NOTES

A MR Compatible Spirometer to Measure Airway Pressure in Chiari I Patients during Valsalva Manuevers

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Purpose: An MR compatible spirometer was designed to aid in neuroradiology research to understand the pathophysiology of Chiari I malformations. The goal was to determine if the Valsalva maneuver, which causes headaches in Chiari I patients, exacerbates the CSF flow abnormalities.

Materials and Methods: To determine the effect of a Valsalva maneuver on CSF flow, MR images are acquired with the subject breathing normally and performing a Valsalva maneuver. For the latter, the subject breathes through the MR compatible spirometer. The device consists of a tube with attached mouthpiece and a compressed air/vacuum controlled valve. The Valsalva maneuver is performed by instructing the subject to breathe out through the spirometer and closing a valve in the airway to raise intra-thoracic pressure. The actual pressure achieved by the subject is recorded by means of the spirometer. The changes in CSF flow are monitored by MR and compared with the pressure changes. Six healthy subjects breathed through the spirometer and then forcefully blew against the closed valve to test the device.

Results: In the six subjects, an increase in intra-thoracic pressure for 30 seconds was achieved in each subject. The pressure increases ranged from 42 to 89 mm Hg. Conclusions: The new MR-compatible spirometer facilitates the performance of a Valsalva maneuver and monitors the magnitude of the Valslava maneuver achieved.

Key Words: Chiari I malformation, Valsalva maneuver, cerebrospinal fluid, intra-thoracic pressure, spirometer

The Chiari I malformation is a developmental abnormality characterized by the displacement of the cerebellar tonsils into the cervical spinal canal. According to prevailing theory, obstruction of cerebral spinal fluid (CSF) flow in patients with Chiari I malformation has a role on the pathogenesis of symptoms. Partial obstruction of the cervical spinal canal sufficient to increase CSF velocities produces higher CSF pressure fluctuations in the cranial vault and, therefore, likely increases ambient pressures in the subarachnoid space which affects both the spinal cord and brain.

Research further suggests that headaches experienced by Chiari I patients are often accentuated by physical exertion, Valsalva maneuvers (sneezing, coughing or straining), head dependency, and sudden changes in posture [1]. The Valsalva-induced headache is characteristic of the Chairi I malformation. Although the mechanism of the Valsalva-induced headache is not known, Valsalva maneuvers theoretically increase spinal venous volume and CSF pressure and may exacerbate the CSF flow obstruction [2, 3].

To study the change in CSF flow that Chiari I patients experience during Valsalva maneuvers, MR images must be acquired with the subject breathing normally and also while performing a Valsalva maneuver. In order to monitor the patient's effort in performing the Valsalva maneuver, an MR compatible spirometer was designed to acquire measurements in airway pressure. This device allows researchers to correlate a quantified increase in airway pressure to a quantified change in CSF flow.

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MATERIALS AND METHODS

The spirometer design consists of three essential components: a mouthpiece attached to a short tube with air port holes, a valve system that can be closed to simulate a Valsalva maneuver, and a transducer to measure pressure.

The main component of the spirometer is a cylindrical plastic tube constructed to fit into a disposable mouthpiece at one end and sealed with a cap at the opposite end. The tube features four side air ports arranged circumferentially near the end of the tube furthest from the mouthpiece. These holes allow the patient to breathe normally through the device while it is placed in the mouth. To simulate a Valsalva maneuver, the side air port holes are covered while the subject is exhaling forcibly. Air pressure is used to close the side ports. When exhaling against the obstruction, the subject increases intra-thoracic pressure, the normal result of a Valsalva maneuver.

The valve system contained within the device consists of a plug, end cap, and stopper. Figures 1 and 2 show the major valve components and valve airflow patterns respectively. The plug is a solid, plastic cylinder with a diameter equal to the inner diameter of the spirometer tube and functions to cover four air side ports. The capped end of the tube has an inlet for attaching air supply tubing. By supplying air pressure to the capped end of the tube, the plug can be slid along the inside of the tube from the capped end towards the mouthpiece. Moving the plug in this manner covers the air port holes. Using a vacuum, the plug can be slid along the inside of the tube in the opposite direction, thus opening the air ports. A plastic, ring-shaped stopper fits tightly within the tube and is positioned such that it limits the movement of the plug to properly cover and uncover the air ports. Thus when compressed air is supplied to the device, the plug slides forward until becoming flush with the stopper. This completely covers the holes and provides an air-tight, closed surface which the patient can breathe out against while mimicking a Valsalva maneuver.

The pressure measurements produced during the Valsalva maneuver are recorded through the use of an electronic transducer positioned between the stopper and the mouthpiece. This placement ensures that when the air port holes are covered, the transducer records the pressure of the exhalation in the closed portion of the spirometer tube between the mouthpiece and the face of the plug. This measurement provides quantitative data of the patient effort during the Valsalva maneuver.

All of the design components were made entirely of plastic, except for the transducer. Most pressure transducers available are either designed for industrial control processes or precision research measurements. Neither type is designed to operate in the MR environment, since metallic casings are generally used to reduce deformations of supports. However, inexpensive thin film transducers with small amounts of metal are available. These are generally designed to be PC-board mountable and are typically more sensitive to temperature. Also, they have limited accuracy (~1% full scale with perfect calibration). However, in the MR environment RF and gradient induced noise is expected to dominate; making the transducer's stochastic error relatively insignificant.

A second device was designed specifically for anesthetized patients on ventilator support. This design consists of a small tube which is connected between the ventilator and patient tubing. A transducer is incorporated into the tube to measure pressure. Since it is not possible to perform a Valsalva maneuver by closing the airways of these patients, an increase in pressure was simulated by keeping the lungs inflated for 30 s. Prior to patient use, this device was tested using a Servo i ventilator connected to mechanical test lungs. Using this setup, the ease of operation and accuracy of pressure measurements were tested. The pressure readout from the device was compared to the built-in pressure monitor on the Servo i.

Preliminary testing was conducted to determine pressures experienced during normal breathing and Valsalva maneuvers. Six subjects (male and female) were tested to determine minimum and maximum pressures during normal breathing and Valsalva maneuvers. In doing so, an estimate of the typical pressures that would be generated during the Valsalva maneuver was able to be obtained. This data was useful for future testing to ensure that the observed pressures were in the usable range of the transducer. Also, the data could be checked to see if the pressure measurements were consistent going from a normal environment to the high magnetic field environment of the scanner.

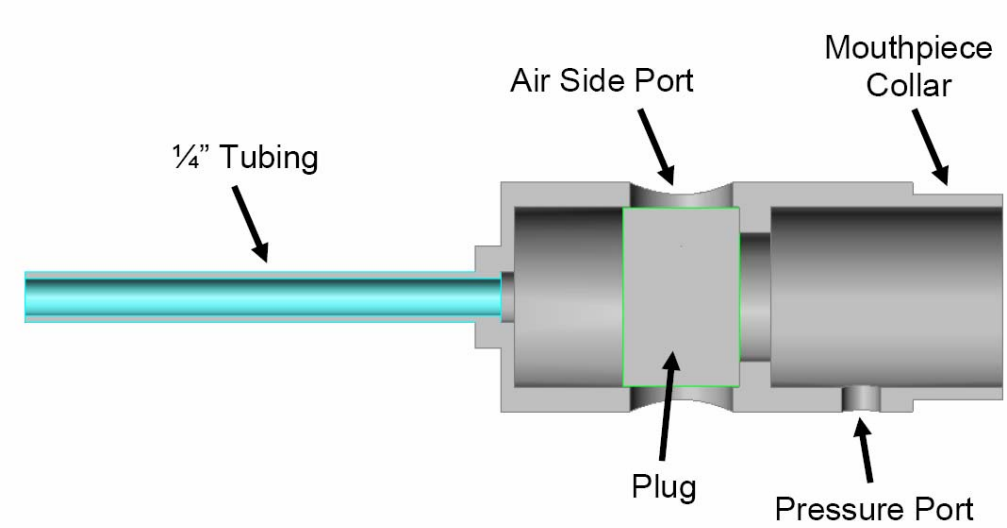

Figure 1: A length-wise cross sectional view of the device. Compressed air and vacuum are supplied via the ¼ inch tubing. The sliding plug has rubber ends to reduce air leakage. The pressure port will contain a transducer to record exhalation pressure values during the mimicked Valsalva maneuver.

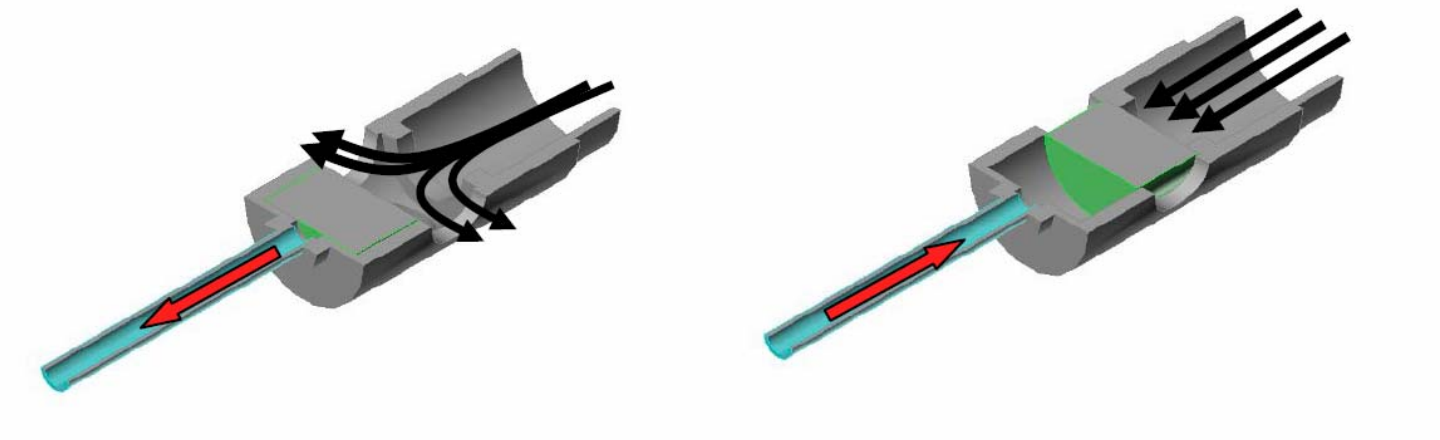

Figure 2: Airflow patterns (originating from the mouthpiece) with the plug in the rest state (left) and activated state (right). Black arrows represent the patients airflow while red arrows indicate pneumatic forces. Negative pressure is applied via the ¼ inch tubing in the rest state and positive pressure is applied in the activation state.

Susceptibility and noise related artifacts as well as the accuracy of pressures were evaluated on a 1.5 T scanner (Twin-speed Excite 12.0; GE Healthcare, Waukesha, WI). Using a computer controlled pump (Shelley Medical Systems, London, ON), the transducer was placed proximal to a 75% stenosis phantom. A square wave flow pattern was used to establish a pressure waveform, with a period of 2.5 s and maximum amplitude of 200 mm Hg. Gated pressure waveforms were obtained in two possible states; outside of the magnetic field and with the device in the bore during a typical gradient echo sequence. Careful effort was taken to ensure that the orientation of the tubing and pump did not change significantly from state to state. Pressures were recorded for a period of 5 min, for approximately 240 independent pressure period realizations.

For compatibility testing, 3D gradient-recalled echo images were taken with and without the device and examined for artifact and noise. For data analysis purposes, pressure readings were segmented according to trigger position. For each time point, in each state, measures of mean and standard deviation were calculated. These distributions were then compared using simple regression analysis.

A single consenting volunteer, was scanned using the developed protocol to test logistics and feasibility. 30 second CINE-Phase Contrast exams were performed, during normal breathing and during a valsalva maneuver. Recorded airway pressures were plotted and compared to CSF flow rates.

RESULTS

The preliminary testing consisted of testing airway pressures using the MR compatible spirometer outside the MR environment. The airway pressures during normal breathing were in the range of 1 to 4 mm Hg. The pressures monitored by the spirometer for intra-thoracic pressure during the Valsalva maneuver range from 42 to 89 mm Hg [Table]. All of the pressures fell within the usable range of the transducer.

Table 1

Subject	Sex	Age	Max Valsalva Pressure (mmHg)	Max Free Breathing Pressure (mmHg)
1	F	8	41.9	2.1
2	F	11	49.5	3.5
3	M	14	63.9	2.8
4	F	15	62.4	3.1
5	M	18	82.2	2.5
6	F	21	88.6	1.2

Pressures outside MR were found to be well correlated with those acquired outside MR (R2=0.998, Slope=1.01). The average SNR of the pressure waveform dropped from 40.99 outside MR to 26.8 inside the MR bore during scanning, likely due to RF and gradient induced noise. No visible artifacts were present in the 3D GRE images; nor was there a significant change in SNR (24.57 with the device vs. 23.52 without the device).

The device for anesthetized patients proved to be ventilator-compatible and accurate in its pressure measurements. The device fit securely between the ventilator and patient tubing without any leakage. Additionally, the pressures measured by the device matched the readouts displayed on the Servo i monitor.

Recorded pressures curves, as shown in figure 3, show an adequate waveform for further analysis. The device operated smoothly, with pressures corresponding to the valsalva's performed on healthy individuals out side MR. Only minor increases in setup time where observed. In this healthy volunteer, mild changes in flow rates were observed during the induced valsalva maneuver, as shown in figure 4.

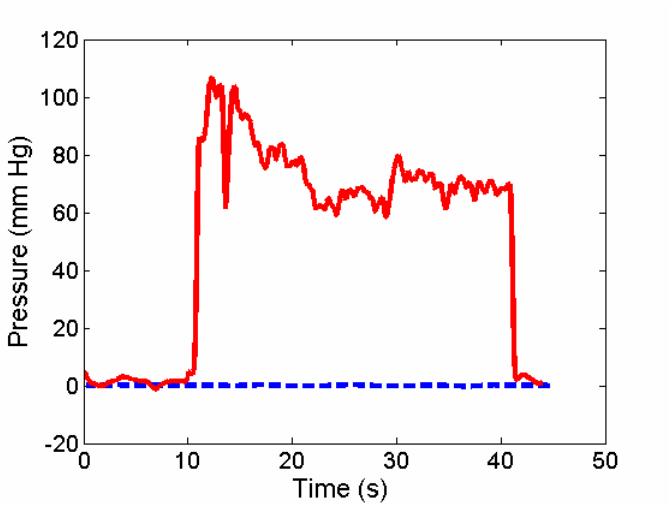

Figure 3: Baseline (dashed-blue) and valsalva (solid-red) pressure waveforms obtained during a 2D CINE Phase Contrast exam. Pressure data was recorded for 45 seconds, starting 10 seconds before the start of the exam

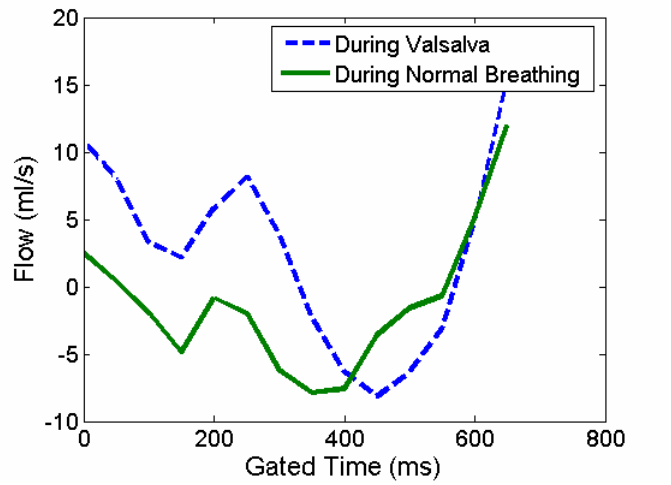

Figure 4: CINE-CSF flow waveforms obtained during normal breathing and valsalva. A small net increase in flow was observed during the valsalva.

DISCUSSION

An MR compatible spirometer was designed of the following components: a mouthpiece attached to a short tube with air port holes, a valve system that can be closed to simulate a Valsalva maneuver, and a transducer to measure pressure. A second device was designed specifically for anesthetized patients on ventilator support. This design consists of a small tube which is connected between the ventilator and patient tubing. SNR and susceptibility testing showed that both configurations did not compromise MR imaging performance.

A testing protocol was developed for using the device with human subjects through an approved IRB protocol. The MR spirometer is to be used to obtain necessary pressure measurements both during normal breathing and while performing a Valsalva maneuver. Both healthy volunteers and Chiari patients would be instructed to use the device according to the same protocol. The patient will enter into the MR suite, and the technician will aid in the adjustment of the patient's position on the table with a standard head coil. The spirometer will be secured to the head coil via adhesive wrap and placed into the patient's mouth with the air ports open for normal breathing. The wire from the transducer will be connected to a computer outside the MR suite with LabView software for data analysis. The air tubing will be connected to the compressed air and vacuum supply ports in the MR suite. The patient will be instructed to remain breathing normally, and a baseline MR scan will be acquired. If desired, pressure recording during normal breathing could be obtained at this time. The patient will then be instructed to "take a deep breath in." The compressed air should then be supplied to the spirometer in order to activate the valve system and close the air ports. This will simulate the Valsalva maneuver, and the patient will be instructed to "exhale as hard as you can" against the closed valve. Pressure transducer measurements will be collected via the computer as the patient exhales. During this exhalation, a second MR image will be obtained. After approximately 30 s of exhalation, the vacuum air source will be turned on to suction the plug backwards, thus opening the air ports once again. The patient will then be able to resume normal breathing. The use of the spirometer can be repeated as necessary. The device should be sanitized or disposed of after each use.

The constructed devices will be used on Chiari patients to correlate measured changes in airway pressure during Valsalva-like maneuvers with measured changes in CSF flow. This will aid in determining the role of thoracic pressure in obstructing CSF flow in these patients. Ideally, the data collected will aid in anticipating the onset of neurological signs and symptoms, allowing for early intervention. Prior to the construction of these devices, Valsalva maneuvers were used in research without the capability of monitoring the amount of patient effort or duration of expiration.

The devices have yet to be used in a clinical setting, so optimization of the protocol and logistics may be necessary. To operate the valve system, compressed air and vacuum must be available in the MR suite. Additionally, a wire must connect from the transducer (inside of the scan room) to the laptop running the LabView program (outside of the scan room). The setup and ease of use will vary depending on the scan room.

The simple spirometer design allows for easy and inexpensive large-scale manufacturing. The cost of materials for producing one device is less than $50, with the transducer itself costing approximately $40. The device can be disposable or sanitized and reused depending on the user's preference.

The accuracy of the pressure measurements and the MR compatibility have been shown through testing, and the devices are ready for clinical use. By acquiring data in a clinical setting, it may be possible to obtain valuable information regarding the pathogenesis of Chiari I malformation. Additionally, through more extensive testing in a variety of settings valuable information about the devices, such as failure rates, will be obtained.

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