Cardiothoracic Anesthesia, Respiration and Airway

Left and right ventricular diastolic dysfunction as predictors of difficult separation from cardiopulmonary bypass

[La dysfonction ventriculaire diastolique gauche et droite comme prédicteur des difficultés de sevrage de la circulation extracorporelle]

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Purpose: As the evaluation of diastolic function can be complex in the setting of a busy cardiac operating room, its assessment may benefit from an algorithmic approach using transesophageal echocardiography. We developed a diagnostic algorithm which was then applied in a series of cardiac surgery patients to determine whether moderate to severe left ventricular diastolic dysfunction (LVDD) and right ventricular diastolic dysfunction (RVDD) can predict difficult separation from cardiopulmonary bypass (DSB).

Methods: An algorithm using pulsed-wave Doppler interrogation of the mitral and tricuspid valve, the pulmonary and hepatic venous flow, and tissue Doppler interrogation of the mitral and tricuspid annulus was developed. The study was divided in two phases involving two groups of patients undergoing cardiac surgery. In phase I, echocardiographic evaluations of patients (n = 74) were used to test the reproducibility of the algorithm and to evaluate inter-observer variability using Cohen's kappa values which were calculated in three specific periods. In phase II, the algorithm was applied to a second group of patients (validation group, n = 179) to explore its prognostic significance. The primary end-point in phase II was DSB.

Results: In phase I, the kappa coefficients for LVDD and RVDD algorithms were 0.77 and 0.82, respectively. In phase II, moderate or severe degrees of LVDD were observed in 29 patients (16%) and moderate to severe RVDD was observed in 18 patients (10%) before cardiac surgery. Both moderate and severe LVDD (P = 0.017) and RVDD (P = 0.049) before surgery were observed more frequently in patients with DSB.

Conclusion: Moderate and severe LVDD and RVDD can be identified with very good reproducibility, and both degrees of diastolic dysfunction are associated with DSB.

***Objectif**: L'évaluation de la fonction diastolique pouvant être complexe dans le contexte d'un bloc opératoire très actif en chirurgie cardiaque, on pourrait tirer profit d'un algorithme pour son évaluation avec l'échocardiographie transœsophagienne. Nous avons développé un algorithme en cardiochirurgie pour déterminer si la dysfonction ventriculaire diastolique gauche (DVDG) modérée ou sévère et la dysfonction ventriculaire diastolique droite (DVDD) pouvaient être des prédicteurs de difficultés de sevrage de la circulation extracorporelle (DSCE).*

***Méthode** : Un algorithme utilisant l'examen Doppler pulsé pour évaluer la vélocité des valvules mitrale et tricuspide, la vélocité des veines pulmonaire et hépatique et l'examen Doppler tissulaire*

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des anneaux mitral et tricuspide a été mis au point. L'étude, en deux phases, a comporté deux groupes de patients devant subir une opération cardiaque. Pendant la phase I, des évaluations échocardiographiques de patients (n = 74) ont permis de vérifier la reproductibilité de l'algorithme et d'évaluer la variabilité inter-observateur d'après les valeurs Kappa de Cohen qui ont été calculées à trois moments spécifiques. Pendant la phase II, l'algorithme a été appliqué au second groupe de patients (groupe de validation, n = 179) pour explorer sa portée pronostique. Le principal paramètre de la phase II était les DSCE.

***Résultats** : Pendant la phase I, les coefficients kappa pour les algorithmes de DVDG et DVDD ont été respectivement de 0,77 et 0,82. Pendant la phase II, des DVDG modérées ou sévères ont été observées chez 29 patients (16 %) et des DVDD chez 18 patients (10 %) avant l'opération cardiaque. Des DVDG modérées et sévères (P = 0,017) et des DVDD (P = 0,049) préchirurgicales ont été observées plus souvent chez les patients qui présentaient des DSCE.*

***Conclusion** : Des DVDG et des DVDD modérées et sévères peuvent être observées avec une très bonne reproductibilité et les deux degrés de dysfonction diastolique sont associés à des DSCE.*

THERE is growing interest in evaluating diastolic function[1] in cardiology and in cardiac surgery. Left ventricular diastolic dysfunction (LVDD) is associated with a poorer prognosis in patients with left-sided heart failure,[2] right-sided heart failure[3] and septic shock.[4] We and others have reported previously that LVDD is an independent predictor of difficult separation from cardiopulmonary bypass (DSB)[5] and postoperative complications.[5–7] However, in several studies, the severity of diastolic dysfunction was not examined, and newer modalities such as tissue Doppler imaging[8] were not applied to the evaluation of LVDD.[5–7]

With respect to evaluating the importance of right ventricular diastolic dysfunction (RVDD), currently available data are limited. An abnormal hepatic venous flow (HVF) pattern is commonly observed after cardiac surgery[9–12] and may suggest right atrial and ventricular dysfunction. Abnormal HVF, suggesting abnormal right ventricular filling, is the most common diastolic abnormality observed in hemodynamically unstable patients after cardiac surgery.[13] Furthermore, it has been shown that an abnormal preoperative HVF pattern is associated with hemodynamic instability after cardiac surgery.[14] While there are different degrees of LVDD and RVDD,[15] their incidence and prognostic importance related to cardiac surgery have not been established. As assessment of LVDD and RVDD can be complex and particularly challenging in the environment of a busy cardiac operating room, we identified that patients might benefit from adoption of an algorithmic approach to evaluation of their cardiac function. We hypothesized that a simple algorithm can be used to stratify the severity of LVDD and RVDD with good reproducibility, and that diastolic dysfunction (DD) grading of this algorithm as marker of abnormal ventricular filling would be predictive of DSB after cardiac surgery.

Methods

To evaluate the reliability and the prognostic value of a new algorithm for the evaluation of bi-ventricular diastolic function, we performed a study in two phases. In phase I, following approval of the research protocol from the Ethics Institutional Review Board, informed consent was obtained from patients for their participation in a randomized trial evaluating the intraoperative use of amiodarone. For each patient, a transesophageal echocardiography (TEE) examination was performed to determine the reproducibility of an algorithm for assessment of biventricular diastolic function. In phase II, the prognostic significance of this algorithm was tested in a larger cohort of patients (validation group, n = 179) who underwent cardiac surgery during the time period December, 2001 - August, 2003. Written informed consent was obtained from each patient prior to his/her participation in the data-collection process (i.e., before TEE insertion and pulmonary artery catheterization), using the consent form approved by the Research Ethics Committee.

In phase I, patients of either sex undergoing valvular surgery alone or in combination with other types of cardiac surgery were included. The phase II validation group included consecutive male and female patients undergoing elective coronary revascularization, valvular surgery, thoracic aortic surgery, heart transplantation or congenital heart disease surgery. A complex operation was defined as a combination of two or more procedures. Patients were excluded if there were specific contraindications to the use of TEE. Such contraindications included, but were not limited to: esophageal disease, weight < 40 kg or inability to insert the probe. In addition, patients with atrial fibrillation, paced or non-sinus rhythms were excluded from the analysis. Left ventricular diastolic dysfunction was not evaluated in patients with mitral stenosis or severe mitral or aortic regurgitation. Right ventricular diastolic dysfunction evaluation was not performed in the presence of severe tricuspid regurgitation and tricuspid annuloplasty. The evaluation of LVDD and RVDD was also not performed if the

Doppler signals were not obtained, or if the signal quality was judged by the anesthesiologist performing the examination or the reviewer, to be inadequate for interpretation.

The anesthetic management of this population has been described previously[5,14] and was similar for all patients. Patients were monitored with a pulmonary artery catheter, electrocardiogram, pulse oximeter, capnograph and radial artery catheter. A tidal volume of 6–8 $mL \cdot kg^{-1}$ with an appropriate respiratory frequency was set to achieve a $PaCO_2$ of 40 ± 5 mmHg. Anesthesia was induced with sufentanil and midazolam, then maintained with either isoflurane or sevoflurane according to the preference of the attending anesthesiologist. Thereafter, a multiplane TEE probe (Hewlett Packard Sonos 5500, Omniplane 3.5-5.0 MHz, Andover, MA, USA) was inserted. A standard TEE examination (see below) was performed during a period of hemodynamic stability prior to chest opening, before cardiopulmonary bypass (CPB), (during phase I) and again during sternal closure (in phases I and II). Baseline hemodynamic profiles were obtained from a radial artery catheter, a pulmonary artery catheter, and the TEE examination was performed following induction of anesthesia prior to median sternotomy. The following hemodynamic variables were recorded: heart rate, mean arterial pressures (MAP), mean pulmonary artery pressure (MPAP), central venous pressure, pulmonary capillary wedge pressure (PCWP) and cardiac output. Cardiac index (CI) was calculated.

Difficult separation from cardiopulmonary bypass was defined as systolic blood pressure < 80 mmHg confirmed with central measurement (femoral or aortic), in association with either diastolic pulmonary artery pressure or PCWP > 15 mmHg, during progressive weaning from CPB and requiring the use of inotropic or vasopressive support (norepinephrine > 4 $\mu g \cdot min^{-1}$, epinephrine > 2 $\mu g \cdot min^{-1}$, dobutamine > 2 $\mu g \cdot kg^{-1} \cdot min^{-1}$, milrinone bolus > 50 $\mu g \cdot kg^{-1}$, then > 0.5 $\mu g \cdot kg^{-1} \cdot min^{-1}$, intra-aortic balloon pump or mechanical support)[5,13,14] to enable weaning from CPB. The same definition was used for patients in whom off-pump bypass was used and associated with hemodynamic instability at the end of the procedure.

All intraoperative TEE examinations were performed by anesthesiologists with National Board Certification in perioperative echocardiography or more than ten years of experience in TEE. The TEE examination included 2D examination in the mid-esophageal 4-, 2- and long-axis views and transgastric short-axis view at the mid-papillary level, with additional colour flow imaging of the mitral, aortic and tricuspid valves in order to detect any significant valvular abnormality. This was followed by a pulsed-wave Doppler examination of the pulmonary venous flow (PVF) and transmitral flow in the mid-esophageal view at 0°. Mitral annulus interrogation with tissue Doppler imaging (TDI) was performed according to published guidelines.[16]

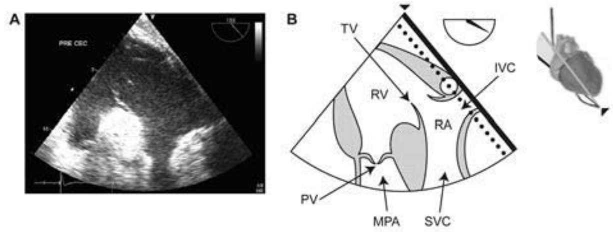

FIGURE 1 A) Deep transgastric right ventricular long axis view. This view allows the evaluation of both the pulsed-wave Doppler interrogation of the tricuspid valve and tissue Doppler imaging of the tricuspid annulus along the dotted line. B) The darker line on the right side of the triangular sketch is matched to the thicker line on the triangular slice of the 3D icon. IVC = inferior vena cava; MPA = mean pulmonary artery; PV = pulmonic valve; RA = right atrium; RV = right ventricle; SVC = superior vena cava; TV = tricuspid valve.

Tissue Doppler interrogation of the mitral annulus can be performed at several sites: antero-lateral at 0°, inferior and anterior at 90° and infero-lateral at 120°. We measured the lateral velocity as it has been shown to be more reproducible.[8] Early mitral annular tissue Doppler velocities (Em) below 8 $cm \cdot sec^{-1}$ are consistent with DD and above 12.5 $cm \cdot sec^{-1}$ are considered normal.[17] However, these values are mostly derived from awake patients undergoing transthoracic echocardiography. Normal values in patients under general anesthesia are unknown. Furthermore, tissue Doppler data is affected by the angle between the moving target and the Doppler beam, which can be quite different between transthoracic and transesophageal examination. This is why 8 $cm \cdot sec^{-1}$ was selected as the cut-off for an abnormal value, but in the algorithm legend a value between 8–12.5 $cm \cdot sec^{-1}$ could be considered within normal range.

The classification of LVDD was based on the Canadian consensus guidelines[18] and the newer criteria.[19] Mild LVDD was defined by E/A (early filling to late or atrial filling ratio) < 1 in transmitral flow, or 1< E/A < 2, with S/D (systolic to diastolic ration) > 1 in PVF and Em < 8 $cm \cdot sec^{-1}$ or Em < Am (atrial component of the mitral annular tissue Doppler velocity). Moderate LVDD was considered present when E/A

> 1 and ≤ 2 with S/D < 1 and Em < 8 cm·sec^{-1}, or Em < Am. Severe LVDD was diagnosed when E/A > 2 with S/D < 1.

The transtricuspid pulsed Doppler flow was obtained from a mid-esophageal view between 40–70°. The transtricuspid Doppler and tricuspid annular velocities were also obtained with a deep transgastric long axis view at 120–145° with right-sided rotation (Figure 1). In this view, the tricuspid annulus interrogation axis is parallel to the Doppler axis. Furthermore, the HVF can be visualized in some patients with this view. A lower esophageal view with right sided rotation was also used to obtain the HVF. Normal right ventricular diastolic function[15] was defined using normal values reported for Doppler transtricuspid flow,[20] HVF[11,21,22] and TDI of the tricuspid annulus.[23,24] A normal HVF was defined as a ratio of systolic to diastolic velocities greater than 1 with the atrial wave reversal less than half the maximum systolic wave velocity.[21] Mild RVDD was defined by E/A < 1 in transtricuspid flow velocities, or 1 < E/A < 2, with S/D > 1 in HVF and Et (early component of the tricuspid annular tissue Doppler velocity) < At (atrial component of the tricuspid annular tissue Doppler velocity) or an atrial reversal wave more than half of the systolic wave of the HVF. Moderate or severe RVDD was present if a reduced or inverted systolic waveform was present on the Doppler HVF signal, respectively.

An algorithm for the evaluation of LVDD and RVDD was established using a consensus between two cardiac anesthesiologists and two cardiologists who were experts in TEE (Figures 2 and 3). The development of the algorithm was based on our previous reports[5,13,14,25,26] and tissue Doppler examinations[19] for the evaluation of DD. In phase I, the Doppler signals obtained intraoperatively from three examinations (two before, and one after CPB) were reviewed and analyzed off-line in a random and blinded fashion, by two anesthesiologists. In phase II, the attending anesthesiologist classified left and right diastolic function on-line, using the algorithm. Two examinations were performed (before and after CPB), but only the pre-CPB or baseline TEE examination (as a predictor of DSB) was entered into the data set for subsequent analysis of DSB. Abnormal diastolic profiles were separated in two groups: normal or relaxation abnormalities were classified as normal to mild DD, pseudonormal, and restrictive patterns were classified as moderate and severe DD.

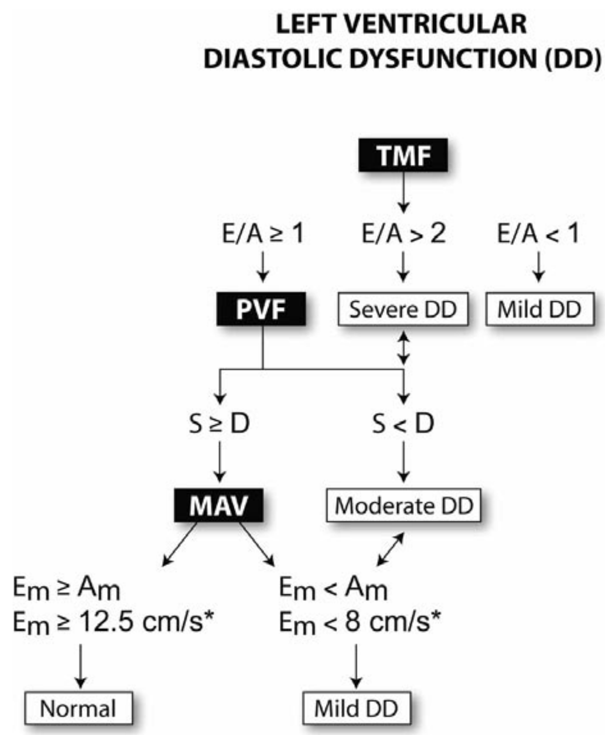

FIGURE 2 Algorithm used in the diagnosis and classification of left ventricular diastolic dysfunction (DD). The diastolic function is classified using pulsed-wave Doppler of the transmitral flow (TMF), pulmonary venous flow (PVF) and tissue Doppler examination of mitral annular velocity (MAV). Patients with pacemaker, atrial fibrillation, non-sinus rhythm, mitral stenosis, severe mitral and aortic insufficiency are excluded from analysis. A = atrial component of the TMF; Am = atrial component of the MAV; D = diastolic component of the PVF; E = early filling of the TMF; Em = early component of the MAV; S = systolic component of the PVF.*Normal Em is within an 8–12.5 cm·sec^{-1} interval (see text).

Statistical analysis

In phase I, agreement on the algorithm between the two cardiac anesthesiologists (A.D., P.C.) was assessed using Cohen's kappa[27] at three time points: before and after chest opening, and after CPB. Values between 0.6 and 1.0 were considered to indicate good agreement, while values from 0.40 to 0.59, 0.2 to 0.39 and 0 to 0.19 defined moderate, fair, and poor agreement respectively. Phase II data are presented as mean ± SD for continuous variables and *n* (percentage) for categorical variables. Pearson Chi-square tests were used to compare categorical variables according to grades (normal-mild *vs* moderate-severe). For continuous variables, a Student's *t* test was used to compare grades (normal-mild *vs* moderate-severe). Sample size was calculated based on the prevalence

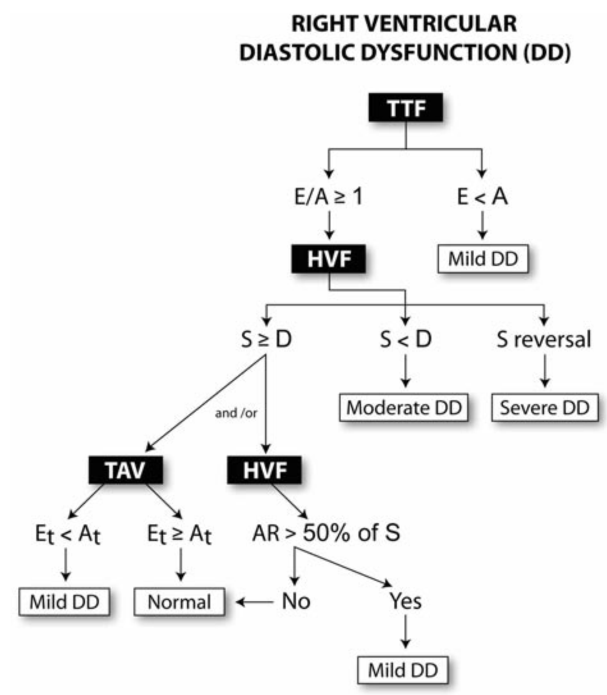

FIGURE 3 Algorithm used in the diagnosis and classification of right ventricular diastolic dysfunction (DD). Diastolic function is classified by pulsed-wave Doppler of the transtricuspid flow (TTF) and hepatic venous flow (HVF) and tissue Doppler imaging of the tricuspid annulus or tricuspid annular velocity (TAV). Patients with pacemaker, atrial fibrillation, non-sinus rhythm, moderate to severe tricuspid regurgitation and tricuspid annuloplasty are excluded from analysis. A = atrial component of the TTF; AR = atrial reversal component of the HVF; At = atrial component of the TAV; D = diastolic component of the HVF; E = early filling of the TTF; Et = early component of the TAV; S = systolic component of the HVF.

LEFT VENTRICULAR DIASTOLIC FUNCTION

		REVIEWER #2			
		Normal or Mild	Moderate or Severe	Non Evaluable	
REVIEWER #1	Normal or Mild	96	0	23	119 (50-37-32)
	Moderate or Severe	1	70	0	71 (23-13-35)
	Non Evaluable	0	0	3	3 (1-1-1)
		97 (46-28-23)	70 (23-12-35)	26 (5-11-10)	193

FIGURE 4 Pooled analysis of left ventricular diastolic function evaluation between reviewers #1 and #2 for phase I of the study. The numbers in parentheses indicate the measurements done during three periods: before chest opening, before cardiopulmonary bypass (CPB) and after CPB.

of DSB observed in previous studies.[5,14] For LVDD, a two-group χ^2 test with a two-sided significance level of 0.05 would achieve 66% power to detect a difference between a group 1 proportion, π_1, of 0.409 and a group 2 proportion, π_2, of 0.655 (odds ratio of 2.743) when the sample sizes are 115 and 29, respectively (a total sample size of 144). For RVDD, a two-group χ^2 test with a 0.05 two-sided significance level would have 50% power to detect a difference between a group 1 proportion, π_1, of 0.476 and a group 2 proportion, π_2, of 0.722 (odds ratio of 2.859) when sample sizes are 145 and 18, respectively (a total sample size of 163). Statistical analyses were done with SAS version 8.02 (SAS Institute Inc., Cary, NC, USA). A P value < 0.05 (two tailed) was considered significant.

Results

Phase I

Seventy-four patients were studied including 43 men and 31 women with a mean age of 67 ± 11 years. A total of 50 isolated valvular surgeries and 24 combined valvular and revascularization procedures were performed. The valvular surgical procedures consisted of 53 aortic valve surgeries, 22 mitral valve surgeries and one tricuspid valve annuloplasty. Twenty-nine measurements for LVDD were excluded because the Doppler signals could not be obtained. The LVDD algorithm was used to evaluate 193 measurements (74, 51 and 68 patients for the three evaluation time points: before chest opening, after chest opening and after CPB respectively). The kappa values were 0.82, 0.57 and 0.77. Fifty measurements for RVDD were excluded for the same reasons as mentioned above. The RVDD algorithm was used to evaluate 182 measurements (70, 52 and 60 patients for the three evaluation time points). The kappa values were 0.69, 0.82 and 0.91. When the three evaluation time points

RIGHT VENTRICULAR DIASTOLIC FUNCTION

REVIEWER #1 \ REVIEWER #2	Normal or Mild	Moderate or Severe	Non Evaluable	
Normal or Mild	81	0	19	100 (59-37-4)
Moderate or Severe	0	78	0	78 (10-15-53)
Non Evaluable	0	0	4	4 (1-0-3)
	81 (48-32-1)	78 (10-15-53)	23 (12-5-6)	182

FIGURE 5 Pooled analysis of right ventricular diastolic function evaluation between reviewers #1 and #2. The numbers in parentheses indicate the measurements done during three periods: before chest opening, before cardiopulmonary bypass (CPB) and after CPB.

were pooled, the LVDD and RVDD algorithm kappa values were 0.77 and 0.82. In the evaluation of LVDD 26/193 (13%) and 3/193 (1.6%) time points were respectively excluded by reviewers #1 and #2 because the Doppler signals were insufficient or of unacceptable quality (Figure 4). In the evaluation of RVDD 23/182 (13%) and 4/182 (2%) time points were excluded by reviewers #1 and #2 (Figure 5).

Phase II: validation group

One hundred seventy-nine patients were studied, including 57 women and 122 men with a mean age of 67 ± 10 yr (Table I). Coronary revascularization procedures were performed in 129 patients, of which 23 were done off-pump. There were seven re-operations, 42 complex procedures, with 54 aortic, nine mitral and three pulmonic valve replacements as well as 19 mitral valve repairs, four thoracic aortic surgeries, one cardiac transplantation, closure of five atrial septal defects, and one ventricular septal defect. Of the 179 patients, 35 (20%) and 16 (9%) patients were respectively excluded from the analysis of left and right ventricular diastolic function using the pre-specified exclusion criteria.

The hemodynamic values and outcome data are shown in Table II. Patients with moderate to severe LVDD at baseline tended to have higher PCWP (15 ± 5 mmHg *vs* 13 ± 4 mmHg, $P = 0.0597$) compared to those with normal to mild LVDD. The presence of moderate to severe RVDD at baseline was also associated with lower MPAP (19 ± 6 mmHg *vs* 22 ± 6, $P = 0.0551$) and lower CI (1.8 ± 0.4 *vs* 2.0 ± 0.4, $P = 0.0458$) compared to patients with normal to mild RVDD. Patients with moderate to severe LVDD and RVDD tended to have longer intensive care unit and hospital stays but this did not reach statistical significance (Table II). There were five (2.8%) deaths and no difference between groups was observed. Difficult separation from cardiopulmonary bypass was observed in 92 patients (51.4%) and was more frequent in patients with moderate to severe LVDD and RVDD. Difficult separation from cardiopulmonary bypass was present in 19 patients (65.5%) with moderate or severe LVDD compared with 47 patients (40.9%) with normal left ventricular diastolic function or mild LVDD ($P = 0.0173$). Difficult separation from cardiopulmonary bypass was also observed in the 13 (72%) patients with moderate to severe RVDD compared with the 69 patients (48%) who had normal right ventricular diastolic function or mild RVDD ($P = 0.0486$).

Discussion

The algorithms proposed in this study for the assessment of left and right ventricular diastolic function are simple, while their application is reproducible and useful in the stratification of patients at risk of developing DSB. In this discussion, we will first analyze the technical aspects of the echocardiographic evaluation of LVDD and RVDD and then present the clinical implications of this study along with its limitations. Obtaining the echocardiographic signals for the evaluation of diastolic function using TEE is relatively easy and its interpretation is reproducible. Available data were considered adequate to classify LVDD and RVDD in the majority of patients. One reviewer consistently excluded more time points than the other; however, these patients were classified as normal by the other reviewer. In addition, the identification of moderate and severe LVDD and RVDD was almost identical for both reviewers and this population could represent the most important group at risk for DSB.[6,7]

In a multivariate analysis, we have previously observed that LVDD was a better predictor of hemodynamic instability after cardiac surgery compared to systolic dysfunction.[5] However in that study, patients were not graded according to the severity of DD. Moreover, newer modalities such as tissue Doppler were not used at that time. Two groups[6,7] have recently observed that more severe forms of LVDD

TABLE I Diastolic function and demographic data

	n (179)	Left ventricular diastolic function Normal-mild LVDD (n = 115)	Moderate-severe LVDD (n = 29)	NE (n = 35)	Right ventricular diastolic function Normal-mild RVDD (n = 145)	Moderate-severe RVDD (n = 18)	NE (n = 16)
Sex (%) F	57	34 (60)	8 (14)	15 (26)	44 (77)	5 (9)	8 (14)
M	122	81 (67)	21 (17)	20 (16)	101 (83)	13 (11)	8 (6)
Age (yr)	67 ± 11	68 ± 11	65 ± 10	65 ± 11	67 ± 10	65 ± 12	68±12
Procedures (%)							
CABG	106	71 (67)	16 (15)	19 (18)	87 (82)	10 (9)	9 (8)
OPCABG	23	18 (78)	5 (22)	0 (0)	22 (96)	1 (4)	0 (0)
Re-operations	7	2 (29)	1 (14)	4 (57)	3 (43)	1 (14)	3 (43)
Complex*	42	19 (45)	4 (10)	19 (45)	33 (78)	2 (5)	7 (17)
AVR	54	38 (70)	7 (13)	9 (17)	44 (81)	3 (6)	7 (13)
MVR	9	1 (11)	0 (0)	8 (89)	6 (67)	0 (0)	3 (33)
PVR	3	1 (33)	1 (33)	1 (33)	1 (33)	1 (33)	1 (33)
Heart transplantation	1	0 (0)	0 (0)	1 (100)	0 (0)	1 (100)	0 (0)
ASD	5	2 (40)	1 (20)	2 (40)	4 (80)	1 (20)	0 (0)
VSD	1	1 (100)	0 (0)	0 (0)	1 (100)	0 (0)	0 (0)
MV repair	19	0 (0)	0 (0)	19 (100)	14 (74)	1 (5)	4 (21)
Aortic surgery	4	2 (50)	2 (50)	0 (0)	2 (50)	2 (50)	0 (0)

ASD = atrial septal defect; AVR = aortic valve replacement; CABG = coronary artery bypass graft; DSB = difficult separation from bypass; LVDD = left ventricular diastolic dysfunction; MV = mitral valve; MVR = mitral valve replacement; NE = not-evaluable using exclusion criteria; OPCABG = off-pump coronary artery bypass graft; PVR = pulmonic valve replacement; RVDD = right ventricular diastolic dysfunction; VSD = ventricular septal defect. *Complex surgeries = defined as a combination of revascularization and valvular surgery.

TABLE II Diastolic function and hemodynamic data before CPB and outcome data after surgery

	Left ventricular diastolic function Normal-mild LVDD (n = 115)	Moderate-severe LVDD (n = 29)	NE (n = 35)	Right ventricular diastolic function Normal-mild RVDD (n = 145)	Moderate-severe RVDD (n = 18)	NE (n = 16)
HR (beats·min^{-1})	54 ± 10	53 ± 11	63 ± 16	55 ± 11	58 ± 14	64 ± 18
CVP (mmHg)	11 ± 4	12 ± 5	11 ± 5	11 ± 4	11 ± 5	12 ± 5
PCWP (mmHg)	13 ± 4	15 ± 5*	15 ± 6	14 ± 4	12 ± 5	16 ± 6
MAP (mmHg)	77 ± 12	74 ± 12	72 ± 11	76 ± 12	74 ± 13	73 ± 12
MPAP (mmHg)	21 ± 5	23 ± 7	25 ± 10	22 ± 6	19 ± 6**	26 ± 10
CI (L·min^{-1}·m^{-2})	2.0 ± 0.5	2.0 ± 0.4	2.0 ± 0.5	2.0 ± 0.4	1.8 ± 0.4&	1.9 ± 0.6
ICU length of stay (days)	3.1 ± 4.6	3.2 ± 5.2	4.0 ± 4.3	2.9 ± 4.1	4.1 ± 7.2	5.6 ± 5.3
Hospitalization duration (days)	7.4 ± 6.5	8.7 ± 9.8	9.1 ± 6.0	7.5 ± 6.2	10.1 ± 12.1	10.3± 6.7
Mortality *n* (%)	4 (3.5%)	1 (3.4%)	0	5 (3.4%)	0	0
DSB *n* (%)	47 (41%)	19 (66%)†	26 (74%)	69 (48%)	13 (72%)#	10(63%)

CI = cardiac index; CPB = cardiopulmonary bypass; CVP = central venous pressure; DSB = difficult separation from bypass; HR = heart rate; ICU = intensive care unit; LVDD = left ventricular diastolic dysfunction; MAP = mean arterial pressure; MPAP = mean pulmonary arterial pressure; PCWP = pulmonary capillary wedge pressure; RVDD = right ventricular diastolic dysfunction. *P = 0.0597 comparing normal-mild *vs* moderate-severe LVDD; **P = 0.0551 comparing normal-mild *vs* moderate-severe RVDD; &P = 0.0458 comparing normal-mild *vs* moderate-severe RVDD; †P = 0.0173 comparing normal-mild *vs* moderate-severe LVDD; #P = 0.0486 comparing normal-mild *vs* moderate-severe RVDD.

are associated with complications after cardiac surgery. This is consistent with our clinical observations and with large population studies in cardiology[28] showing the relationship between LVDD and outcomes.

Right ventricular diastolic dysfunction could represent an additional marker to identify populations at higher risk of requiring vasoactive support and potentially other adverse clinical outcomes. We have previously documented that in hemodynamically unstable patients in the intensive care unit, abnormal right ventricular filling abnormalities were the most common echocardiographic observation.[13] We also noted in a pilot study that abnormal HVF, when present before cardiac surgery, was associated with increased need for vasoactive support after cardiac surgery.[14] Again, in these two previous studies, patients were not graded according to the severity of RVDD whereas in the present study we confirm that moderate to severe RVDD is associated with lower CI and increased risk of DSB.

In this study, normal (n = 33) to mild RVDD (n = 112) was present in 145 patients (81%), moderate to severe RVDD existed in 18 patients (10%) whereas RVDD function was not evaluable in 16 patients (9%). The overall incidence of RVDD was 74%, which is higher than that reported by Mishra who observed abnormal HVF in 11% of patients undergoing coronary revascularization.[29] We have previously observed that abnormal HVF suggestive of RVDD is less common in patients undergoing coronary revascularization as compared to valvular surgery, and reported the presence of abnormal HVF in 41% of patients undergoing valvular surgery[14] (including mild, moderate and severe RVDD). The higher percentage of patients with RVDD in the current study is most likely related to the use of tissue Doppler which provided for greater sensitivity in detection of mild RVDD. This echocardiographic modality was not available in the previous study.[14] The elevated incidence of RVDD in patients with valvular disease may reflect maladaptation to pulmonary hypertension, which is frequently present in this population. This factor alone could explain why DSB was more frequently observed in patients with abnormal RVDD as our pilot study suggested. Interestingly, in the present study, CI was lower in patients with moderate to severe RVDD whereas MPAP was not "abnormally elevated". The absence of an observed association between pulmonary hypertension and moderate to severe RVDD may be related to the large number of patients who underwent coronary artery bypass grafting in the current series, in contrast to the Carricart study[14] where only valvular surgical patients were selected.

There are several limitations to this study. First, we grouped LVDD into two categories instead of the four standard grades. This grouping was necessary for the analysis because a left ventricular restrictive pattern is uncommon before surgery. We observed that restrictive LVDD was indeed present in two patients (1%) in the phase II validation group and in six patients (1.2%) in our TEE database of 500 consecutive patients. The same observations applied to RVDD where a restrictive pattern was also present in only two patients (1%) in the phase II validation group. It would have been futile to have enrolled the large number of patients that would have been necessary to evaluate the independent significance of restrictive LVDD and RVDD on our primary outcome of interest. Mild RVDD, on the other hand, is relatively common, and was observed in the majority of our population (81%) since we began incorporation of tissue Doppler evaluation of our cardiac surgery patients.

The primary goal of the study was to develop and validate a simple algorithm of diastolic dysfunction and explore its predictive value with respect to difficulty in weaning from cardiopulmonary bypass. This is why a phase II validation group was used with DSB as a primary end-point. This study represents the largest published series of patients in whom biventricular diastolic function was assessed in the cardiac surgical setting using the newer Doppler modalities and where the results were also correlated with hemodynamic data. We observed an association between moderate to severe LVDD and RVDD and DSB. However, the number of patients with these diastolic filling abnormalities was insufficient to subject to a multivariable analysis. The relative importance of DD compared to other variables in relation to DSB and mortality should be investigated in a larger population of cardiac surgery patients. The results from the present study are consistent with our earlier work which demonstrated that both abnormal left[5] and right[13,14] ventricular diastolic profiles are associated with hemodynamic instability.

The two anesthesiologists responsible for clinical management of the study patients were not blinded to the echocardiographic data for ethical and practical reasons, and this generates potential for some bias. However, intraoperative anesthetic management was directed towards maintenance of adequate MAP rather than optimization of diastolic parameters and ventricular filling patterns. We also identify that evaluation of LVDD and RVDD is not possible in up to 10–20% of cardiac surgical patients for several reasons including rhythm abnormality, severe valvular disease, and inability to obtain a complete set of Doppler images. Finally, several diastolic parameters change with increasing age, including mitral and tricuspid annular velocities,[30] and the algorithm was not age-adjusted accordingly for the sake of simplification. However, as most age-related changes in ventricular function involve relaxation abnormalities, patients with normal function and mild diastolic abnormalities were analyzed together, which would have minimized the potential confounding influence of age-related differences in cardiac function.

In summary, the severity of LVDD and RVDD can be determined before cardiac surgery using a simple algorithm. Moderate to severe LVDD and RVDD are associated with a greater risk of DSB and with greater hemodynamic abnormalities. Further multicentre studies with larger populations will be necessary to explore the value of the identification of LVDD and RVDD and the therapeutic implications of incorporating this information into the routine perioperative management of cardiac surgery patients.

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