International Journal of Cardiology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Cardiology

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

Exploring energy loss by vector flow mapping in children with ventricular septal defect: Pathophysiologic significance☆

Takashi Honda [a,*], Keiichi Itatani [b], Manabu Takanashi [a], Atsushi Kitagawa [a], Hisashi Ando [a], Sumito Kimura [a], Norihiko Oka [c], Kagami Miyaji [d], Masahiro Ishii [a]

[a] Department of Pediatrics, Kitasato University School of Medicine, Kanagawa, Japan
[b] Department of Cardiovascular Surgery, Kyoto Prefectural University of Medicine, Kyoto, Japan
[c] Department of Thoracic and Cardiovascular Surgery, Wakayama Medical University, Wakayama, Japan
[d] Department of Cardiovascular Surgery, Kitasato University School of Medicine, Kanagawa, Japan

ARTICLE INFO

Article history:
Received 26 December 2016
Received in revised form 18 May 2017
Accepted 9 June 2017
Available online xxxx

Keywords:
Energy loss
Vector flow mapping
Right-to-left ventricular interaction
Ventricular septal defect

ABSTRACT

Background: Vector flow mapping is a novel echocardiographic flow visualization method, and it has enabled us to quantitatively evaluate the energy loss in the left ventricle (intraventricular energy loss). Although intraventricular energy loss is assumed to be a part of left ventricular workload itself, it is unclear what this parameter actually represents. The aim of the present study was to elucidate the characteristics of intraventricular energy loss.

Methods: We enrolled 26 consecutive children with ventricular septal defect (VSD). On echocardiography vector flow mapping, intraventricular energy loss was measured in the apical 3-chamber view. We measured peak energy loss and averaged energy loss in the diastolic and systolic phases, and subsequently compared these parameters with catheterization parameters and serum brain natrium peptide (BNP) level.

Results: Diastolic, peak, and systolic energy loss were strongly and positively correlated with right ventricular systolic pressure ($r = 0.76$, 0.68, and 0.56, $p < 0.0001$, $= 0.0001$, and 0.0029, respectively) and right ventricular end diastolic pressure ($r = 0.55$, 0.49, and 0.49, $p = 0.0038$, 0.0120, and 0.0111, respectively). In addition, diastolic, peak, and systolic energy loss were significantly correlated with BNP ($r = 0.75$, 0.69 and 0.49, $p < 0.0001$, < 0.0001, and $= 0.0116$, respectively).

Conclusions: In children with VSD, elevated right ventricular pressure is one of the factors that increase energy loss in the left ventricle. The results of the present study encourage further studies in other study populations to elucidate the characteristics of intraventricular energy loss for its possible clinical application.

1. Introduction

Recent technological innovations in imaging modalities have made it possible to evaluate the nature of intraventricular and intravascular blood flow [1–5]. Echocardiography vector flow mapping is one such novel technology, and it can visualize the flow vectors and streamlines in the heart and blood vessels [6]. The flow vectors and streamlines are composed of flow velocity vectors horizontal and perpendicular to the echo beam, which are measured based on the color Doppler and speckle tracking data, respectively. Furthermore, based on the theory of energy dispersion, echocardiography vector flow mapping enabled us to calculate the energy loss in an arbitrarily specified area [6].

The concept of energy loss was originally proposed for accurate evaluation of ventricular workload by Garcia et al. [7]. They proposed energy loss index to estimate energy loss in patients with aortic stenosis (AS), and Bahlmann et al. subsequently reported that energy loss index could be a surrogate parameter reflecting the severity of AS [8]. Energy loss has also been estimated by using computer flow simulation studies to assess hemodynamics following congenital heart surgery using procedures such as the Norwood or Fontan procedure [9–11]. However, there were few studies evaluating energy loss in clinical practice due to the technical difficulty of energy loss measurement [12,13], and the characteristics and clinical utility of energy loss are yet to be fully clarified. Therefore, we consider that the direct measurement of energy loss using echocardiography vector flow mapping is a novel approach and that this technology will possibly provide new knowledge about ventricular function and hemodynamics [14].

Furthermore, the sum of energy loss inside the left ventricle (intraventricular energy loss) can be calculated on echocardiography vector flow mapping [15,16]. Intraventricular energy loss is the energy lost as the result of blood flow collision in the left ventricle, and represents

☆ Authors' statements: All the authors share responsibility for all aspects of the reliability and freedom from bias of the data presented and their discussed interpretation.

* Corresponding author at: Department of Pediatrics, Kitasato University School of Medicine, 1-15-1 Kitasato, Minami-ku, Sagamihara, Kanagawa 252-0374, Japan.
E-mail address: ipponda_honda@msn.com (T. Honda).

http://dx.doi.org/10.1016/j.ijcard.2017.06.035
0167-5273/© 2017 Elsevier B.V. All rights reserved.

how efficiently the blood flows inside the left ventricle. Although intraventricular energy loss is assumed to be a part of left ventricular workload itself, no other approaches have to this point assessed this type of energy. Therefore, intraventricular energy loss measured using echocardiography vector flow mapping is a novel parameter to evaluate this type of ventricular workload. In the present study, in order to elucidate the characteristics of intraventricular energy loss, we compared intraventricular energy loss measured on echocardiography vector flow mapping with hemodynamic parameters obtained from catheterization, echocardiography, and laboratory testing in children with ventricular septal defect (VSD).

2. Methods

2.1. Patient selection and study protocol

Children with VSD who were scheduled to be examined for possible surgical procedures in Kitasato University Hospital from April 2013 through February 2014 were enrolled. In our institute, the criteria for surgery include congestive heart failure symptoms or right coronary cusp prolapse with aortic valve regurgitation. Based on the most recent guideline from the Japanese Circulation Society, we performed catheterization and echocardiography for such infants before their surgical procedures [17]. In this study, we excluded patients who had patent ductus arteriosus, large left-to-right interatrial shunting (>6 mm), or other cardiac anomalies. In addition to these routine examinations, we performed echocardiography vector flow mapping to evaluate flow vectors, streamlines, and intraventricular energy loss on the same day. To clarify the hemodynamic parameters that influence intraventricular energy loss, we subsequently compared intraventricular energy loss and conventional parameters obtained from catheterization, echocardiography and laboratory testing. The current study was a prospective study, and all the procedures were approved by the Institutional Review Board of Kitasato University Hospital (B13-84).

2.2. Vector flow mapping echocardiography image and energy loss measurement

We obtained apical 3-chamber views by using a Prosound α10 with a cardiac phased array probe, UST-5296 (Hitachi, Ltd., Tokyo, Japan) and recorded vector flow mapping color image loops in two cardiac cycles. We also set up a frame rate of between 30 and 40 frames per second. Data were stored in an image server and were subsequently analyzed using an echo image analyzer (DAS-RS1, Hitachi, Ltd.), which can automatically construct images with flow vectors and streamlines and calculate flow energy loss based on energy dispersion inside the specified area. In this study, we traced the left ventricular inner wall to specify the left ventricle using this image analyzer. We subsequently obtained the images of flow vectors and streamlines, and measured intraventricular energy loss for each time frame to obtain an energy loss time curve (Fig. 1).

2.3. Intraventricular energy loss parameters

As shown in Fig. 1, the energy loss time curve demonstrated a peak during the diastolic phase in all 26 patients; therefore, we defined peak energy loss as the maximum energy loss in the diastolic phase. We also calculated the average energy loss during diastolic and systolic phases and defined these parameters as diastolic and systolic energy loss, respectively. Based on a previous report, energy loss was corrected according to body surface area [16].

2.4. Catheterization method

We performed catheterization to measure hemodynamic parameters according to the guideline from the Japanese Circulation Society [17]. Left ventricular systolic and end-diastolic pressures (LVSP, LVEDP), and right ventricular systolic and end-diastolic pressures (RVSP, RVEDP) were obtained. We also calculated systemic blood flow volume (Qs), pulmonary blood flow volume (Qp), Qp/Qs, systemic artery resistance (Rs), and pulmonary artery resistance (Rp) based on the Fick method. Left ventricular end-diastolic volume index and ejection fraction (LVEDVI and LVEF), and right ventricular end-diastolic volume index and ejection fraction (RVEDVI and RVEF) were measured. Angiographic catheter (Hanmac Medical Products, Inc., NY, USA), wedge pressure catheter (Hanmac Medical Products, Inc.), and pigtail catheter (Gadelius Medical K.K., Tokyo, Japan) were used for the pressure measurements and volumetry. As a contrast agent, we used Iomeron 350 (Eisai Co., Ltd., Tokyo, Japan). Heart rate (HR) and hemoglobin levels were also recorded.

2.5. Echocardiographic parameters

Using a Prosound α10 (Hitachi, Ltd.), we measured left ventricle diastolic diameter (LVDd), systolic diameter (LVDs), intraventricular septum (IVS), posterior wall (PW), and left ventricular ejection fraction (LVEF) from the short axis view. E wave amplitude, A wave amplitude, E/A ratio, and myocardial performance index (MPI) were obtained from the apical 4-chamber view [17].

2.6. Laboratory finding

We measured serum brain natrium peptide (BNP) levels for the evaluation of ventricular workload.

2.7. Statistical analyses

Data were expressed as median and range. Spearman's rank order coefficient was used to evaluate the correlations between intraventricular EL and other parameters. We evaluated intra-observer variability using the Bland–Altman method for all 26 patients. An inter-observer validation study was also performed among 10 randomly selected patients. We performed stepwise multivariate linear regression analyses using JMP 11 (SAS Institute Inc., NC, USA) according to the manufacturer's guideline [18]. The other statistical analyses were performed using Prism 6 software (GraphPad Software Inc., CA, USA) according to the manufacturer's guideline [19].

3. Results

3.1. Patient characteristics

Twenty-six children (11 males) with VSD were enrolled in the present study. Patient ages ranged from 0.9 to 20.3 months (median 3.0 months), and the body surface area (BSA) ranged from 0.22 to 0.50 m^2 (median 0.30 m^2). Furosemide and spironolactone were administered to 23 and 10 patients, respectively. Isosorbide dinitrate and digitalis were prescribed for 8 and 1 patient(s), respectively. Sixteen patients had a small to moderate left-to-right interatrial shunting (<6 mm). The present study also included three infants with left ventricle to right atrium communication, two with peripheral pulmonary stenosis, and two with trivial mitral valve regurgitation. One patient with suspected right coronary cusp prolapse did not undergo surgery because catheterization totally eliminated the possibility of right coronary cusp prolapse. The other 25 patients had undergone VSD closures. Patient characteristics are summarized in Supplementary Table 1.

3.2. Flow vector and intraventricular energy loss

During the rapid filling diastolic phase, two vortices were formed near the mitral valve, and high energy loss was confirmed between direct blood inflow and these two vortices (Fig. 1 and Supplemental