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ORIGINAL ARTICLE

Infant Cardiac Magnetic Resonance Imaging Using Oscillatory Ventilation: Safe and Effective

Alicia H. Chaves · Joseph R. Cava · Pippa Simpson · George M. Hoffman · Margaret M. Samyn

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Abstract Cardiac magnetic resonance imaging (CMR) for infants and young children typically requires sedation. General anesthesia with controlled ventilation can eliminate motion artifact with breath-holds during imaging to limit respiratory artifact, but these may lead to atelectasis or other complications. High-frequency oscillatory ventilation (HFOV) provides ventilation with near-constant mean airway pressure and minimal movement of chest wall and diaphragm, thus obviating the need for breath-holding. Clinical data were collected for 8 infants who underwent CMR with HFOV and 8 controls who underwent CMR with conventional ventilator and breath-hold technique. Data included demographic information, adverse events, and scan-acquisition time. Studies were reviewed for image quality by two cardiologists who were blinded to type of ventilation. There were no significant differences in patient characteristics between the two groups. There was no significant difference in average image quality for cine short-axis or black blood imaging. Total CMR scan time was not significantly different between groups, but the short-axis cine stack was acquired more quickly in the HFOV group (1.8 ± 0.8 vs. 5.0 ± 3.6 min). There were no adverse events in the HFOV group, but scans were terminated early for two patients in the conventional ventilator group. HFOV during CMR is feasible and well tolerated. Image quality is equivalent to that obtained with conventional ventilation with breath-holding technique and allows shorter cine scan times for some sequences.

A. H. Chaves (✉) · J. R. Cava · P. Simpson · G. M. Hoffman · M. M. Samyn
The Herma Heart Center, Children's Hospital of Wisconsin, Medical College of Wisconsin, Milwaukee, WI 53226, USA
e-mail: achaves@peds.umaryland.edu

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Introduction

Cardiac magnetic resonance (CMR) has become a useful imaging modality for pediatric and congenital heart disease patients. Although echocardiography is often sufficient, CMR may provide additional information that guides diagnosis and management for infants with complex heart disease. CMR is particularly helpful in quantitative functional imaging, tissue characterization, and evaluation of venous and arterial structures [13].

Artifact from patient movement and respiratory motion can have a negative impact on image quality. For this reason, infants undergoing CMR often receive pharmacologic restraint of varying degrees along the sedation–anesthesia continuum. The demarcation between deep sedation and general anesthesia is commonly defined by the application of airway management techniques, such as continual manual facemask, laryngeal mask, or endotracheal tube, that permit control of ventilation. Use of general anesthesia (GA) with mechanical ventilation allows for a motionless field during repeated periods of apnea (breath-holds) for image acquisition. The benefits and safety of GA during magnetic resonance imaging (MRI) have been shown [10, 11, 13]; however, GA is not without risk. Infants with congenital heart disease are particularly at risk [3, 6], and breath-holding may contribute to adverse events [12].

The risk of adverse events from GA in this vulnerable population has lead to the continued search for alternatives. The use of deep sedation or a "feed-and-swaddle" method are both viable alternatives [4, 5, 16], C> but neither eliminate respiratory artifact, and both may cause complications. Atelectasis, a common consequence of sedation or GA, may be poorly tolerated in this patient population. Breath-holds performed with conventional ventilation have been associated with atelectasis [1, 9]. High-frequency oscillatory ventilation (HFOV) provides a relatively constant and high mean airway pressure and low tidal volumes at high frequencies; it is widely used in critically ill neonates and infants. HFOV is associated with low risk of lung injury and adequate hemodynamics [15] and may be beneficial in recruiting alveoli in areas of atelectasis [8]. During HFOV, the diaphragm and thus the heart position remain relatively constant, obviating the need for interruptions in ventilation for image acquisition.

We hypothesized that GA combined with the use of HFOV during CMR in infants would be safe and provide equivalent image quality compared with studies performed with the patient under general anesthesia with conventional mechanical ventilation (CMV). Because breath-holds might not be necessary with HFOV, we also hypothesized that use of HFOV would lead to faster scan times by allowing continuous scanning. We compared image quality and adverse event rates for two groups of infants who underwent CMR: The first group received HFOV, and the second age-matched group received CMV.

Methods

With approval from the Children's Hospital of Wisconsin Institutional Review Board, this was a retrospective study of all infants who underwent CMR under general anesthesia with HFOV at Children's Hospital of Wisconsin from June 1, 2009, to December 1, 2010. Age-matched controls, who underwent CMR with general anesthesia and CMV, were chosen from the same time period. Demographic information was collected, including date of birth, date of CMR, sex, height, weight, body surface area (BSA), cardiac diagnoses, anesthetic agents used, ventilator settings, minor and serious adverse events, American Society of Anesthesiologists (ASA) class, and time of scan acquisition. We reviewed clinical data, including temperature, oxygen saturation, heart rate, blood pressure, and end-tidal CO_2, before and after MRI.

The HFOV (SensorMedics; EM Company, Doral, FL) was used during CMR scanning for the HFOV group. The ventilator was positioned outside of the MRI scan room with low compliance tubing passed through an access port in the MRI suite and connected to the exhalation limb of a modified Mapleson breathing circuit with fresh oxygen, air, and anesthetic gas from an MRI-compatible anesthesia delivery system (Aestiva; GE Healthcare, Madison, WI) according to methods described by Hoffman et al. [7]. The anesthesia protocol was similar between groups and relied on a "balanced" low-dose volatile-agent strategy with neuromuscular blockade and with standard monitoring that included pulse oximetry, noninvasive blood pressure, electrocardiogram, and capnometry.

Cardiac imaging was performed on a Siemens 1.5-Tesla (T) Symphony magnet. The scan parameters were not affected by ventilation strategy but were at the discretion of the cardiologist performing the scan. Cine steady-state free-precession (SSFP) short-axis images and T2 turbo spin echo (TSE) black blood axial images were reviewed for quality by two independent CMR-trained pediatric cardiologists who were both blinded to ventilation method. Images were graded on a scale of 1 (poorest image quality) to 4 (best image quality).

Statistical Analysis

Continuous demographic data are presented as a mean (or median). Image quality between the two groups was compared using the numeric scale and Student *t* test or Mann–Whitney test depending on the data. Mean time of study acquisition between the two groups was compared. Parameters indicative of patient status before, during, and after CMR were compared for the scans acquired with HFOV and CMV.

Results

Demographic data are listed in Table 1. There were no significant differences in age, BSA, or ASA score between the two groups. There was no significant difference in image quality for cine imaging (2.6 vs. 2.5, $p = 0.721$ [NS]) or black blood imaging (2.9 vs. 3.0, $p = 0.656$ [NS]) between the HFOV and CMV groups. Examples of image quality are shown in Figs. 1 and 2. Total scan time was not significantly different between groups (69.5 vs. 78.1 min, $p = 0.382$ [NS]), but the short-axis stack was acquired more quickly in the HFOV group (1.8 vs. 5.0 min, $p = 0.005$). All short-axis stacks in both groups were able to be traced for volume measurements.

Vital signs, measured before and after CMR, were not significantly different between the two groups except that diastolic blood pressure was lower in the HFOV group before CMR (33 *vs.* 50 mm Hg, $p = 0.038$). Mean airway pressure was greater (11.9 ± 1.0 vs. 8.9 ± 1.5 mmHg) and FiO_2 lower (0.28 ± 0.05 vs. 0.57 ± 0.21) in the HFOV group. There were no adverse events in the HFOV group, but scans were terminated early for two CMV patients due to hypoxemia, with one requiring continued postprocedural mechanical ventilation (Table 2).

Table 1 Demographic data for oscillator and conventional ventilator groups

Demographic data	HFOV ($N = 8$)	CMV ($N = 8$)
Female sex	6	6
Median (range) age (week)	6.0 (0.1–29.9)	8.0 (0.3–33.7)
Median (range) weight (kg)	3.84 (2.5–6)	4.25 (2.9–7)
Median (range) BSA (m^2)	0.22 (0.17–0.32)	0.24 (0.18–0.33)
Diagnoses ($n = 1$ patient each)	HLHS with scimitar DILV with PA DILV, mitral atresia, d-TGA, and TAPVR Pulmonary atresia with VSD Tetralogy of Fallot Heterotaxy, unbalanced AVSD Double-outlet right ventricle with pulmonary stenosis LV aneurysm	HLHS HLHS, s/p transplant VSD with interrupted aortic arch Rhabdomyoma Heterotaxy: AVSD & d-TGA Heterotaxy: AVSD and PA Vascular ring Vascular ring and VSD
Mean (median, range) ASA score	3.38 (4.0, 2.0–4.0)	3.13 (3.0, 2.0–4.0)

HLHS hypoplastic left heart syndrome, *DILV* double inlet left ventricle, *PA* pulmonary atresia, *d-TGA* d-transposition of the great arteries, *TAPVR* total anomalous pulmonary venous return, *VSD* ventricular septal defect, *AVSD* atrioventricular septal defect

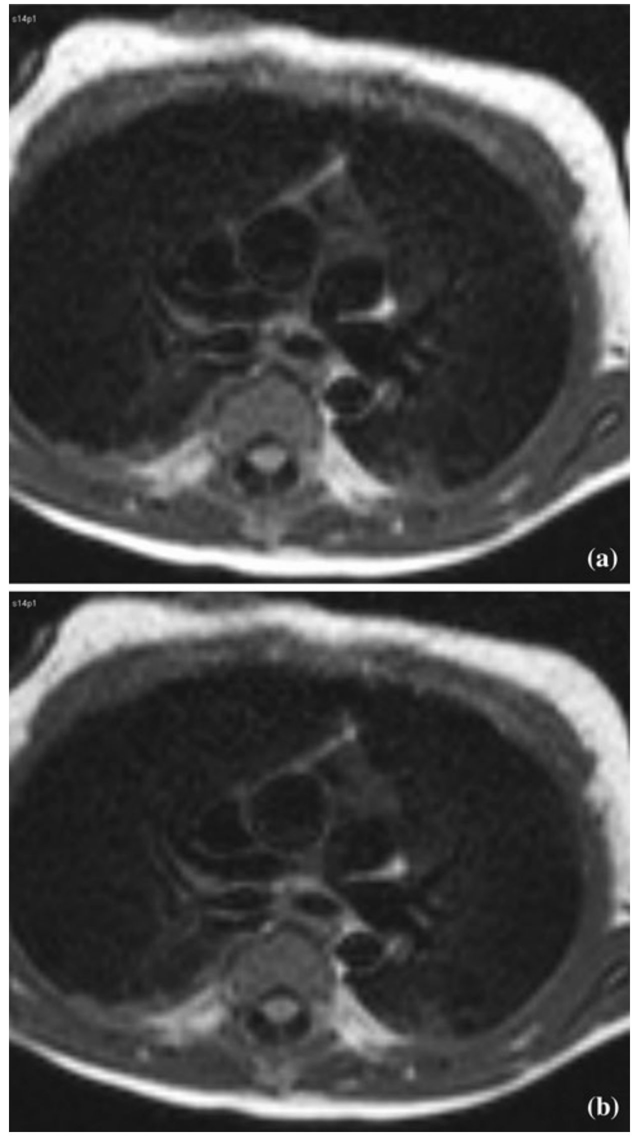

Fig. 1 Axial TSE MRI obtained using a Siemens 1.5-T Symphony magnet with **a** CMV and **b** HFOV

Discussion

This study showed that use of HFOV was feasible and safe in infants undergoing CMR. No adverse events were seen in the HFOV group, whereas two patients in the CMV group had their scans terminated early due to hypoxemia. Image quality of SSFP and TSE black blood sequences was rated as equivalent. Although scan acquisition time was not statistically shorter in the HFOV group, there was a trend to shorter scan time, and the time taken to acquire a short-axis cine stack was significantly shorter.

Although feed-and-swaddle imaging may be performed for infants, this means of accomplishing CMR is not optimal for complex congenital heart disease assessment. Complex CMR scans typically take at least 1 h and require a still patient for diagnostic image quality. Adverse events can occur during CMR regardless of the type of sedation used. Malviya et al. [10] examined the adverse event rate in patients undergoing either computed tomography or MRI of any type. They found a higher rate of adverse events (2.9 vs. 0.7%) in patients receiving sedation versus GA. Image quality was noted to be better with the patient under GA. They noted that patients with higher ASA scores had episodes of hypoxemia and thus required GA. Other studies have confirmed that higher ASA scores, as well as inpatient status, are associated with increased rate of adverse events [3, 12].

Early CMR experience suggested that GA with CMV was the best option for patient safety as well as image quality [3, 13]. In a retrospective study, Fogel et al. [4] showed similar success rates, adverse event rates, and image quality for patients who underwent CMR with deep sedation versus GA. However, the study was not randomized, and there was a larger percentage of patients who were critically ill or who had more complex congenital heart disease in the GA group. A "feed-and-sleep" method

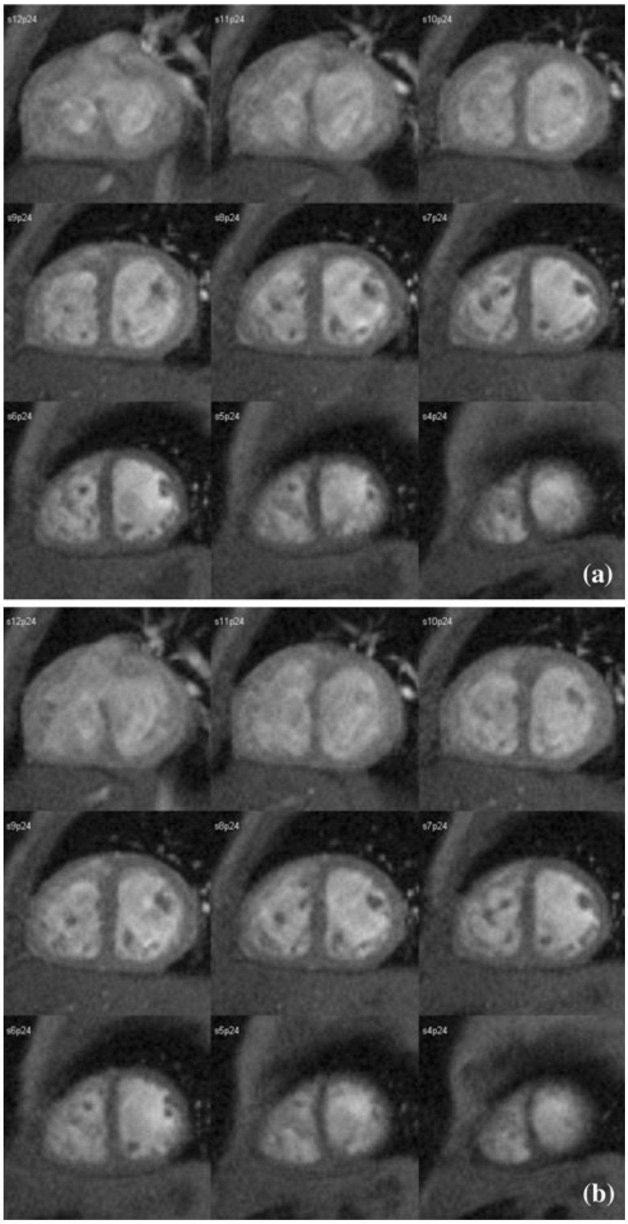

Fig. 2 SSFP MRI obtained using a Siemens 1.5-T Symphony magnet with **a** conventional and **b** oscillatory ventilation

has also shown to be effective in infants having a limited CMR scan, especially one focusing on extracardiac anomalies [5, 16]. Both deep sedation and the feed-and-sleep method provide good options in certain circumstances; however, they may not allow for adequate monitoring or airway protection in some patients.

The use of GA with endotracheal intubation and CMV does provide airway control, but it is not without risks. The hemodynamic consequences of GA can be significant and include superimposition of direct pharmacologic effects, autonomic changes, and respiratory–cardiac interactions of positive pressure ventilation. Breath-holds, which optimize image quality by decreasing respiratory artifact and maintaining a uniform heart position, can promote atelectasis, resulting in recurrent adverse respiratory–cardiac interactions [3, 12, 13]. Prolonged breath-holding allows for acquisition of multiple sequences in quick succession does shorten scan time, but it potentially increase the range of physiologic changes and thus the risk of adverse effects. GA, with or without breath-holds, is associated with increased atelectasis when used during MRI and can cause persistent gas exchange abnormality, particularly in infants [1, 9]. The risk for hypoxemia was illustrated in our study with two patients in the CMV group who experienced hypoxemia, which lead to scan termination.

Table 2 Comparison of scan time, image quality, and adverse events between HFMO and CMV groups

Parameter	HFOV ($N = 8$)	Conventional ($N = 8$)
Mean (median, range) MRI scan time (min)	69.5 (65.0, 42.0–101.0)	78.1 (76.0, 39–103.0)
Mean (median, range) short-axis time (min)	1.8* (1.5, 1.0–3.25)	5.0 (3.6, 2.4–13.4)
Mean (median, range) cine quality score	2.6 (2.5, 2.0–3.5)	2.5 (2.5, 2.0–3.0)
Mean (median, range) TSE quality score ($n = 7$)	2.9 (3.0, 2.0–4.0)	3.0 (3.0, 2.0–3.5)
Probability (95% CI) of adverse events (n)	0 (0, 0.00–0.37)	2 (0.25, 0.03–0.65) %

CI Confidence interval

* $p = 0.005$ (nonsignificant for other values)

Atelectasis during GA is not unique to patients undergoing CMR. Alveolar recruitment strategies, such as using short periods of time with greater mean airway pressures, may be effective in decreasing atelectasis [14]. HFOV allows for a constant mean airway pressure and eliminates the need for breath-holds, theoretically decreasing the risk for atelectasis [8]. We did note a greater mean airway pressure in the HFOV group, but this was without adverse hemodynamic effect. A study comparing the use of HFOV versus CMV in infants undergoing cardiac surgery did demonstrate safety and in fact was associated with a shorter length of intubation and intensive care unit stay [2].

Limitations

Our study was limited by the small number of patients; thus, generalization about the comparative safety of HFOV versus CMV is unwarranted. This study was retrospective; therefore, the groups were not randomized. Although there was no difference in age or ASA score, and complexity of heart disease was similar, there may have been subtle differences in the groups that were not measured. Although certain common CMR sequences were used for all of our patients, the scan protocol was individualized for each patient and scan indication. As a result, it may be misleading to compare scan acquisition time. The use of an HFOV device in conjunction with an anesthetic gas delivery system requires modification of both systems, and the safety and feasibility described herein can only be assured when applied with the highest attention to technical detail.

Future Directions

Future studies are needed to confirm the utility and benefits of using HFOV during CMR in infants. Randomization of larger groups of patients to HFOV and CMV may more accurately measure the adverse event rate, scan time, and image quality with these two methods. Additional comparison of ventricular volumes for patients undergoing CMR with both HFOV and CMV would show that quantification is not altered by ventilation strategy. Finally, comparison of the degree of atelectasis with these two methods should also be considered.

Conclusion

Our study indicates that GA with HFOV is feasible during infant CMR. This means of ventilation did not adversely affect image quality and has the potential for decreasing scan time. It should be considered as a ventilatory method for neonates and small infants with complex congenital heart disease, who are more vulnerable to the adverse physiologic effects of atelectasis and recurrent changes in intrathoracic pressure from breath-holding.

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