Magnetic Resonance Imaging 61 (2019) 233–238

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.elsevier.com/locate/mri

Original contribution

MRI-based methodology to monitor the impact of positional changes on the airway caliber in obstructive sleep apnea patients

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ARTICLE INFO

Keywords:
Obstructive sleep apnea
Airway caliber
Rotational changes
Head and chest rotations
Independent rotations

ABSTRACT

Purpose: To develop a non-invasive MRI-based methodology to visually and quantitatively assess the impact of head and chest rotations on the airway caliber.

Methods: An MRI table set-up was developed for independent rotations of the head and chest along B_0 field and tested for feasibility using phantom scans. The accuracy of the head and chest rotations was validated with ten volunteer scans. A 3T MRI protocol was optimized to image the regions of interest (ROIs) that were the retropalatal (RP) and retroglossal (RG) sections of the upper airway. A workflow for data analysis was developed to assess the changes of the airway caliber following the independent head and chest rotations.

Results: A prototype MRI table setup was established with two separate plates each supporting and rotating the head or chest independently. Subject positioning and image acquisition were finished within seven minutes for each position. Thus, each subject MRI was set up with seven positions and completed for less than one hour. The implemented angles were within 0.3-degree deviation from the targeted angles. The data analysis workflow provided 2D and 3D visualization and quantification with the measurements of cross-sectional area, lateral and anterior-posterior distances of the ROIs. Sharp contrast of the airway and its surrounding tissues facilitated an automatic approach to ROI placement to minimize subjectivity.

Conclusions: The 3T MRI data acquisition and analysis methodology could reliably assess the impact of head and chest rotations on the upper airway caliber to identify the optimal position for obstructive sleep apnea patients.

1. Introduction

Obstructive sleep apnea (OSA) is a common disorder characterized by repetitive occlusion of the upper airway [1]. Untreated OSA can lead to a variety of serious health problems including heart diseases, and neurocognitive dysfunctions [2]. The first line treatment for OSA is continuous positive airway pressure (CPAP) that has been shown to be effective in maintaining and improving the caliber of the upper airway in many OSA patients [3]. However, CPAP has a number of side effects that result in suboptimal compliance [4]. Patients with unbearable side effects or CPAP failure are considered for other treatment options including mandibular advancement splint, surgery, and positional therapy.

Positional therapy (PT) is a non-invasive alternate treatment for OSA, especially for positional OSA patients. The goal of PT is to prevent positional OSA (POSA) patients from the worst position, in many cases, which is the supine position [5–8]. Previous studies showed that PT has similar efficacy and effects on sleep quality compared to CPAP [9,10], particularly with the new generation of PT devices [5,6]. PT not only aims at avoiding the worst position, but also finding the optimal position for an individual patient. One of the most common position methods is to encourage or restrain patients to avoid the supine position [5,7,8,11]. However, it is not effective for all patients and individual patients may have their own optimal sleeping position. A previous study showed that changes of head and body positions lead to dimensional changes in the upper airway [12]. Nevertheless, it is unclear how the variability of the head and body's angulation from the supine position can change the opening of the airway. Thus, it is of high clinical

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https://doi.org/10.1016/j.mri.2019.05.039
Received 26 October 2018; Received in revised form 24 May 2019; Accepted 27 May 2019

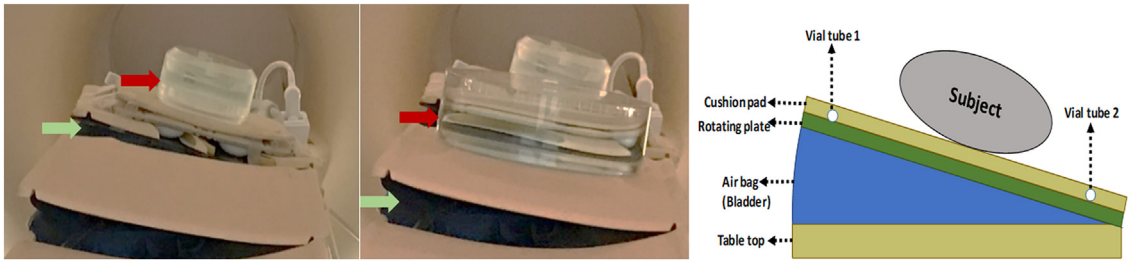

Fig. 1. MRI table setup for independent head and chest rotations. Left image, the plate that supports the head portion. Middle image, the plate that supports the chest portion. Each plate is tilted by an airbag referred to as a bladder (indicated by green arrows) under it. Two cylindrical phantoms (indicated by red arrows) were put on the head (smaller phantom) and chest (bigger phantom) support plate for phantom MRI. Right image, the diagram of the MRI table setup. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interest to quantify effects of positional changes in head and body positions on the upper airway caliber to identify the optimal position for an individual patient as well as avoid positions that lead to obstruction.

Magnetic Resonance Imaging (MRI), with high soft tissue contrast and multi-planar imaging capability, has been applied as a non-invasive modality to assess the upper airway caliber and characteristics for the diagnosis and monitoring of therapy response in OSA patients [12–20]. These studies demonstrated that MRI can be a helpful tool for volumetric analysis [14], anatomic features in association with OSA [16,17], real-time dynamic visualization of upper airway collapse [19], and assessment of therapeutic effects [18].

The goal of this study is to develop an MRI methodology that allows both visual and quantitative assessment of the impact of the positional changes in head and chest on the airway caliber in OSA patients.

2. Methods

This study was approved by the Institutional Board Review before subject enrollment. To fulfill the goal of the study, we detailed three development tasks: 1) design a versatile MRI table setup; 2) optimize an MRI protocol; 3) and develop a data analysis workflow.

2.1. MRI table setup

The requirements for MRI table setup include: 1) allowing the head and chest to be independently rotated; 2) rotations can be performed at any angles from 0° to 90° as long as the patient still fits in the magnet gantry; 3) rotations must be along the B0 field direction; 4) Patients have to remain on the table inside the magnet room when the head and chest were repositioned and images were acquired at different angles.

In addition to these requirements, all materials used inside the magnet room to facilitate the rotation must be non-metallic, i.e. MRI compatible, to avoid potential influence on the image quality. There must be a landmark in the MRI table setup that can be seen on acquired MR images to validate the rotation angles.

2.2. MRI protocol

All MRI scans were done on a 3T scanner (Ingenia CX, Philips Healthcare). Subjects were positioned in the supine position on the MRI table. Two sequences were included in the protocol to image the airway at each rotational position.

Using the body coil, a fast axial 2D T1-weighted (T1W) Fast Field Echo (FFE) sequence (with TR/TE (ms), 3.1/1.5; in-plane FOV (mm), 530 × 530; number of stacks, 2; stack FH (mm), 172; voxel size (mm), 1.0/1.0/40.0; flip angle, 100; scan time (s), 30) was performed to cover both the head and chest of a subject. This sequence was used to measure the implemented angles and to help set up the next sequence below.

An axial high-resolution 3D T1W FFE sequence (with TR/TE (ms), 3.2/1.7; in-plane FOV (mm), 400 × 400; FH (mm), 230; voxel size (mm), 1.0/1.0/2.0; flip angle, 100; scan time (s), 150) was performed to image the regions of interest (ROIs) that are the retropalatal (RP) and retroglossal (RG) sections of the upper airway. The in-plane FOV was rotated at the same angle as the head support plate's angle to avoid cutting off the FOV. To acquire high image quality for this sequence, an anterior 16-channel cardiac coil was placed under the support pad for the head. Thus the coil was tilted at the same angle of the head rotation.

Phantom scans were implemented to test out the feasibility of independent rotations and optimize MRI protocol. MRI scans on ten volunteers (gender: 5 males, 5 females; age range: 21–61 with median of 30) were performed to assess the accuracy of rotation angles and develop a data analysis workflow.

2.3. Data measurement and assessment

IntelliSpace Portal (ISP) (Philips Healthcare) was selected as the workstation for data analysis.

Fast axial 2D T1W images were used to measure the rotation angles on acquired MR images. The measured angles were then compared to the target angles for validation.

A workflow of data analysis was developed based on the high-resolution 3D T1W data to provide both visual and quantitative assessment of the airway caliber for each rotational position.

3. Results

3.1. Performance of MRI table setup

Fig. 1 illustrates the MRI table setup that was established using the phantom scans. In order to facilitate the independent rotational changes of the patient's head and chest, two separate plastic plates, each of which supported the head or chest, were hinged on the left side of the MRI tabletop. The head or chest could be rotated along the B0 field at any different angles. Under each plate is an airbag referred to as a bladder (Fig. 1) that was inflated or deflated by an air pump system outside the magnet room via tubing. Once a new position was established, the two tubes were disconnected to close the magnet room's door for image acquisition. Thus, this setup could be operated efficiently and allow the subject to remain on the table when the head and chest were re-positioned. It is noted that we had an extra MRI tabletop to be used for this study only. Thus, the setup was fixed on the extra MRI tabletop which could be quickly switched with the other MRI tabletop.

To rotate a plate at a specific angle, the unhinged edge of the plate was raised at the corresponding height following the angle-height association as explained in Fig. 2. In this study, we achieved a precision of 0.1 cm for the height. To measure the rotation angles in the acquired MR images, a pair of two Gd-contrast agent vial tubes were placed on the right and left side of each rotating plate. These two tubes had high signal intensities in the MR images and indicated the level of the table rotation (Figs. 1 and 2). On the ISP software, a grid was turned on and a line between the two contrast agent solution tubes were drawn to

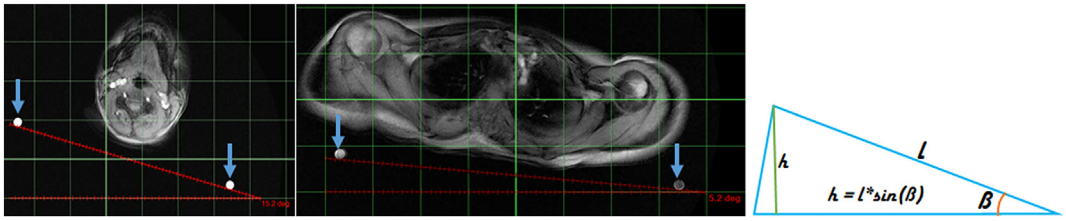

Fig. 2. Blue arrows indicate the vial tubes filled with Gd-based contrast agent. The unhinged edge of each plate is raised at the height to reach the targeted angle (right image). Left image, the measured angle of the head rotation is 15.2° in comparison with the targeted angle of 15°. Middle image, the measured angle of the chest rotation is 5.2° compared to the targeted angle of 5°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measure the actual angles of head and chest rotations (Fig. 2). The analysis of the ten volunteer MRI data showed that an implemented angle was within 0.3° deviation from the corresponding targeted angle (Fig. 2).

The volunteer MRI scans revealed that the two plates could be rotated at up to 25° from the supine position if the Body Mass Index (BMI) was 30 (kg/(m^2)) or less. Thus, ten volunteers who had BMI ranging from 18 to 30 (kg/(m^2)) were included to investigate all angles of interest, which were 25° or lower.

3.2. Performance of MRI protocol

For every time the head and chest were rotated, the positioning and image acquisition could be completed within seven minutes. Therefore, the MRI protocol was set up to image seven different positions of head and chest rotations to investigate the best positional changes to improve the airway opening of OSA subjects in the next phase of the study.

The volunteer data demonstrated that the standardized 3T MRI protocol provided sharp contrast between the airway and surrounding soft tissues including soft palate (Fig. 3) and epiglottis (Fig. 4). The high contrast enabled automatic ROI placement (auto contour) to minimize subjectivity in quantitative assessment.

3.3. Developed data analysis workflow

The workflow of data analysis (Fig. 5) was developed using the volunteer data.

High-resolution axial 3D T1W images were used for the assessment of airway caliber. In addition to the axial view, the images could also be reformatted to coronal and sagittal orientations for 2D visualization (Figs. 3 and 4). 3D visualization included an Endo view and a volumetric view (Fig. 6). The Endo view (see the video provided in Supporting Information) is a dynamic view inside the airway running cranial (the beginning of the RP) to caudal (the end of the RG) of the ROI.

With the sharp contrast between the airway and the surrounding tissues, automatic ROI placement could be done with the auto contour feature on the ISP. Measured quantities were cross-sectional area, lateral distance, and anterior-posterior distance of the airway. All these measurements were automatically calculated from within the selected ROI (Fig. 7) and recorded for further analysis.

The end-point values of interest are the minimum and mean values of the above quantities. The most critical end-points were the minimum and mean cross-sectional area.

3.4. Challenges and solutions

During the development process, it was observed that there was a signal loss at the upper edge of the imaged FOV (Fig. 8) when the 16-channel RF receive-only coil was rotated along with the head support plate. The signal loss was more severe with higher angles. This artifact was present in the first two volunteer MRI data. During the second volunteer scan, the artifact was resolved by running a coil survey scan every time the plate was tilted and before image acquisition (Fig. 8). The coil survey was a 10-second prescan sequence that can be manually added to adjust the signal receiver in a receive coil after it was rotated so that signal loss can be avoided.

When the head and/or chest support tables were tilted, subjects were instructed to keep their head in a comfortable position. Subsequently, padding and plastic L-shape props were used to keep the subject's head and whole body from sliding or further rotating. Another challenge was the motion artifact caused by swallowing. To alleviate the problem, the subject was requested right before the start of the high-resolution scan to refrain from swallowing for a 3-min period. All subjects were able to follow this request.

4. Discussion

Positional therapy, which uses an external device to prevent OSA patients from sleeping in a supine position, has been shown to be effective, comparable with continuous positive airway pressure (CPAP), and at the same time at low cost in a number of studies [5,6,8–11]. However, it remains unknown which non-supine position is optimal for an individual patient to minimize the patient's apnea-hyponea index (AHI). There are a variety of non-supine positions that include head and chest rotations at the same angle or at different angles. The rotational changes were reported to have impact on 2D and 3D configurations of the upper airway [12]. The capability to analyze this impact can pave the way to personalized positional therapy for OSA patients. Therefore, we have developed and demonstrated a non-invasive MRI methodology

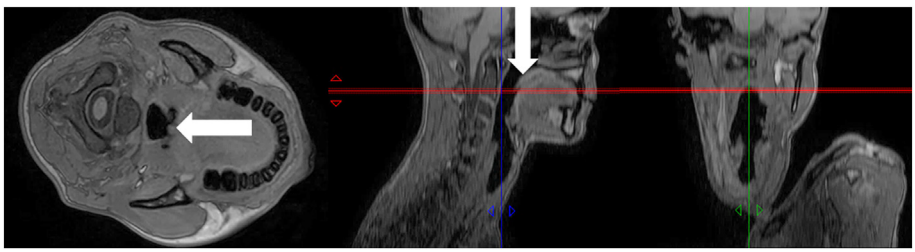

Fig. 3. The signal contrast between airway and the surrounding tissues. The airway has very low signal intensity compared to soft palate (indicated by the white arrows) and other surrounding tissues. The soft palate is the upper landmark for the airway section of interest.

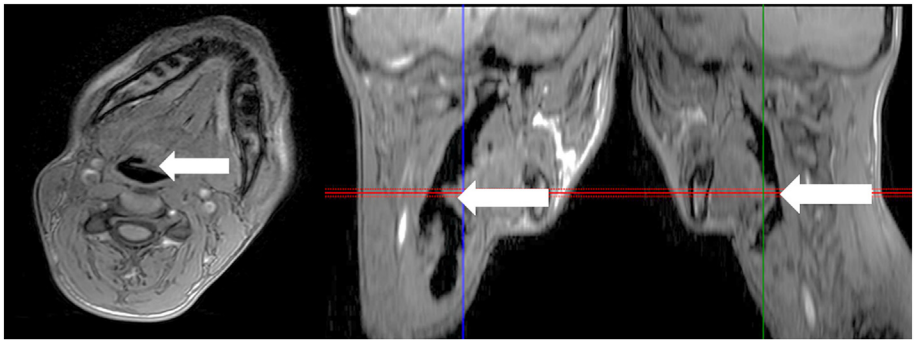

Fig. 4. The signal contrast between airway and the surrounding tissues. The airway has very low signal intensity compared to the epiglottis (indicated by the white arrows) and other surrounding tissues. The epiglottis is the lower landmark for the airway section of interest.

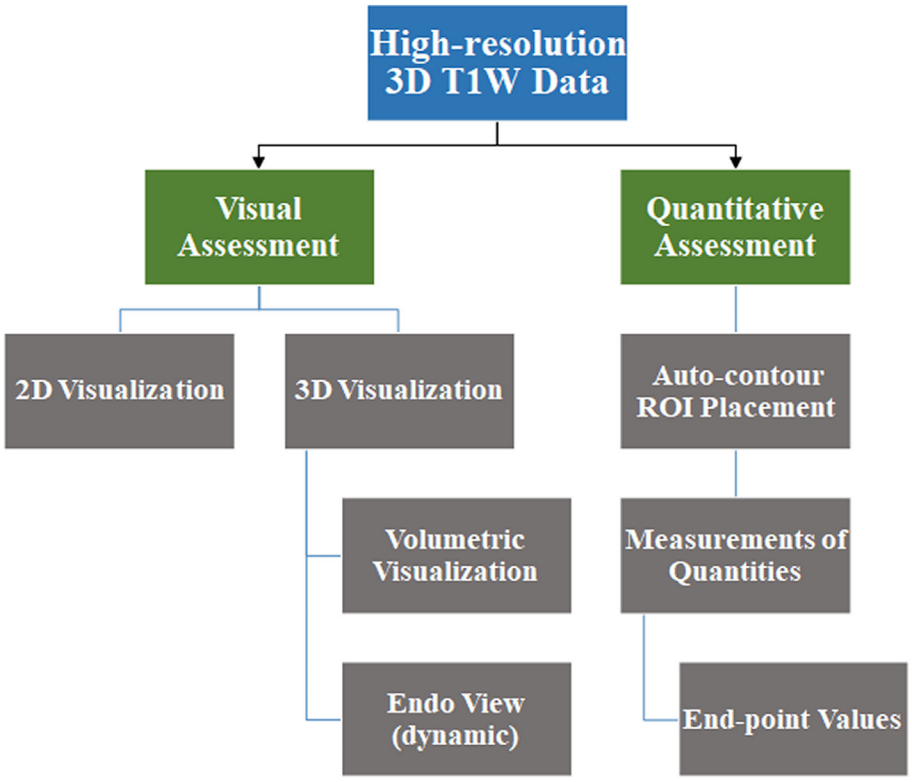

Fig. 5. Data analysis workflow. The analysis includes both visual and quantitative assessments. Visual assessment can be done in 2D or 3D view. Quantitative assessment is based on auto-contour ROI placement to measure the cross-sectional area, lateral distance, and anterior-posterior distance of the airway.

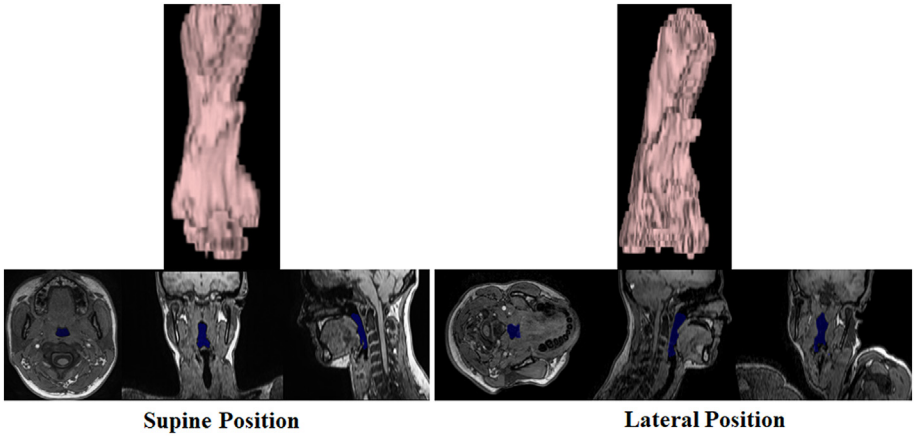

Fig. 6. 3D volume visualization. The change in the airway shape/volume from supine (left images) to lateral position (right images) can be visualized using a 3D volume display.

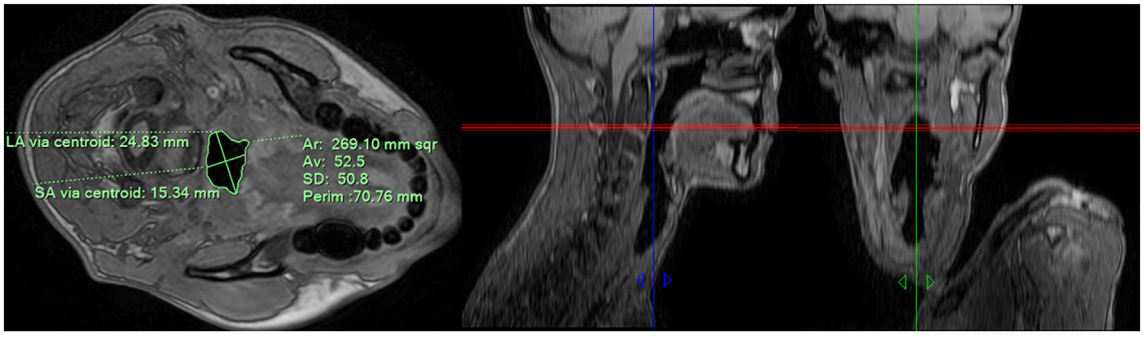

Fig. 7. Quantitative measurement of the airway caliber includes cross-sectional area (denoted as Ar), lateral distance (denoted as LA via centroid), and anterior-posterior distance (denoted as SA via centroid). The patient is in lateral position and the plates are not tilted.

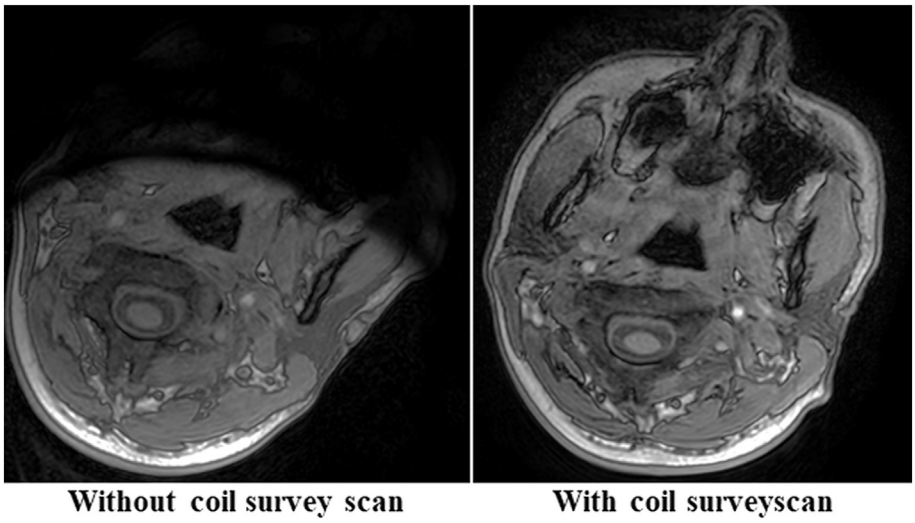

Fig. 8. Signal loss or FOV cutoff due to the rotation of the receive coil (left image) and the FOV was recovered (right image) by performing a coil survey scan after every rotation in the second volunteer MRI.

to analyze the impact of rotational changes in the head and chest on the upper airway caliber with the flexibility to test all angles of interest.

Previous MRI studies have demonstrated that MRI can be used to visualize and quantify the upper airway caliber and its changes after an intervention therapy for OSA [13–15,18,19]. However, none has studied the caliber changes by the head and chest rotations. Our study showed that these rotations could be independently maneuvered and switched from angle to angle so that high quality MR images of the upper airway were immediately acquired to assess the caliber changes.

The precision for the table edge's height in our study was on the order of 0.1 cm. Thus, an implemented angle may deviate by 0.3° d from the targeted angle. In future studies, we could achieve a higher precision, e.g. 0.01 cm, for the height to have an even more precise angulation. In addition, as the fast 2D T1W scan is always performed before the high resolution 3D T1W for planning purpose, the implemented angle can be verified every time the table is tilted.

Our study had several limitations. The potential patient size was an important factor for the feasibility due to the limit in the size of the MRI magnet bore. Only subjects with BMI of 30 (kg/(m2)) or less could fit in the magnet bore when the head and chest were rotated at a high angle (more than 20^0) or the patient was in the lateral position. While people with obesity are at more risk of OSA, there are still a large number of non-obese OSA patients who can be recruited for this MRI-based study. Also, MRI systems with larger bore size are available and can futher benefit from this methodology. Some patients or subjects may have difficulty in refraining from swallowing for 3 min. This may potentially cause some motion artifacts in the images. In a future study, we may develop a motion suppression technique to resolve this limitation.

5. Conclusion

This Phase I study developed and demonstrated a 3 T based MRI methodology to reliably assess the changes in a subject's airway caliber as a result of the head and chest rotations. The experiment set-up allowed remote management so that independent rotations of head and chest can be tested at all angles of interest. The methodology can be readily implemented on existing systems and appears to be an effective investigational tool for accurate airspace quantification as well as its positional changes.

Acknowledgements

We would like to thank Josh Williams at Hill-Rom Inc. for helping us with the rotation plates for the MRI table setup.

This study was supported by Hill-Rom Holdings, Inc. under OSP-60054089 project.

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