Ventricular kinetic energy may provide a novel noninvasive way to assess ventricular performance in patients with repaired tetralogy of Fallot

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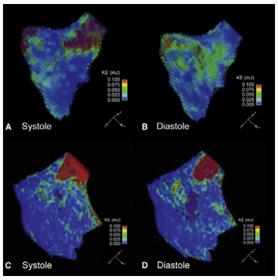
ABSTRACT

Objective: Ventricular kinetic energy measurements may provide a novel imaging biomarker of declining ventricular efficiency in patients with repaired tetralogy of Fallot. Our purpose was to assess differences in ventricular kinetic energy with 4-dimensional flow magnetic resonance imaging between patients with repaired tetralogy of Fallot and healthy volunteers.

Methods: Cardiac magnetic resonance, including 4-dimensional flow magnetic resonance imaging, was performed at rest in 10 subjects with repaired tetralogy of Fallot and 9 healthy volunteers using clinical 1.5T and 3T magnetic resonance imaging scanners. Right and left ventricular kinetic energy (KE_{RV} and KE_{LV}), main pulmonary artery flow (Q_{MPA}), and aortic flow (Q_{AO}) were quantified using 4-dimensional flow magnetic resonance imaging data. Right and left ventricular size and function were measured using standard cardiac magnetic resonance techniques. Differences in peak systolic KE_{RV} and KE_{LV} in addition to the Q_{MPA}/KE_{RV} and Q_{AO}/KE_{LV} ratios between groups were assessed. Kinetic energy indices were compared with conventional cardiac magnetic resonance parameters.

Results: Peak systolic KE_{RV} and KE_{LV} were higher in patients with repaired tetralogy of Fallot (6.06 ± 2.27 mJ and 3.55 ± 2.12 mJ, respectively) than in healthy volunteers (5.47 ± 2.52 mJ and 2.48 ± 0.75 mJ, respectively), but were not statistically significant ($P = .65$ and $P = .47$, respectively). The Q_{MPA}/KE_{RV} and Q_{AO}/KE_{LV} ratios were lower in patients with repaired tetralogy of Fallot (7.53 ± 5.37 mL/[cycle mJ] and 9.65 ± 6.61 mL/[cycle mJ], respectively) than in healthy volunteers (19.33 ± 18.52 mL/[cycle mJ] and 35.98 ± 7.66 mL/[cycle mJ], respectively; $P < .05$). Q_{MPA}/KE_{RV} and Q_{AO}/KE_{LV} were weakly correlated to ventricular size and function.

Conclusions: Greater ventricular kinetic energy is necessary to generate flow in the pulmonary and aortic circulations in repaired tetralogy of Fallot. Quantification of ventricular kinetic energy in patients with repaired tetralogy of Fallot is a new observation. Future studies are needed to determine whether changes in ventricular kinetic energy can provide earlier evidence of ventricular dysfunction and guide future medical and surgical interventions. (J Thorac Cardiovasc Surg 2015;149:1339-47)



RV kinetic energy is a potentially new marker for impaired RV function in rTOF.

Central Message

Greater kinetic energy is required to generate flow in rTOF, which may provide earlier evidence of ventricular dysfunction.

Perspective

Quantification of ventricular kinetic energy in rTOF is a new observation, with a complex relationship between ventricular kinetic energy and great vessel flow. Greater energy losses in rTOF, indicative of increased inefficiency, is a novel method of monitoring declining cardiac function and may provide earlier evidence for intervention than current standard indices.

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CHD

Abbreviations and Acronyms

BSA	=	body surface area
CMR	=	cardiac magnetic resonance
EDVI	=	end-diastolic volume index
EF	=	ejection fraction
ESVI	=	end-systolic volume index
4D	=	4-dimensional
IV	=	intravenous
KE	=	kinetic energy
KE_{LV}	=	left ventricular kinetic energy
KE_{RV}	=	right ventricular kinetic energy
LV	=	left ventricular
MRI	=	magnetic resonance imaging
PA	=	pulmonary artery
PC VIPR	=	vastly undersampled isotropic projection reconstruction
Q_{AO}	=	aortic flow
Q_{MPA}	=	main pulmonary artery flow
rTOF	=	repaired tetralogy of Fallot
RV	=	right ventricular
TOF	=	tetralogy of Fallot

Without surgical intervention, the natural history of tetralogy of Fallot (TOF) can lead to mortality rates of 25% in infants with severe obstruction within the first year of life and up to 95% by age 40 years.[1] TOF is the most common cyanotic congenital heart disease accounting for 9% to 14% of all congenital cardiovascular defects.[2] With advancements in technology and surgical technique, most patients now undergo corrective surgical repair early in life and live into adulthood. Surgical correction of TOF typically involves ventricular septal defect closure, relief of right ventricular (RV) outflow tract obstruction, disruption of the pulmonary valve that results in pulmonary regurgitation, and placement of an outflow patch.[3] Expected postoperative pulmonary regurgitation has been associated with progressive RV dilatation and ventricular dysfunction.[4] Alterations in hemodynamics that frequently occur after repair ultimately contribute to poor long-term outcomes, including progressive exercise intolerance, ventricular arrhythmia, and sudden cardiac death.[5]

Cardiac magnetic resonance (CMR) has become the gold standard to monitor patients with repaired TOF (rTOF). Volumetric and functional CMR parameters are used to guide the decision of when to perform pulmonary valve replacement to protect from the long-term sequelae of chronic pulmonary insufficiency.[6] Monitoring with conventional CMR relies on detecting underlying morphologic changes, such as RV dilatation, to signify dysfunction. The newer 4-dimensional (4D) flow magnetic resonance imaging (MRI) technique can detect abnormal RV diastolic flow patterns in rTOF even when RV volumes or function is not substantially abnormal.[7,8] Although pulmonary valve replacement results in reversal of RV dilation, the risk of cardiac death and arrhythmias may not be averted.[9] More sensitive markers of RV dysfunction could help guide therapy and timing of pulmonary valve insertion.

Ventricular kinetic energy (KE) measurements provide a novel method of monitoring cardiac function[10,11] and may provide an earlier imaging biomarker of declining ventricular efficiency in patients with rTOF compared with conventional measurements of ventricular size and function, which are based on morphologic changes. Previous studies have demonstrated the feasibility of calculating KE noninvasively with 4D flow MRI.[12,13] In addition, 4D flow MRI provides aortic and main pulmonary artery (PA) flow data allowing the relationship of KE and the generated ventricular outflow to be evaluated. Traditionally, the ventricular–vascular relationship or coupling is described by elastance of each component, derived from pressure-volume loops.[14] With the availability of 4D flow MRI, an analogous ventricular KE and vascular outflow relationship can be studied. To our knowledge, there have been no previous studies that have examined ventricular KE measurements in patients with rTOF. The purpose of this study was to assess differences in ventricular KE between rTOF and healthy volunteers using 4D flow MRI.

MATERIALS AND METHODS

Subjects

This single-center prospective cohort study was approved by the university Institutional Review Board. Data were acquired in compliance with all applicable Health Insurance Portability and Accountability Act regulations. Written informed consent was obtained from all subjects aged 18 years or more. For subjects aged 18 years or less, written informed consent was obtained from parents or legal guardians and assent obtained from subjects aged 6 years or more. Ten patients with rTOF (age 20.6 ± 12.2 years) and 9 healthy volunteers (age 38.9 ± 15.1 years) were included in this study. Healthy volunteers responded to public recruitment advertisements and were selected to participate after passing a health screening for cardiovascular disease. All subjects underwent CMR examinations after obtaining appropriate consent/assent.

Cardiac Magnetic Resonance

In subjects with rTOF, the clinically indicated CMR performed to measure ventricular size and function was followed by an investigational 4D flow MRI acquisition. Subjects with rTOF were scanned at 1.5T (HDx, GE Healthcare, Waukesha, Wis) or 3.0T (MR750, GE Healthcare), depending on the clinical availability of the scanners at the time of the examination and need for sedation. In healthy volunteers, 4D flow MRI and 2-dimensional cine balanced steady-state free precession were performed on 3.0T scanners (MR750, GE Healthcare).

Details of the 4D flow MRI sequence, phase contrast with vastly undersampled isotropic projection reconstruction (PC VIPR), have been reported.[7,15] Briefly, 4D flow MRI parameters were as follows: field of view = 260 to 320 mm, spatial resolution = 1.3 mm isotropic, repetition time = 8.8 to 10.9 ms (1.5T) and 6.2 to 3.7 ms (3.0T), echocardiography time = 2.8 to 3.7 ms (1.5T) and 2.0 to 2.2 ms (3.0T), velocity