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Seeing Sleep:

Dynamic Imaging of Upper Airway Collapse and Collapsibility in Children

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Sleep disordered breathing in children ranges from snoring which has a prevalence of 12% to obstructive sleep apnea syndrome which has a prevalence of 2 to 3% in the general population [1]. The underlying causes of pediatric obstructive sleep apnea (OSA) are extremely complex. There are bony structural influences as seen in craniofacial abnormalities, and soft tissue abnormalities such as a large tongue, redundant soft tissue, or compliance/collapsibility issues. In some groups, such as Down syndrome a combination of these factors come into play. Add to this the escalating epidemic of obesity and metabolic syndrome, it is not surprising that obstructive apnea and sleep disordered breathing is increasing.

Sleep-disordered breathing has significant adverse effects on the lives of children and their families. Interrupted sleep in children can lead to sleepiness during normal activities, learning difficulties, and can aggravate attention deficit disorder and other behavior disorders. Additional effects that have been linked to OSA, especially in adulthood, include metabolic syndrome, hypertension, cardiovascular disease and stroke. The foundation for these comorbidities is laid in childhood and certainly would be aggravated by OSA.

In normal children, removal of the tonsils and adenoids is highly effective in treating OSA and snoring, but there is a subset of patients who only partially respond to this first line treatment. Children who often continue to have significant OSA after adenotonsillectomy include those with asthma, obesity, metabolic syndrome, craniofacial abnormalities, Down syndrome, and older age [2]. When persistence of OSA is documented by polysomnography further treatment is often needed. The first line treatment is continuous positive airway pressure applied by a facemask or nasal mask during sleep. However, patient compliance is a significant problem, especially in children with a limited capacity to understand the need for wearing the apparatus.

This difficultly often brings patients back to their medical provider to find other options for treatment. For moderate or severe, persistent OSA in children this often bring us to surgical options including repeat adenoidectomy, lingual tonsillectomy, midline posterior glossectomy, tongue suspension, supraglottoplasty, pharyngoplasty, or nasal turbinate reduction and septoplasty. However, the effectiveness of surgical treatment of pediatric patients with refractory OSA has only been about 60% [3]. Most of the surgical techniques have focused on making the airway larger or suspending tissue so that it is less liable to collapse. These are largely anatomical methods of addressing the issue, and ignore many of the neurophysiologic and tissue compliance factors that affect the collapsibility and obstruction in the airway. We believe there is a real opportunity here for novel imaging tests, based on magnetic resonance, to enable a breakthrough in our understanding of pediatric OSA and the ability to select optimal therapy.

Imaging Methods

Static anatomical imaging of the upper airway is easily performed on current commercially available MRI scanners. Established protocols include 3D axial and sagittal T1- and T2-weighted fast spin-echo scans, each taking roughly 2–4 minutes during free breathing [4], [5]. Patient motion is typically not a problem during wakefulness. However, during natural sleep or drug induced sleep (sedation or general anesthesia designed to simulate sleep), patients often thrust their tongue and jaw. In such cases, it is helpful to use respiratory triggering during expiration, when the airway is largest and most static. These static images can identify the recurrent adenoid tonsils, enlarged lingual tonsils, elongated soft palates, enlarged tongues (relative to the oral cavity) and areas of narrowing, all of which are amenable to surgical intervention.

Dynamic 2D imaging of the airway is also easily performed on current MRI scanners. Typical temporal resolution of the images is from 250 milliseconds (ms) to 500 ms using a 2D gradient echo or balanced steady-state-free-precession real-time imaging sequence. Images are obtained over a 30 second (or longer) acquisition in the midline sagittal plane, axial in the retroglossal airway just above the epiglottis, and oblique plane (transaxial to the airway) through the nasopharyngeal airway. Displaying the images as a movie provides a picture of the airway dynamics. Numerous studies have shown the airway to be more dynamic in patients with obstructive sleep apnea resulting in ballooning during expiration and collapse during inspiration, as shown in Figure 1 and Movie 1. It is the combination of anatomy and dynamics that aid the surgeon in clinical practice to better target the therapy. For instance, cine MRI awake or under drug induced sleep or natural sleep, has been shown to help inform surgical decisions and improve outcomes [6].

A number of new methods are emerging for the study of airway dynamics that, for now, require specialized MRI software or experimental apparatus. These techniques incorporate some combination of parallel imaging, compressed sensing, novel gating strategies, and novel stimuli. Compressed sensing (or constrained reconstruction) strategies have been recently shown to work particularly well for cine 2D and 3D proton density weighted airway imaging because the resulting movies are sparse in total variation (or generalized total variation) and have small regions that are moving compared to the full slice or volume being imaged. Novel gating strategies and stimuli allow for synchronization with respiration on conventional hardware [7], and the study of airway tissue compliance during wakefulness and sleep [8].

One nascent method is real-time 3D imaging of the upper airway using compressed sensing [9]. The latest technology is able to achieve 1.8 to 2.0 mm spatial resolution, with 600 ms temporal resolution, which enables visualization of the entire airway during naturally occurring apneas [10], as shown in Figure 2 and Movie 4. A current limitation of this technology is acoustic noise, and it remains to be seen if patients can reach REM sleep during this type of scan.

Another nascent method is active airway compliance testing, which involves the generation of negative pressure via inspiratory load (one to three breaths) [8] during ultrafast 2D imaging of the airway in cross section [11]. Under these conditions, airway motion is extremely rapid requiring at least 10 frames per second and millimeter spatial resolution. As shown in Figure 3 and Movie 5, this enables in-vivo measurement of the pressure – airway area relationship. Extrapolation of these measurements provides insight into the airway closing pressure, called P_{crit}. Such experiments can be repeated to reveal differences in the closing pressure between, for instance, wakefulness and sleep. These scans could also provide information about regional soft-tissue mechanical properties, and exactly how to do this is an active area of investigation.

Cine MRI is advantageous for studying the anatomy and neurophysiology of the upper airway because it allows observation, recording and repetition of experiments in an individual under a controlled situation without radiation and without endoscopy. Real-time or retrospective analysis of airflow, anatomy and dynamics of the entire upper airway can yield detailed information about neurophysiologic response and tissue compliance. The airway can be observed and recorded during wakefulness, natural sleep or drug-induced “sleep” before and after changing variables to observe neurophysiologic changes which are often different in patients with OSA resulting in an airway more susceptible to collapse. Imaging can inform patient-specific computational models that can be used to test the effects of surgery and determine the best surgical approach or develop new approaches [12].

Conclusion and Perspective

MRI is an emerging clinical method for evaluating the airway in OSA, and is able to be accomplished on all standard commercial MRI units. MRI is used at only a few centers to guide treatment decisions, but this number is growing as more otolaryngologists train at centers that use this modality routinely. Growth, however, depends on having imagers and surgeons collaborate to build a program. MRI at many of these centers is being used to investigate the anatomical and neurophysiologic factors that contribute to OSA.

At centers performing research investigations is a glimpse of the future. Advances in technology including silent imaging modes [13], 4D imaging of airway dynamics using compressed sensing [9], and layering with sleep-lab technology could further enhances the role of imaging in the treatment decision process for patients with refractory OSA. Currently, these are works in progress at various centers across the country and are being used to discover generalizable information to help guide treatment in the future. Ultimately, one can imagine having an “MRI Sleep Lab” to inform the decision making in treatment of refractory OSA with physiologic phenotyping of patients that allows optimal treatment and better outcomes. Additionally, such an “MRI Sleep Lab” could be used to study the effects of non-surgical treatment on the airway such as neuromuscular stimulation or drugs.

The best medicine is the prevention of disease, but once disease develops cure is the next goal. In refractory sleep disordered breathing a "cure" has been multifaceted and elusively difficult. Perhaps this is due to an incomplete understanding of the physiologic and anatomic underpinnings of obstructive sleep apnea mechanisms. MRI in combination with sleep lab techniques is one promising tool that can provide deeper insight and provide for better treatments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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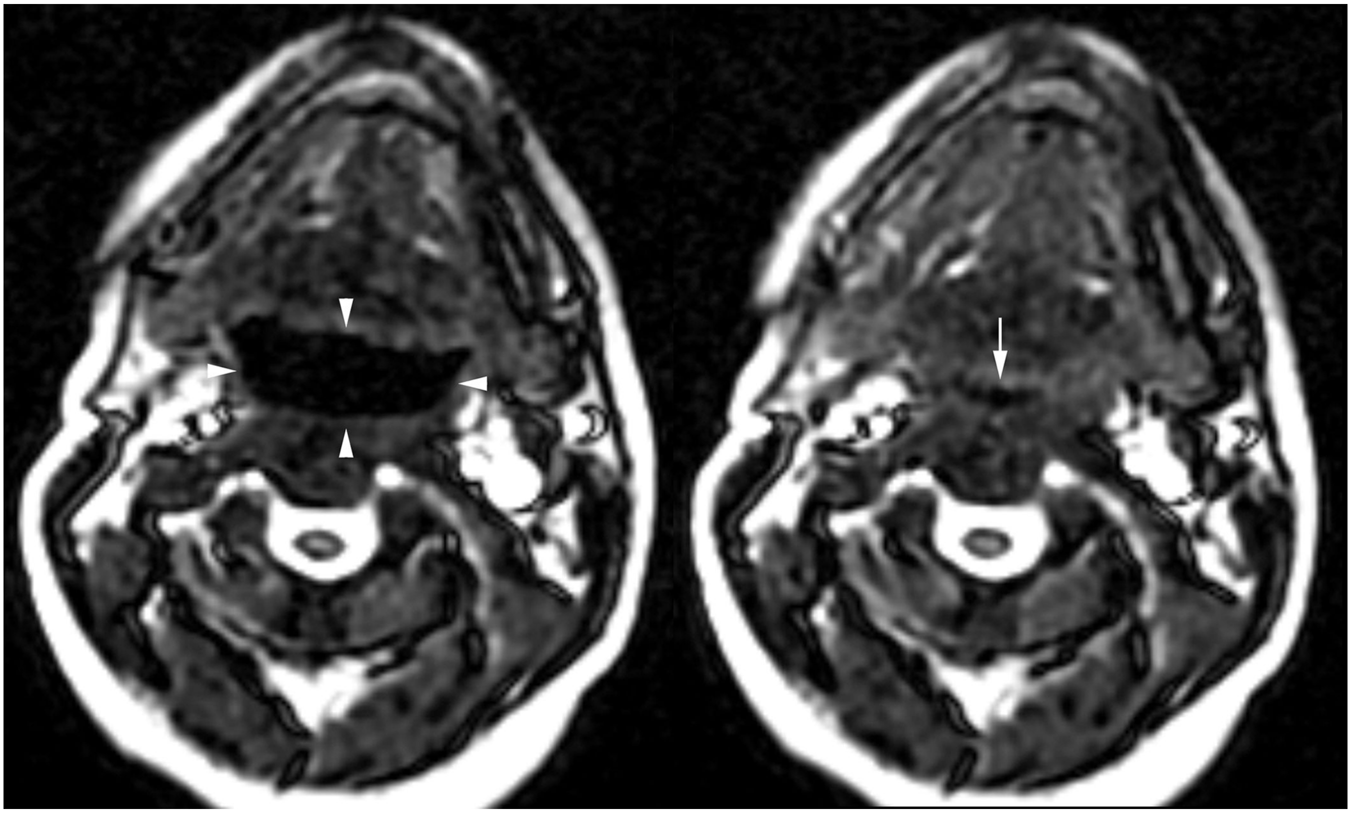

Figure 1.
Real-time 2D imaging of the airway during a breathing cycle. Shown here are axial images from a 13-year-old-male with Down syndrome and severe OSA by polysomnography. The airway is seen during (a) expiration (arrowheads) and (b) early inspiration (arrow). The pattern of collapse in this patient is primarily anterior-posterior (glossoptosis). Please also view supplemental movies #1, #2, and #3, which respectively contain midline sagittal, axial retroglossal, and axial nasopharyngeal movies from this patient. The sagittal movie shows dynamic motion but incomplete collapse. The axial retroglossal movie shows dynamic motion with complete collapse. The axial nasopharyngeal movie shows moderate dynamics and incomplete collapse.

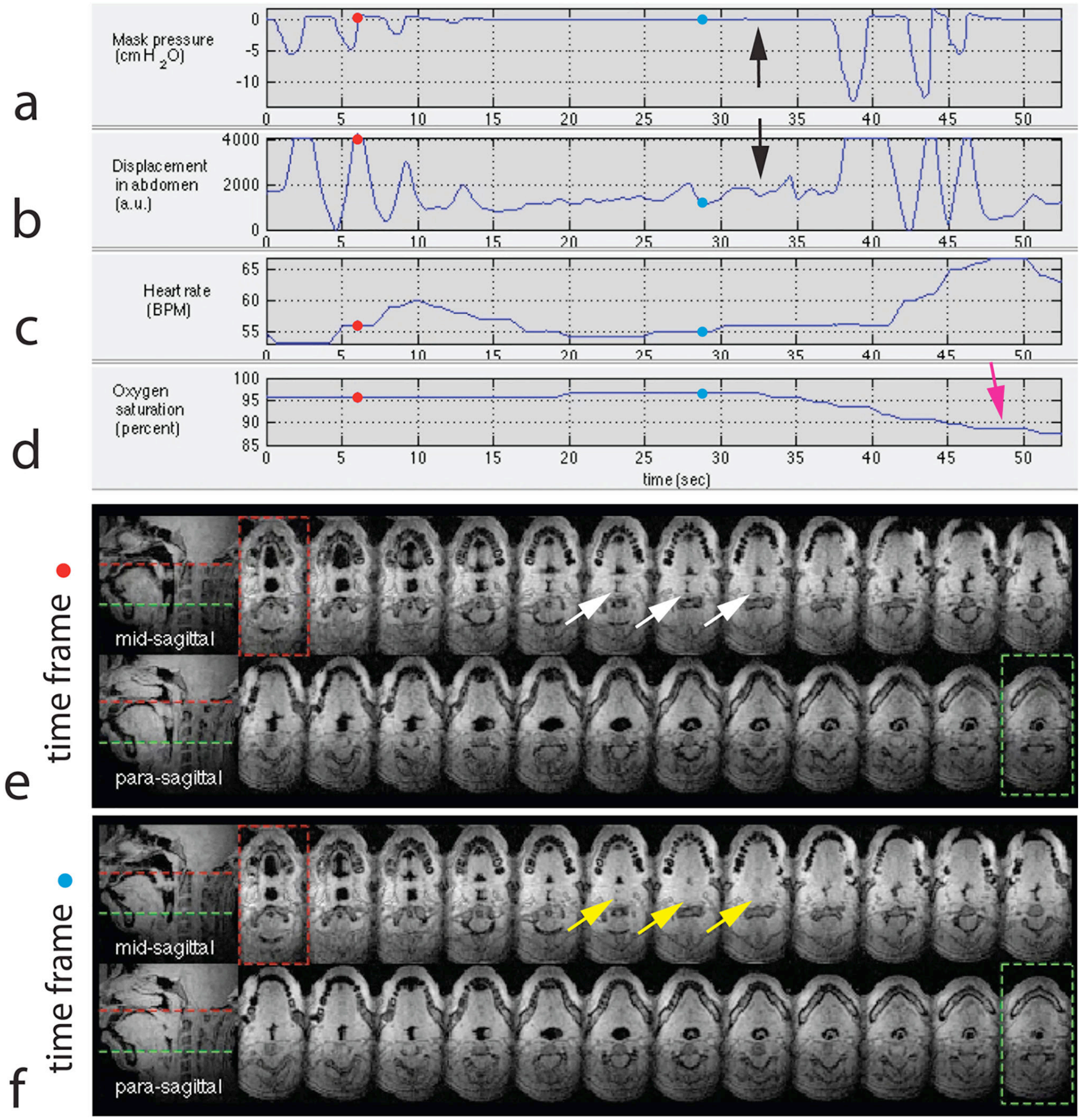

Figure 2.

Real-time 3D imaging enables complete visualization of events during natural sleep. Shown here is data from a 13-year-old-male primary snorer. Waveforms shown are (a) mask pressure, (b) abdominal respiratory effort, (c) heart rate, and (d) oxygen saturation simultaneously measured during an MRI scan. Representative axial and sagittal slices are shown for two time frames (e) prior to (red dots), and (e) during (blue dots) an obstructive apnea. A 25 second obstructive apnea is indicated by zero mask pressure and respiratory effort (black arrows) total airway collapse is observed in the retropalatal slices (yellow arrows compared to white arrows). Oxygen saturation drop is observed after the obstructive apnea (magenta arrow in **d**). Please also view supplemental movie #4.

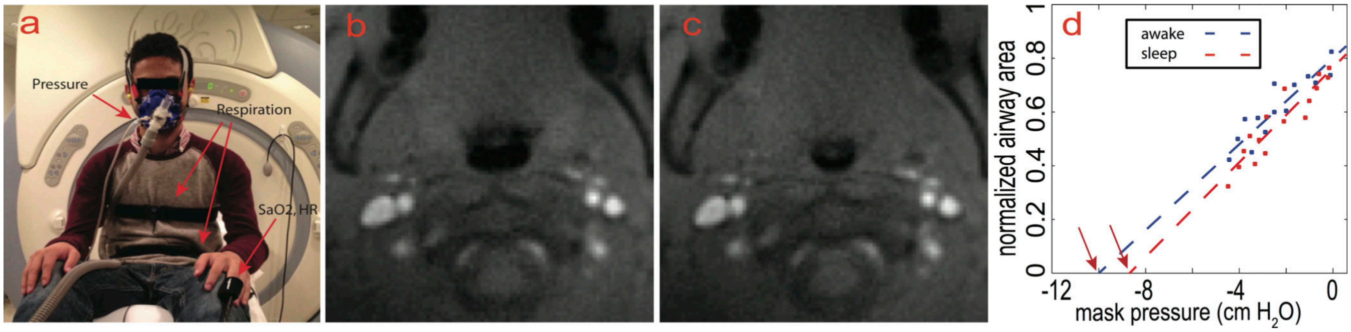

Figure 3.

Airway compliance can be actively tested using an inspiratory load and ultra-fast 2D imaging. The apparatus consists of a (a) facemask with pressure transducer, and a controller in the MRI operator room (not shown). Shown here are axial images from a 15-year-old-female primary snorer (b) before occlusion and (c) maximal narrowing during the occlusion. Please also view supplemental movie #5. Segmentation of these images enables estimation of the (d) pressure-airway area relationship, which can be determined by performing a linear regression from all data during a single occluded breath. Notice that the estimated airway closing pressure (arrows) in this subject is higher during sleep (red) than wakefulness (blue).