Dynamic Phantom with Heart, Lung, and Blood Motion for Initial Validation of MRI Techniques

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Purpose: To develop an anthropomorphic phantom to simulate heart, lung, and blood motion. Magnetic resonance imaging (MRI) is sensitive to image distortion and artifacts caused by motion. Imaging phantoms are used to test new sequences, but generally, these phantoms lack physiological motion. For the validation of new MR-based endovascular interventional and other techniques, we developed a dynamic motion phantom that is suitable for initial in vitro and more realistic validation studies that should occur before animal experiments.

Materials and Methods: An anthropomorphic phantom was constructed to model the thoracic cavity, including respiratory and cardiac motions, and moving blood. Several MRI methods were used to validate the phantom performance: anatomical scanning, rapid temporal imaging, digital subtraction angiography, and endovascular tracking. The quality and nature of the motion artifact in these images were compared with in vivo images.

Results: The closed-loop motion phantom correctly represented key features in the thorax, was MR-compatible, and was able to reproduce similar motion artifacts and effects as seen in vivo images. The phantom provided enough physiological realism that it was able to ensure a suitable challenge in an in vitro catheter tracking experiment.

Conclusion: A phantom was created and used for testing interventional catheter guiding. The images produced had similar qualities to those found in vivo. This phantom had a high degree of appropriate anthropomorphic and physiological qualities. Ethically, use of this phantom is highly appropriate when first testing new MRI techniques prior to conducting animal studies.

Key Words: motion phantom; catheter tracking; in vitro endovascular; angiography

appropriate dynamic phantom with anthropomorphic motions to validate new methods prior to animal testing, thus, would be more ethical, faster, easier, and cheaper. The benefits of standardized testing using a phantom would still apply, and the addition of a motion phantom would provide realistic motion effects and allow for a new level of technical efficacy testing between static phantoms and animal models.

Several investigators have proposed methods for construction of MR motion phantoms. Biederer and Heller (8) described an artificial thorax that holds an excised porcine heart and lung preparation in place. However, this phantom does not include the respiratory and cardiac motion, and thus does not cause motion artifacts. Chang et al (9) constructed a lung phantom that incorporates respiratory motion; however, in this case the phantom consists only of a lung—the heart and circulatory system were absent. Other phantoms (10) have also simulated the effects of respiratory motion; however, the effects of cardiac motion were not modeled. The closest commercially available phantom is a dynamic multimodality heart phantom (Shelley Medical, London, ON, Canada). This phantom provides anthropomorphic heart motion, but not circulatory or respiratory motions. Most dynamic phantoms only attempt to mimic either heart or lung motion, and do not combine cardiac and respiratory motion with blood flow. A phantom that combines these features could be used for a variety of thoracic imaging evaluations; in particular, it could be used for demonstration and validation of catheter tracking in the chest.

Development of a thoracic circulatory system phantom with both heart and lung motion would be particularly useful when developing new MRI techniques for catheter tracking. The purpose of this development is to demonstrate a proof-of-concept MR-compatible imaging phantom for validating endovascular catheter tracking in the presence of motion. The proposed phantom would be closed loop, meaning that the circulating fluid would be contained within the vessels of the phantom. Heart and lung motion would simulate the motion generating effects similar to those found in the animal models or live patients. We predict that this anthropomorphic phantom will be able to produce consistent and realistic motion artifacts, and will thus allow for better in vitro testing of MR endovascular and other techniques.

**MATERIALS AND METHODS**

**Phantom Construction**

The phantom was constructed in a large plastic container (50 × 100 × 18 cm) that was used to hold the phantom and provide protection from leaks. A lid was used to prevent possible spills from ruptures due to overpressure. A small sheet of wood (44 × 86 cm) was placed in the container to provide support for the phantom and to provide anchor points for the heart, vasculature, and lungs. Silicone (Dragon Skin, Smooth-On, Easton, PA) was used to create a two-chambered heart for the phantom due to its favorable material, mechanical, and MR signal properties. A heart mold was constructed from a rigid anatomical teaching model. The silicone heart was injection-molded in two pieces and then joined. The two chambers of the heart were connected with simplified pulmonary and systemic circulatory circuits (Fig. 1). One-way valves were constructed using the fingers of a latex glove; small cuts were made in the finger ends allowing fluid flow in one direction but providing resistance to reverse flow due to valve collapse (similar to a duckbill valve (11, 12)). One-way valves were located in the aorta, superior vena cava, and inferior vena cava where these vessels connected to the heart. Latex tubing was used to construct the blood vessels. Latex was chosen since it is flexible, tough, and provides some signal in MR images. The latex tubing was available in a range of diameters ranging from 6.35 mm (¼") to 12.7 mm (½"), and could therefore be used for both the major and minor blood vessels. The latex tubing was connected together to mimic a simplified upper-body circulatory system (Fig. 1). Water was used to mimic the blood. Lungs were constructed by filling plastic bags with cellulose sponge. The sponge was cut into small pieces (≈2 cm³) before being placed into the 1-L bags to allow for easier inflation and compression. The bags were modified to fit onto the end of standard respirator tubing and attached to the base of the phantom. Water was then added to the sponge inside the lung bags to provide an MR signal level similar to human lung tissue. Additionally, saline bags were placed around the blood vessels and lungs in order to provide a background MR signal and to help load the imaging coil.

**Phantom Motion**

A dual phase respirator (Harvard Apparatus, Holliston, MA) was used to generate motion in the lungs. The respirator has adjustable speed and stroke volume, so the respiratory motion in the phantom can be adjusted. For testing of the phantom the respirator was set to a stroke volume of 400 mL and a speed of 20 breaths per minute. A hydraulic system was constructed to drive (ie, contract) the heart. This system was made from two 12-mL syringes connected by a long tube and filled with isopropanol alcohol (13). Hydraulic line pressure could be adjusted or net back-pressure altered by modifying the number of elastic bands attached to the syringes at each end of the hydraulic system. A motor (Banebots Planetary Gear Motor with RS-385 Motor, Loveland, CO) equipped with a cam-shaft and controlled by pulse-width modulation via an H-bridge (Devantech MD03, Attleborough, UK) was used to actuate the first syringe that was located outside the scanner room. When required, a flow pump (Fisher Scientific, Ottawa, ON) was attached to circulate the fluid rather than relying on the actuated heart. A series of valves spaced around the circulatory system allowed the system to be filled or drained, as well as allowing for both open and closed (and the preferred) operating modes. In the open circulation mode, fluid is introduced to the
system via the pump and drained into the surrounding bucket. As with the respirator and motor, the circulatory pump was located outside the MR room. A functional schematic diagram of the phantom is shown in Fig. 1.

**Phantom Imaging**

The constructed phantom was scanned on a clinical 3 T MR scanner (GE Signa VH/i, GE Healthcare, Waukesha, WI). Image data were collected with a single channel body coil. A series of conventional anatomical scans of the phantom were collected. Static images of the heart in the heart and lung phantom were collected using a fast gradient recalled-echo (FGRE) sequence and compared with gated FGRE images of a human heart. Ungated images were also collected of the human heart and compared images of the beating phantom heart. An FGRE sequence was used in the ungated comparison (with TR/TE/flip angle of 3.6 msec / 2.1 msec / 30°).

A 3D time of flight (TOF) acquisition with TR/TE/flip angle of 6.4 msec / 4.2 msec / 30° was used to image the entire phantom. The 3D acquisition size was 256 × 128 × 32, over a field of view (FOV) of 48 × 24 × 9.6 cm. The slabs were overlapped 50% and a total of nine slabs were collected. The slabs were perpendicular to the phantom aorta. Because the purpose of this experiment was to showcase the vasculature near the heart, the phantom heart and lungs were static and blood flow was provided via the pump.

To assess the motion of the lungs, rapidly acquired FGRE images were collected parallel to long axis of the left lung. To scan rapidly at 5.2 Hz, the matrix acquisition size was reduced to 64 × 128 for a 24 × 24 cm FOV. Slice thickness was 5 mm and TR/TE/flip angle 1.6 msec / 3.0 msec / 30°. A region of interest was placed on the lung images and the signal were plotted versus time to assess the lung motion.

MR contrast agent (0.5 M, Magnevist; Berlex, Pointe-Claire, QC, Canada) was injected at 2 mL s⁻¹ into the fluid of the phantom (flowing at 50 mL s⁻¹) resulting in an expected concentration of 0.02 M (4% by volume). The contrast agent was injected into the modeled inferior vena cava using a syringe and allowed to flow through the phantom. A time-resolved SPGR imaging sequence was used to image the contrast agent passage through the phantom. Images were collected over a 48 × 48 cm FOV and the slice was 20 cm thick to encompass the entire phantom vasculature. TR/TE/flip angle were 3.2 msec / 1.6 msec / 30° and the image acquisition rate was 2.5 Hz. A frame from the start of this temporal series was subtracted from the rest to generate digital subtraction images.

As a final test, an MR-compatible catheter (5F, straight tipped Cordis, Markham, ON, Canada) was filled with 0.02 M contrast agent and inserted into the...
phantom. Catheter tracking images were collected as the catheter was moved in the descending aorta. For the tracking experiments, roadmap vascular images were first collected, then rapid multicycle projection dephaser (mcPD) (14) tracking images were collected while moving the catheter. The tracking images were then fused to the roadmap images. The phantom images were compared with in vivo image results from a canine model using the same acquisition protocol.

RESULTS

Static images of the phantom heart compared favorably with gated images of a human heart (Fig. 2a vs. 2c). The static images demonstrate the high degree of anthropomorphic matching with in vivo results obtained by the two-chambered heart. Very little susceptibility effect (from the silicone) was observed near the interface of the heart and blood mimic (Fig. 2a). Similarly, the ungated human and phantom images both had motion artifact in the phase-encode direction (Fig. 2b vs. 2d).

The TOF anatomical scans (Fig. 3) show the blood mimic in the constructed phantom and compared favorably with the schematic and photograph of the phantom (Fig. 1). The phantom vascular geometry is accurately depicted, verifying that the phantom can also be used for validating the accuracy of angiographic and other flow-sensitive sequences.

The temporal signals from the region of interest placed on the lungs in a dynamic series of images validates the signal variation encountered during lung motion (Fig. 4). This period and characteristic of this motion can be adjusted by changing the phase parameter on the respirator.

Time-resolved contrast-enhanced images visualized the flow in the phantom (Fig. 5). The sequence of images shows the right side of the heart, then the pulmonary circulation, then the left side of the heart and the systemic circulation filling over a period of 3 seconds.

Catheter tracking images collected of the phantom were compared to in vivo tracking images (Fig. 6). The catheter is clearly depicted in both the phantom and animal experiments. Similar artifacts, particularly at the level of the heart and lungs, to those found in animal studies can be generated with phantom. This indicates that passive catheter tracking is possible using the motion phantom, which suggests that this phantom may be useful in testing interventional techniques.

DISCUSSION

This dynamic phantom provides a platform for the initial testing of interventional and other diagnostic MR techniques without resorting to animal models. By using this phantom, the capabilities of new techniques can be initially evaluated in the presence of realistic thoracic motions before requiring animal studies. This ability is important because it would reduce the reliance on animal models during initial experimental evaluations of technical efficacy. Our results demonstrate that the phantom heart and lung motion produce similar artifacts to those found in vivo and, therefore, provide a realistic degree of difficulty when testing MR protocols.

With respect to the robustness of the phantom and repeatability of the experiments, imaging was performed on several days when validating the phantom with similar results. Some difficulties were found trying to increase the heart rate past 100 beats per minute in the phantom; we believe this is due to the hydraulic system implementation. For future iterations on this design, pneumatics or piezoelectric systems

Figure 2. Comparative images of (a,b) a human and (c,d) the phantom heart. Shown are (a) gated human heart image, (b) ungated human heart image highlighting motion artifacts, (c) static phantom heart image, and (d) ungated phantom heart image highlighting motion artifacts.

Figure 3. Time-of-flight angiographic (maximum intensity projection) of the phantom.
will be considered, as they are not expected to suffer from (as much) temporal restriction.

The focus of this endeavor was to investigate motion phantom construction for the specific application of endovascular catheter tracking. In addition to endovascular therapy, there are several other applications where a motion phantom could be useful, such as respiratory device navigation and validating of cardiac gating and motion correction. Although this particular phantom might not be suitable for all types of experiments, the methods used for the construction could be modified to fit the needs of said experiments. This phantom is not to be commercially available; rather, the methods used to construct the phantom from

**Figure 4.** On the left is an image map where the gray scale intensity represents the standard deviation of the temporal signals. The white circle indicates the region of interest. The signal over time from the region of interest demonstrates how the temporal series of images changes over time. These changes could be modulated by adjusting the settings on the respiratory (see text).

**Figure 5.** Rapidly acquired MR angiography images showing the flow from the inferior vena cava through the phantom. Shown are digital subtraction images obtained by subtracting the first image (at 0 seconds) from the subsequent images.
inexpensive materials could be copied by other investigators.

The complexity of the presented phantom could be enhanced with the addition of several more features. The lung motion, for example, could be diaphragm-driven rather than respirator-driven. This change would mean the lung motion would be more physiologically realistic (rather than the current predominantly single direction). The circulatory system model could be made more accurate and complex (e.g., adding branching additional vessels to the pulmonary and systemic circulations). Additional future work could consist of adding additional organs and tissues to make it more anthropomorphic. The addition of bone, muscle, fat, and other tissues would allow for more realistic scans, and could also mimic other image artifacts difficulties that arise from encountering multiple tissue types (e.g., chemical shift).

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Figure 6. Comparison of passive catheter tracking results in the phantom (top row) and a canine model (bottom row). The phantom presents similar challenges to tracking a catheter as found in an animal.