the simplified version of the first design which consists only air pressure sensor and the interaction object as shown inside the minimum circuit part of Figure 4a. Assuming that there is no air-leakage in the system, this is useful to reduce the number of components in the system and to increase the scalability of the pneumatic system (e.g., although in a normal setup, a four-button variable sensing device would require four air pumps, eight solenoid valves, and four pressure sensors, in simplified design, the same device only require four pressure sensors to be functional). This design is limited to interaction objects that can return to its original shape after pressed or squeezed by users. Therefore, interaction object such as air pockets that need to be inflated first before can be used as an interaction device cannot use this design.

The last design is for delivering smell to users inside fMRI is shown in Figure 4a. By modifying the design in Figure 6, we can use the same components to allow different stimulation for the users. Air pressure sensor continuously reads internal air pressure of the system, if the internal air pressure is lower than the required threshold (air-flow that deliver the smell is weak), the solenoid valve is switched off and air-pump increases pressure for the fragrance chamber. If the internal air pressure is higher than the threshold (strong air-flow), the solenoid is activated allowing the smell to be delivered to the user. By monitoring the air pressure to be close to the threshold value, this system can maintain a stable flow of smell to the user. It is to be noted that the fragrance particle will diffuse over time and make the smell weaker if used for a long period of time.

## 4.2 Fabrication

We fabricated the pneumatic devices using plastic welding and two different 3D printers (one for rigid

material and one for flexible material). The fabrication process using plastic welding is straightforward, affordable, and fast, but have low replicability. Fabricating using 3D printer takes a little bit longer time to design and print, but is very replicable when printing multiple custom devices.

### 4.2.1 Fabrication by plastic welding

In a condition where 3D printing is not available, plastic welding offers a fast way to develop a prototype for air-pocket used in pneumatic systems. We used plastic welding method to develop a simple air pocket by heat pressure molding off-the-shelf 0.3 mm thick polyethylene sheets (plastic) into a square and attaching a pneumatic tube on one end of the pocket. Although this method is error-prone (e.g., it is difficult to form an airtight pocket in single try), it is one of the fastest and most cost-effective ways to fabricate a custom-sized air-pocket. To ensure the air pocket was airtight, we used airtight tape (Teflon tape) and heated it with a heat gun to close any possible openings. Using this simple method, we were able to increase the fabrication success rate of this method. The fabricated air pocket can sustain internal air pressure of 4.5 PSI before breaking. One example of air-pocket that developed by this method is shown in Figure 5a. This air pocket can be used as an on-off button and also a pressure sensitive button.

### 4.2.2 Fabrication by 3D Printer

Although plastic welding can be used to fabricate air pockets, its choice of geometry and shape is limited and difficult to reproduce the same result multiple times. Therefore, we combined the air pocket that we fabricated using plastic welding with rigid 3D printed part to improve variation of a pneumatic device that we can develop.

In order to make the appearance of the air pocket more appealing, we 3D printed a case for four air pockets (Figure 1e) using a uPrint SE printer with ivory color ABSplus material. This allows the four air-pockets to work as a four-button pneumatic device. Using the same 3D printer, we also 3D printed a handle for the joystick device (Figure 1d). Since the 3D printed part is used only as a container, we designed so that it does not have any over-hanging geometry in order to reduce any support material in printing result. By avoiding over-hanging geometry, the fabrication process will become faster because it eliminates the need to remove the supporting material and cleaning process.

For soft and flexible parts of the system, we used a FORM2 printer with flexible resin, to fabricate soft and elastic part of our system, for example, a soft pneumatic button (Figure 5b). Although flexible resin from formLabs can not elongate as much as TangoPlus used in [21], it has a higher tensile strength which allows the printed parts to be more robust from breaking. Additionally, in this 3D printer, there is no supporting material. In order to print any overhanging geometry, FORM2 uses mesh-like supporting structure to hold the

geometry (Figure 5d). One feature of this 3D printer is that it allows printing a hollow geometry without any internal support structure. Therefore, there is no need to clean the internal part of the printed result. However, naively printing hollow structure will result in failure of the 3D printed structure. In order to print overhanging and/or hollow geometry, the geometric should be tilted/positioned in such a way (around 15 to 20°) that each layer of the 3D printed structure can support the hollow part without any supporting structure.

## 5 Applications

In this section, we will illustrate some potential applications of fMRI-compatible pneumatic-based interaction devices. Figure 6 shows the pneumatic system that we used for all of the following application. The pneumatic system consists of an off-the-shelf MIS-2500-015G air pressure sensor from Metrodyne with a pressure range of 15 PSI (68.95 milli bar) (Metrodyne, 2012) to monitor the pressure levels, two 2-way solenoid valve (model EXA-C6-02C-3) to regulate the system pressure.

### 5.1 Pedal Simulation

Figure 1c shows a pedal interface constructed from woods, PVC tubes, and two lens blower which are the same items used for hand squeeze device shown in Figure 5c. With two pressure-sensitive input devices connected together, the pedal device can simulate interaction for acceleration and brake in car simulation. The pedal can detect when the user accelerates or brakes, or detect whether the user makes a slow acceleration/brake or fast. Currently, there is no pressure sensitive pedal device available commercially, thus this device open an opportunity for brain researchers, to better investigate human behavior when driving, i.e., not only investigate whether user press acceleration or brake, but also investigate how strong the user needs to press the pedals, or when the user makes a mistake, how much pressure the user already applied to pedal before realizing the mistake.

### 5.2 Game Interaction

Figure 7 shows two game interfaces that are controlled by the fMRI-compatible pneumatic devices. One game is a side-scrolling game, where the user controls the vertical position of red squares to avoid yellow bars. The control is done by pushing the pneumatic air-pocket (Figure 5a), pressing the pocket will move the red square up, and releasing it will move the red square down. The movement speed is controlled by how strong the user press the pocket in a short period of time. We also used two hand-squeeze devices to provide input for a simplified version of the guitar-hero-like game. The user needs to squeeze the right or left device when the red or green circle hit the target area.

### 5.3 Wearable Wrist Haptic Feedback

We develop two flexible pneumatic buttons (Figure 5b) and put them together to make a wearable wrist haptic device. Since the buttons are made from flexible material, increasing internal air pressure of the pneumatic system can elongate the button giving a soft pressure feedback. This wearable haptic device can be used by brain researchers to study human reaction to the haptic feedback that generated by smartwatch on the wrist. Since normal smartwatch cannot be used inside fMRI environment, this pneumatic wearable haptic device is a good alternative to reproduce smartwatch haptic feedback inside fMRI. The wearable wrist can be expanded by using more pneumatic buttons.

### 5.4 fMRI-compatibility Evaluation

We conducted an experiment to evaluate the fMRI-compatibility of the pneumatic device. A device needs to satisfy three characteristics to be called fMRI-compatible. First, it must be safe to use and not do any harm to the users in any way. Second, the device should not affect the scanned image of the fMRI. Third, the device must be able to work properly within a high magnetic field while the fMRI is running [6, 12].

The prototypes were designed to be compact, soft and free from any para-magnetic material so that they will not be affected by the magnetic field of fMRI. Even if the prototype hits the users in an accident, it will not harm the users in any way. In order to be used for fMRI environment, a minimum of 7 meters in tube length is needed as the participant needs to use the device from inside the fMRI room. Therefore we used a tube with 10 meters in length to allow more movement.

The experiment was supervised by a fMRI researcher/expert. As shown in Figure 8, we placed the pneumatic response device on the fMRI bed together with a fMRI phantom (an object used to evaluate the fMRI device that responds similarly to how human tissue and organs act) [23]. The fMRI has different scanning sequences for different purposes. We used a sequence that used the whole frequency range of the fMRI device so that if the device did not affect any of the readings, the device can be said to be fMRI-compatible with any scanning sequence.

We conducted the fMRI scanning sequence in three conditions. The first condition was scanning with the phantom only, this was to provide the baseline scanned image of the fMRI that is not affected by any device. The second condition was scanning with the phantom and the prototype in the off condition. This was done to investigate whether the prototype material affected the scanned image. The third condition was scanning with the phantom and the prototype in the running condition. This condition was done to test whether the prototype had any effect on the scanned image from the fMRI.

The scanned images from the three conditions are shown in Figure 8. One criterion to define that the scanned image is free from disturbance is that the image should show random noise. If there was any disturbance in the scanning process, the image should show a white

line (vertical/horizontal) on the image. During scanning in the third condition, we also tested whether the scanning process affected the performance of the pneumatic response device by monitoring the pressure sensor reading. We found that during the scanning process the fMRI did not affect the pressure sensor reading (i.e., the sensor reading worked properly). Based on the resulting images and the sensor readings, the fMRI researcher concluded that the pneumatic response device has no effect on the scanned images and that it was fMRI-compatible.

## 6 Conclusion

We have described the process of developing air-flow based interaction devices and air-pressure-based (pneumatic) interaction devices for interaction in a fMRI environment. We have evaluated the interaction devices for their compatibility with the fMRI environment and its ability to provide continuous pressure value as an input parameter. We also have provided design considerations to develop air-based interaction device for use in fMRI environment. Furthermore, some applications of the interaction devices are presented. While many considerations were made for the pneumatic systems, we believe that our design rationale and fabrication approach can guide the fMRI researchers to develop interaction devices for fMRI experiments. The evaluation result suggested that the proposed method is promising and that the development of various types of fMRI response device can open up new research opportunities for fMRI researchers.

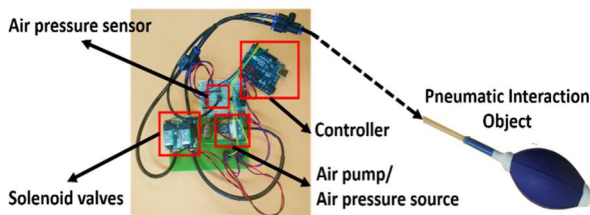
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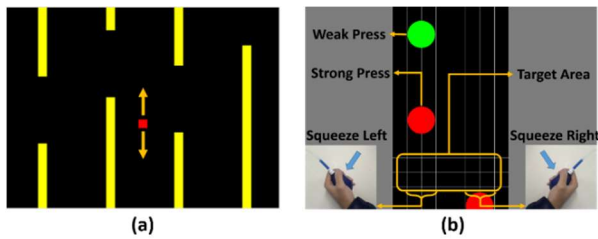
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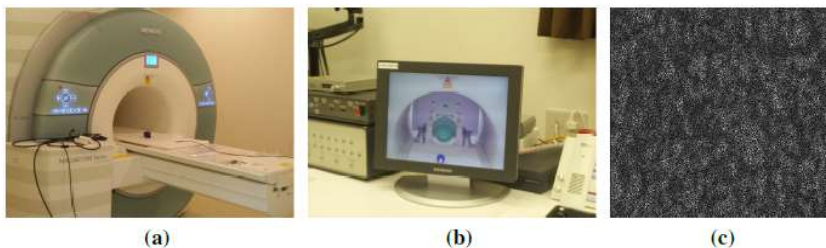
**Fig. 5.** (a) an air-pocket fabricated by plastic welding, (b) a soft button fabricated by 3D printer with flexible material, (c) a hand squeeze device built from off-the-shelf lens blower, (d) a freshly printed four-button flexible pneumatic device with mesh supporting structures, and (e) finished 3D printed four-button flexible pneumatic device



**Fig. 4** Pneumatic-based interaction system used for application



**Fig. 7.** Two game interfaces that are controlled by the fMRI-compatible pneumatic devices. (a) side scrolling game and (b) a musical game



**Fig. 8.** Experimental setup for fMRI-compatibility test and result images. (a) The pneumatic device was put on the fMRI bed to be tested, (b) a view of the pneumatic device while the fMRI was running, (c) noise scan result for the normal condition without the one