CLINICAL RESEARCH

Echocardiographic assessment of right ventricular systolic function in a population of unselected patients before cardiac surgery: A multiparametric approach is necessary

Évaluation échographique de la fonction systolique ventriculaire droite dans une population de patients non sélectionnés avant chirurgie cardiaque: une approche multiparamétrique est nécessaire

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Received 6 April 2014; received in revised form 16 June 2014; accepted 20 June 2014
Available online 11 September 2014

KEYWORDS
Right ventricular function;

Summary
Background. — According to recent USA guidelines, right ventricular (RV) dysfunction can be diagnosed on the basis of a single parameter, such as tricuspid lateral annular systolic velocity (S') < 10 cm/s or RV fractional area change (RVFAC) < 35%.

Abbreviations: ASE, American Society of Echocardiography; AT, Acceleration time; AUC, Area under the curve; IVA, Isovolumic acceleration; IVC, Inferior vena cava; IVRT, Isovolumic relaxation time; IVV, Peak isovolumic velocity; MRI, Magnetic resonance imaging; PVR, Pulmonary vascular resistance; RA, Right atrial; RMPI, Right myocardial performance index; RV, Right ventricle/ventricular; RVEF, Right ventricular ejection fraction; RVFAC, Right ventricular fractional area change; RVOT, Right ventricular outflow tract; S', Doppler-derived tricuspid lateral annular systolic velocity; SPAP, Systolic pulmonary artery pressure; TAPSE, Tricuspid annular plane systolic excursion; TDI, Tissue Doppler Imaging; TR, Tricuspid regurgitation; TVI, Time velocity integral.

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http://dx.doi.org/10.1016/j.acvd.2014.06.007
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Right ventricle fractional area change; 2D strain; Isovolumic acceleration; Right myocardial performance index

**Aims.** — To assess these recommendations in a large unselected cohort of patients awaiting cardiac surgery and evaluate less validated RV function criteria.

**Methods.** — Among the consecutive patients, 413 were prospectively enrolled and underwent comprehensive echocardiography, including $S'$, RVFAC and other RV parameters (right myocardial performance index; acceleration time, isovolumic velocity and isovolumic acceleration [IVA]; RV dp/dt; isovolumic relaxation time; two-dimensional [2D] strain). We defined subgroups of highly probable RV dysfunction ($S' < 10 \text{ cm/s}$ and RVFAC $< 35\%$) and highly probable normal RV function ($S' \geq 10 \text{ cm/s}$ and RVFAC $\geq 35\%$) as reference groups. Indices of preload and afterload were also recorded.

**Results.** — Of 413 patients, 320 (77.5\%) had normal RV function. In 93 patients, $S'$ and/or RVFAC were abnormal; both were abnormal in 39 (42\%) patients. Using our reference groups, IVA $\leq 1.8 \text{ m/s}^2$ and basal 2D strain $\geq 17\%$ were of most value in diagnosing RV dysfunction. IVA was least load dependent while basal 2D strain appeared to be afterload and preload dependent.

**Conclusion.** — In this large population, $S'$ and RVFAC were sometimes discrepant, supporting the need for a multiparametric approach when evaluating RV function. Among seven less validated criteria, IVA and 2D strain had the best diagnostic value. Unlike 2D strain, IVA was not influenced by loading conditions.

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**Background**

Right ventricular (RV) systolic dysfunction has long been recognized as being of prognostic value in various pathological conditions. However, the definition of RV dysfunction using echocardiography has evolved significantly in recent years. In the past, RV function was assessed visually, until studies focusing on tricuspid annular displacement demonstrated convincing results [1,2]. Since then, numerous echocardiography-Doppler criteria have been proposed and clinical guidelines were published recently by the American Society of Echocardiography (ASE) [3]. The guidelines recommend performing and reporting at least one of the following: RV fractional area change (RVFAC); Doppler-derived tricuspid lateral annular systolic velocity ($S'$); tricuspid annular plane systolic excursion (TAPSE); and right myocardial performance index (RMIPI). Among these criteria, abnormal RV function should be suspected when $S'$ is $< 10 \text{ cm/s}$, TAPSE is $< 16 \text{ mm}$, RVFAC is $< 35\%$ or RMIPI (tissue Doppler) is $> 0.55$. As proposed by the ASE guidelines,

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**MOTS CLÉS**

Fonction ventriculaire droite; Fraction de raccourcissement de surface du ventricule droit; 2D strain; Accélération de la contraction isovolumique; Indice de Tei

**Résumé**

**Contexte.** — Les récentes recommandations américaines proposent de diagnostiquer la dysfonction ventriculaire droite (VD) sur au moins un critère validé tel que le pic de vitesse systolique annulaire tricuspid ($S'$) $< 10 \text{ cm/s}$ ou la fraction de raccourcissement de surface VD (FRSVD) $< 35\%$.

**Objectifs.** — Le but de notre étude a été d’évaluer ces recommandations sur une large population de patients non sélectionnés en attente de chirurgie cardiaque, et d’évaluer d’autres indices de fonction VD moins validés.

**Méthodes.** — Parmi les patients, 413 ont bénéficié d’un examen échocardiographique complet incluant $S'$, FRSVD et d’autres paramètres VD non routiniers: indice de Tei, dp/dt; temps de relaxation isovolumique; temps d’accélération, vitesse de la contraction isovolumique et accélération de la contraction isovolumique (IVA); 2D strain. Nous avons défini un sous-groupe de patients ayant une forte probabilité de fonction VD normale ($S' \geq 10 \text{ cm/s}$ et FRSVD $\geq 35\%$) et un sous-groupe ayant une forte probabilité de fonction VD ($S' < 10 \text{ cm/s}$ et FRSVD $< 35\%$) comme nos groupes de référence. Les indices de pré- et post-chARGE ont également été recueillis.

**Résultats.** — Parmi les 413 patients, 320 (77,5\%) patients ont une fonction VD très probablement normale ($S'$ et FRSVD normaux). Chez 93 patients, $S'$ et/ou FRSVD sont anormaux mais seuls 39 (42\%) patients ont les 2 critères simultanément pathologiques. En utilisant nos groupes de référence, l’IVA $\leq 1.8 \text{ m/s}^2$ et le 2D strain basal $\geq 17\%$ ont la meilleure valeur diagnostique pour détecter une dysfonction VD. De plus, l’IVA est indépendante des conditions de charge alors que le 2D strain est pré- et post-chARGE dépendant.

**Conclusion.** — Dans cette large population, $S'$ et FRSVD sont parfois discordants soulignant la nécessité d’une approche multiparamétrique pour évaluer la fonction VD. Parmi 7 nouveaux paramètres, l’IVA et le 2D strain basalt ont la meilleure valeur diagnostique. Contrairement au 2D strain, l’IVA reste indépendante des conditions de charge.

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‘combining more than one measure of RV function may more reliably distinguish normal from abnormal function’. Various combinations are possible, such as S’ and RV FAC [4]; however, on the basis of the quality of validation [3], the combination of RV FAC with S’ is probably the best.

Interestingly, criteria evaluating RV function based on various physiological approaches are available, such as isovolumic acceleration (IVA; derived from peak isovolumic velocity [IVV] and acceleration time [AT]), RV dp/dt or two-dimensional (2D) peak longitudinal strain. However, normality thresholds are not yet available or are not fully validated. In addition, RV FAC using tissue Doppler has been validated less.

The aim of the present study was: to describe the distribution of well-validated criteria (S’, RV FAC) in routine clinical practice; to evaluate the diagnostic value of less validated echocardiographic parameters (RV FAC using tissue Doppler, IVA, RV dp/dt and 2D peak longitudinal strain); and to study the influence of loading conditions, as measured by echocardiography, on each parameter.

Methods

Study population

The study group consisted of 422 patients recruited in the Department of Cardiology and Cardiac Surgery at the Clinique Saint-Augustin (Bordeaux, France). This prospective study enrolled patients awaiting cardiac surgery over a 5-month period.

Nine patients (2.1%) were excluded from all subsequent analyses because of inability to record RV FAC or S’; accordingly, data from 413 patients were analysed.

Using recently published ASE guideline thresholds [3], patients were split into three groups. Group 1 included those with highly probable normal RV function defined by S’ ≥10 cm/s and RV FAC ≥35%. Group 2 involved those with probable RV dysfunction defined by the presence of one of two criteria: S’ <10 cm/s or RV FAC <35%. Group 3 included patients with highly probable RV dysfunction defined by the presence of two criteria: S’ <10 cm/s and RV FAC <35%. To test other RV function parameters, groups 1 and 3 only were used, due to the high certainty of RV function assessment in these groups (normal or abnormal).

The local ethics committee (CPP-SOO3, University of Bordeaux 2, France) approved the study protocol and all included patients gave their consent.

Echocardiographic studies

Echocardiographic studies were performed on a Vivid7 or a VividE9 ultrasound system (GE Vingmed Ultrasound SA, Horten, Norway) equipped with multifrequency transducers (1.5–4 MHz). All examinations were performed by experienced sonographers, according to ASE guidelines [3,5] the day before the surgical procedure, and were stored on a digital workstation for subsequent off-line analysis (EchoPAC PC, GE Vingmed Ultrasound SA, Horten, Norway).

Echocardiographic measurements of right ventricular systolic function

A modified apical four-chamber view focused on the right ventricle (RV) was used to measure RV area, by tracing the RV endocardium both in systole and diastole [3]. RV FAC (%) was defined as ((end-diastolic RV area — end-systolic RV area) / end-diastolic RV area) × 100 [6,7].

All measurements using pulsed-wave tissue Doppler imaging (TDI) (Fig. 1) were performed in a four-chamber view focused on the RV using a tissue Doppler mode with a pulsed-wave Doppler sample volume placed in the basal segment of the RV free wall. Special care was taken to ensure optimal image orientation, to avoid underestimation of velocities. The following data were obtained: S’ was defined as the peak longitudinal velocity of the basal RV free wall [2,8]; isovolumic relaxation time (IVRT) was defined as the time from the end of the ejection period (S’) to the beginning of tricuspid e’ wave; RV FAC obtained by the TDI method (pulsed-wave velocity of the tricuspid annulus) was defined as the ratio of the sum of IVRT and isovolumic contraction time divided by ejection time (S’ duration) [9]; IVA (m/s²) was defined as the IVV divided by the time interval from onset of the isovolumic wave to its peak velocity (acceleration time [AT]) [10].

RV dp/dt (mmHg/s) was calculated by measuring the time required for the tricuspid regurgitation (TR) continuous-wave Doppler signal to increase in velocity from 0.5 to 2 m/s [11]. Using the simplified Bernoulli equation, dp/dt was calculated as 15 mmHg divided by this time.

An apical four-chamber view used for 2D strain analysis was obtained using second-harmonic imaging, with frequency, depth and sector width adjusted for frame-rate optimization (60–100/s). All parameters were averaged over three consecutive beats. In postprocessing analysis, the region of interest was obtained by tracing the RV endocardial borders at the level of the basal septum, the apex and the basal free wall at end-systole. However, from this tracing, we limited our analysis to the basal segment for two main reasons: strain measurement reproducibility of the basal segment is better than that of the apical segment [12], related to a poorer quality image; regional afterload heterogeneity leads to conflicting data between basal and apical 2D strain [13,14]. The longitudinal myocardial deformation (defined as the peak longitudinal systolic strain) was expressed as a percentage of the longitudinal shortening of basal segment in systole compared with in diastole.

Echocardiographic measurements of right ventricular end-diastolic area

RV preload assessment included end-diastolic RV area and inferior vena cava (IVC) maximal and minimal diameters obtained from a subcostal view at end-expiration, after sniff test and quiet breathing. The IVC collapse index (%) was defined as [(maximal IVC – minimal IVC) / maximal IVC] × 100. Maximal IVC diameter and collapse index were used to assess preload according to the ASE guidelines [3,15]. Normal right atrial (RA) pressure (3 mmHg) was defined by an IVC diameter < 2.1 cm and a collapse > 50%, whereas an IVC diameter > 2.1 cm that collapsed by < 50%
suggested high RA pressure (15 mmHg). RA area [16] was measured at end-systole (four-chamber view).

RV afterload assessment included the following:
- systolic pulmonary artery pressure (SPAP) was determined from peak TR velocity using the simplified Bernoulli equation and combined with an estimated RA pressure (based on the IVC collapse index);
- pulmonary vascular resistance (PVR) was estimated using peak TR velocity and RV outflow tract (RVOT) time velocity integral (TVI) – the formula published by Abbas et al. [17] was applied, i.e. 
  
PVR = (peak TR velocity / RVOT TVI) \times 10 + 0.16;
- pulmonary AT derived from pulsed-wave Doppler recordings was defined as the time interval from onset of the RVOT anterograde flow to its peak velocity.

Reproducibility

Twenty-five data sets were chosen randomly to assess intraobserver variability by repeating measurements 4 weeks apart (J. Peyrou). Interobserver agreement was assessed by a second observer (M. Simon) using the same data sets.

Statistical analyses

Continuous data are expressed as means ± standard deviations and discrete parameters as absolute numbers and percentages. The groups were tested using a Chi² test to compare categorical parameters. The clinical and echocardiographical data from the patients’ group were compared using the two-sample Student’s t test or Wilcoxon’s rank sum (Mann-Whitney) non-parametric test, as appropriate, according to the variance R test. The relationships between additional parameters (RMPI, dP/dt, IVRT, IVV, AT, IVA, basal 2D strain) and the validated criteria of RV function (S’ and RVFAC) as well as the load dependency of parameters were tested by means of Pearson’s correlation. Receiver operating characteristic curve analysis was performed to test the diagnostic accuracy for discrimination between patients with RV dysfunction (group of patients with high probability of RV dysfunction) and those with normal RV function, and to determine optimal cut-off values. Intraobserver and interobserver reproducibility were analysed using the Pearson correlation coefficient, the concordance correlation coefficient according to the Lin method and the coefficient of variability. All P values were two-sided and values < 0.05 were considered statistically significant. All statistical analyses were performed using Stata software version 11.0 (StataCorp LP, College Station, TX, USA).

Results

Patient characteristics

Four-hundred and thirteen patients (mean age 70.3 ± 10.3 years) were enrolled, of whom 63% were awaiting valve surgery, 49% coronary artery bypass grafting and 3% other cardiac surgery (myxoma resection, atrial septal defect closure, pericardectomy, aortic dissection repair, coarctation repair). Thirty-four patients (8%) had chronic atrial fibrillation. Table 1 shows patients’ characteristics in each group.

Age, sex, blood pressure and cardiovascular risk factors did not differ significantly between normal and RV dysfunction groups. Compared with normal subjects (group 1), patients with probable or highly probable RV dysfunction (groups 2 and 3) had a lower left ventricular...
Table 1  Characteristics of patient groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1 (normal RV function) (n = 320)</th>
<th>Group 2 (probable RV dysfunction) (n = 54)</th>
<th>Group 3 (highly probable RV dysfunction) (n = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex-ratio</td>
<td>2.42</td>
<td>2.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Age (years)</td>
<td>70 ± 10.3</td>
<td>72 ± 9.1</td>
<td>71.5 ± 10.7</td>
</tr>
<tr>
<td>Cardiovascular risk factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypertension</td>
<td>215 (67.2)</td>
<td>30 (55.5)</td>
<td>22 (56.4)</td>
</tr>
<tr>
<td>Dyslipidaemia</td>
<td>205 (64.1)</td>
<td>33 (61.1)</td>
<td>19 (48.7)</td>
</tr>
<tr>
<td>Overweight (BMI &gt; 25 kg/m²)</td>
<td>193 (60.3)</td>
<td>30 (55.5)</td>
<td>24 (61.5)</td>
</tr>
<tr>
<td>Tobacco use</td>
<td>105 (32.8)</td>
<td>16 (29.6)</td>
<td>14 (35.9)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>598 (18.7)</td>
<td>12 (22.2)</td>
<td>7 (17.9)</td>
</tr>
<tr>
<td>Familial history</td>
<td>23 (7.1)</td>
<td>5 (9.3)</td>
<td>3 (7.7)</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACEls/ARBs</td>
<td>173 (54.1)</td>
<td>29 (53.7)</td>
<td>21 (53.8)</td>
</tr>
<tr>
<td>Diuretics</td>
<td>115 (35.9)</td>
<td>26 (48.1)a</td>
<td>24 (61.5)a</td>
</tr>
<tr>
<td>Beta-blockers</td>
<td>135 (42.2)</td>
<td>28 (51.8)</td>
<td>22 (56.4)</td>
</tr>
<tr>
<td>Calcium channel blockers</td>
<td>80 (25.0)</td>
<td>6 (11.1)a</td>
<td>6 (15.4)</td>
</tr>
<tr>
<td>Statins</td>
<td>217 (67.8)</td>
<td>34 (63.0)</td>
<td>23 (59.0)</td>
</tr>
<tr>
<td>Platelet inhibitors</td>
<td>188 (58.7)</td>
<td>28 (51.8)</td>
<td>22 (56.4)</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>168 (52.5)</td>
<td>22 (40.7)</td>
<td>22 (56.4)</td>
</tr>
<tr>
<td>Severe valvular heart disease</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aortic stenosis</td>
<td>142 (44.4)</td>
<td>23 (42.6)</td>
<td>18 (46.1)</td>
</tr>
<tr>
<td>Aortic regurgitation</td>
<td>12 (3.7)</td>
<td>1 (1.9)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Mitral stenosis</td>
<td>11 (3.4)</td>
<td>2 (3.7)</td>
<td>1 (2.5)</td>
</tr>
<tr>
<td>Mitral regurgitation</td>
<td>25 (7.8)</td>
<td>15 (27.8)a</td>
<td>3 (7.7)</td>
</tr>
<tr>
<td>Main surgical procedures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CABG</td>
<td>168 (52.5)</td>
<td>22 (40.7)</td>
<td>14 (35.9)</td>
</tr>
<tr>
<td>Valve replacement</td>
<td>182 (56.9)</td>
<td>32 (59.2)</td>
<td>17 (43.6)</td>
</tr>
<tr>
<td>Valve repair</td>
<td>23 (7.2)</td>
<td>12 (22.2)a</td>
<td>2 (5.1)</td>
</tr>
<tr>
<td>AAA repair</td>
<td>36 (11.2)</td>
<td>5 (9.2)</td>
<td>2 (5.1)</td>
</tr>
</tbody>
</table>

Data are presented as ratio, mean ± standard deviation or number (%). AAA: ascending aortic aneurysm. ACEI: angiotensin-converting enzyme inhibitor; ARB: angiotensin receptor blocker; BMI: body mass index; CABG: coronary artery bypass graft; RV: right ventricular. a Only significant P values (<0.05) are indicated, comparing RV dysfunction groups (group 2 or 3) with normal subjects (group 1).

Ejection fraction (65.2 ± 11.3%, 59.9 ± 13.9% and 50.8 ± 17.3%, respectively; P < 0.001) and a higher SPAP (36.6 ± 12.2%, 45.9 ± 19.2% and 53.8 ± 21.9%, respectively; P < 0.001).

Right ventricular function parameters

Of 413 patients, 320 (77.5%) had normal RV function (group 1: S’ ≥ 10 cm/s and RVFAC ≥ 35%) and 93 patients (22.5%) had suspected RV dysfunction (S’ < 10 cm/s and/or RVFAC < 35%). Among these 93 patients, 54 (58%) had a discrepancy between indices, suggesting probable RV dysfunction (group 2: S’ < 10 cm/s but RVFAC ≥ 35% or S’ ≥ 10 cm/s but RVFAC < 35%) and 39 patients had concordant indices suggesting highly probable RV dysfunction (group 3: S’ < 10 cm/s and RVFAC < 35%).

As shown in Table 2, RMPI, IVRT, IVV, IVA and basal 2D strain were statistically different between patients with normal RV function and patients with probable (group 2) or highly probable (group 3) RV dysfunction. dP/dt and AT were not statistically different.

Receiver operating characteristic curve analysis was performed to calculate the best cut-off value to predict RV systolic dysfunction (Table 3, Fig. 2). The best parameters for predicting RV systolic dysfunction were basal 2D strain and IVA. The sensitivity of these parameters was similar (86%) while specificity was higher for basal 2D strain (98%). When patients with atrial fibrillation (34 patients) were excluded, the statistical analysis did not change significantly.

Correlation analyses between right ventricular function parameters and loading conditions

Tables 4 and 5 highlight the relationship between RV function parameters and loading conditions. IVA correlated neither with RV preload nor with RV afterload indices. Basal 2D strain correlated with all RV preload...
parameters and with PVR. There was a significant positive correlation between IVRT and RA area but not with other preload parameters. IVRT was also correlated with RV afterload parameters, such as SPAP and PVR.

Feasibility

RV function parameters

The feasibilities of S' and RVFAC were 99.3% and 98%, respectively (S' could not be evaluated in three patients due to...
Echocardiographic assessment of right ventricular systolic function

Table 5 Correlation between Doppler-derived tricuspid lateral annular systolic velocity, right ventricular fractional area change, age and right ventricular loading conditions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>S’ (n = 410)</th>
<th>RVFAC (n = 405)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>P</td>
</tr>
<tr>
<td>Age</td>
<td>-0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>RV preload</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RV EDA</td>
<td>0.06</td>
<td>0.23</td>
</tr>
<tr>
<td>Maximal IVC</td>
<td>-0.04</td>
<td>0.44</td>
</tr>
<tr>
<td>IVC collapse index</td>
<td>0.028</td>
<td>0.59</td>
</tr>
<tr>
<td>RA area</td>
<td>-0.10</td>
<td>0.04a</td>
</tr>
<tr>
<td>RV afterload</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPAP</td>
<td>-0.134</td>
<td>0.023a</td>
</tr>
<tr>
<td>PAT</td>
<td>0.072</td>
<td>0.16</td>
</tr>
<tr>
<td>PVR</td>
<td>-0.236</td>
<td>0.001a</td>
</tr>
</tbody>
</table>

EDA: right ventricular end-diastolic area; IVC: inferior vena cava; PAT: pulmonary acceleration time; PVR: pulmonary vascular resistance; RV: right ventricular; RVFAC: right ventricular fractional area change; S’: Doppler-derived tricuspid lateral annular systolic velocity; SPAP: systolic pulmonary arterial pressure.

a P value < 0.05.

Figure 2. Receiver operating characteristic analysis of right myocardial performance index (RMPI), isovolumic relaxation time (IVRT), isovolumic acceleration (IVA) and basal two-dimensional (2D) strain. 2D strain (purple line) and IVA (orange line) had the best discriminative value for identifying RV dysfunction, while RMPI and IVRT displayed acceptable values. AUC: area under the curve.

Poor-quality TDI peak signal velocity; RVFAC could not be measured in eight patients due to poor echocardiographical window, artefacts and reverberation.

RMPI, IVRT, IVA, AT, IVA could be measured in 94.6%, 98%, 84%, 85% and 84% of patients, respectively. In 25 patients (6.1%), basal 2D strain was not measurable due to non-accurate tracking.dP/dt could not be measured in 155 patients (37.5%), mainly due to suboptimal TR Doppler signal velocity with incomplete initial slope.

Loading conditions parameters

Peak TR could not be measured in 116 patients (28%), mainly due to poor quality of continuous-wave Doppler signal velocity. When measurable, TR was mild in 98%, moderate in 1.5% and severe in 0.5% of patients.

End-diastolic RV area, maximal IVC, IVC collapse index and RA area were measurable in 95.4%, 96%, 95.1% and 99.7% of patients, respectively.

Intraobserver and interobserver reproducibility

Interobserver and intraobserver reproducibilities were high for S’, RMPI, IVA, and 2D strain (Tables 6 and 7). Moreover, the concordance of reproducibility showed a close agreement between intraobserver and interobserver measurements for S’, RMPI, IVA and 2D strain. Interobserver and intraobserver correlation was lower for RVFAC (r = 0.66 and 0.78 respectively; both P = 0.001) with coefficients of variation of 8.6% and 7.4%, respectively.

Discussion

In our large prospective study focusing on RV function, the main results were as follows:

• S’ and RVFAC were concordantly impaired in only 39 patients, while 54 patients fulfilled one impaired parameter out of the two;
• among newer parameters, we found that IVA ≤ 1.8 m/s² (sensitivity 86%, specificity 80%) and basal 2D strain ≥ −17% (sensitivity 86%, specificity 97%) had the best diagnostic value for diagnosing RV dysfunction;
• IVA was not significantly influenced by loading conditions, while basal 2D strain was both preload and afterload dependent.

Recent guidelines [3] recommend the systematic reporting of at least one of these parameters: TAPSE, S’ and RVFAC with or without RMPI. As stated in the recommendations, S’ < 10 cm/s and/or RVFAC < 35% should raise suspicion.
Table 6 Interobserver reproducibility.

<table>
<thead>
<tr>
<th>Coefficient of variation</th>
<th>Correlation coefficient</th>
<th>Concordance correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>P</td>
</tr>
<tr>
<td>S' (n = 410)</td>
<td>2.5%</td>
<td>0.92  &lt; 0.001</td>
</tr>
<tr>
<td>RVFAC (n = 405)</td>
<td>8.6%</td>
<td>0.66  &lt; 0.001</td>
</tr>
<tr>
<td>RMPI (n = 390)</td>
<td>4.9%</td>
<td>0.84  &lt; 0.001</td>
</tr>
<tr>
<td>IVRT (n = 405)</td>
<td>7.4%</td>
<td>0.79  &lt; 0.001</td>
</tr>
<tr>
<td>dP/dt (n = 258)</td>
<td>7.9%</td>
<td>0.78  &lt; 0.001</td>
</tr>
<tr>
<td>IVA (n = 347)</td>
<td>1.9%</td>
<td>0.96  &lt; 0.001</td>
</tr>
<tr>
<td>Basal 2D strain (n = 388)</td>
<td>3.4%</td>
<td>0.87  &lt; 0.001</td>
</tr>
</tbody>
</table>

2D: two-dimensional; CI: confidence interval; IVA: isovolumic acceleration; IVRT: isovolumic relaxation time; r: Pearson’s correlation coefficient; rho_c: Lin’s concordance correlation coefficient; RMPI: right myocardial performance index; RVFAC: right ventricular fractional area change; S’: Doppler-derived tricuspid lateral annular systolic velocity.

of abnormal RV function, particularly in a young adult. TAPSE and S’ measure the same phenomenon—the longitudinal displacement of the tricuspid annulus—using two different techniques. In the present study, to avoid redundancy, we used only S’, as it appeared more reproducible than TAPSE and more easily recordable. In addition, S’ is best correlated to RVEF by magnetic resonance imaging (MRI) than TAPSE [6]. We found that S’ and RVFAC were highly feasible (> 98%). Interobserver and intraobserver reproducibility was better for S’ (2.5% and 2.7%) than for RVFAC (8.6% and 7.4%). However, RVFAC reproducibility is sufficient to allow clinical application, as currently recommended by guidelines regarding extensive studies. Surprisingly, S’ and RVFAC were discordant in 13% of patients; these apparent discrepancies could be explained mainly by the fact that these indices are more complementary than similar: S’ is a regional parameter while RVFAC is more global; S’ explores longitudinal function while RVFAC is more global; S’ can deteriorate due to initial subclinical myocardial damage before any RV ejection fraction (RVEF) impairment [18]; S’ and RVFAC can be modified differently by load [19]—in the present study, S’ was found to be afterload dependent while RVFAC was both preload and afterload dependant; S’ has a low diagnostic value when there is severe TR [20], but in our study, TR was trivial or mild in 98% of our patients; conflicting data exist concerning possible physiological diminution of S’ amplitude with age, but in the present study we found no significant relationship between age and S’ or RVFAC (Table 5). These discrepancies emphasize the limitations of a single parameter approach to identifying RV systolic dysfunction, leading to an incorrect evaluation in a majority of cases. A combination of echocardiographical criteria appears mandatory, particularly when RVFAC and S’ are discordant, highlighting the need to use additional parameters.

Additional parameters for estimation of RV function (RMPI, IVRT, dP/dt, IVA and 2D strain) have been described in the literature and highlighted in recent guidelines. Their use relies on data arising from single-centre studies that included a small number of patients, explaining the lack of well-validated thresholds as yet. These validation studies were based on various reference methods: scintigraphy, echocardiography and MRI. In our study, echocardiography was preferred to MRI as the reference method for various reasons: validated guidelines for S’ and RVFAC are available; RV function in daily practice is evaluated using echocardiography in a large majority of cardiology wards, MRI use in practice is limited by availability and cost; echocardiography allows the study of many complementary physiological

Table 7 Intraobserver reproducibility.

<table>
<thead>
<tr>
<th>Coefficient of variation</th>
<th>Correlation coefficient</th>
<th>Concordance correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>P</td>
</tr>
<tr>
<td>S’ (n = 410)</td>
<td>2.7%</td>
<td>0.89  &lt; 0.001</td>
</tr>
<tr>
<td>RVFAC (n = 405)</td>
<td>7.4%</td>
<td>0.78  &lt; 0.001</td>
</tr>
<tr>
<td>RMPI (n = 390)</td>
<td>4.4%</td>
<td>0.87  &lt; 0.001</td>
</tr>
<tr>
<td>IVRT (n = 405)</td>
<td>5.5%</td>
<td>0.88  &lt; 0.001</td>
</tr>
<tr>
<td>dP/dt (n = 258)</td>
<td>7.7%</td>
<td>0.80  &lt; 0.001</td>
</tr>
<tr>
<td>IVA (n = 347)</td>
<td>2.1%</td>
<td>0.94  &lt; 0.001</td>
</tr>
<tr>
<td>Basal 2D strain (n = 388)</td>
<td>3.9%</td>
<td>0.83  &lt; 0.001</td>
</tr>
</tbody>
</table>

2D: two-dimensional; CI: confidence interval; IVA: isovolumic acceleration; IVRT: isovolumic relaxation time; r: Pearson’s correlation coefficient; rho_c: Lin’s concordance correlation coefficient; RMPI: right myocardial performance index; RVFAC: right ventricular fractional area change; S’: Doppler-derived tricuspid lateral annular systolic velocity.
aspects of RV function (longitudinal or global function, isovolumic period and deformation), while the MRI approach is limited to RV EF; our study is instantaneous, while studies using MRI are not usually performed on the same day (this point is particularly important as it is well known that load variations modify RV EF whatever the technique of measurement applied); echocardiography can simultaneously evaluate loading conditions and function in contrast to MRI; RV EF measurement using MRI is at least as challenging as echocardiography and many questions are not still standardized (do we have to include valvular plane in the measurement? What about apical trabeculations? Which protocol of acquisition [short-axis or long-axis]? Are different manufacturers’ software packages equivalent for calculating RV volumes and RV EF?). MRI studies illustrate these limitations: in an interstudy reproducibility work [21], MRI showed a variation of 8.3% (4.3–10.4%) for RV EF measurement and 14.1% (8.1–18.1%) for end-systolic volume. In the literature, the interobserver coefficient of variation of RV EF measurement has been found to be up to 10.7% [22] and can increase to 16% in particular situations [23]. For all these reasons, echocardiography was preferred to MRI to define our reference method according to guidelines [3].

In our study involving 413 patients, parameters derived from pulsed-wave TDI (IVA, RMPI, IVTR) and 2D strain discriminated normal RV function from RV dysfunction with a sensitivity ranging from 68% to 86% and a specificity ranging from 71% to 98%. Basal RV 2D strain and IVA had the best diagnostic value (area under the curve [AUC] 0.95 and 0.86, respectively).

Initially described by Vogel et al. [10] as an index of RV contractile function, IVA has also been validated as a prognostic parameter in various studies [24–27]. In our study, IVA was largely feasible (84%) and highly reproducible, as shown by Tayareci et al. [24]. Our cut-off value of 1.8 m/s² (2.2 m/s² in the study by Vogel et al.) discriminated patients with RV dysfunction from normal patients, with a sensitivity of 86% and specificity of 80% (AUC 0.86).

The RV 2D strain study was deliberately limited to the basal segment in our analysis, as described in the methods. Highly feasible and reproducible, a cut-off value of −17% (AUC 0.95) had a sensitivity of 86% and a specificity of 98% for detecting RV dysfunction. In the literature, global longitudinal strain using RV FAC as a gold standard [28] has been validated with a similar value (−16%). Moreover, in a population of patients referred for cardiac surgery, RV global longitudinal strain was shown to have prognostic value, using a threshold of −21% [29,30].

RMPI measurement was highly feasible (95.4%) and reproducible, with a cut-off value of RMPI ≥ 0.60 allowing an acceptable discrimination (AUC 0.79) to predict RV dysfunction with a specificity of 80%. These findings are in agreement with the recent guidelines, which propose a cut-off value of 0.55.

A reliable index of RV contractility should be as little load dependent as possible. In our study, IVA was found to be the least load-dependent, adding to its interesting diagnostic value. These results are in accordance with physiology (isovolumic contraction period is known to be less load dependent) and prior clinical studies [10,19]. On the other hand, basal 2D strain appeared to be afterload and preload dependent. Although afterload dependency is in accordance with prior studies [13,31–33], we also found a significant decrease in basal 2D strain with increased preload, which has not been reported in the literature, to our knowledge, except in athletes [34].

In the present study, RMPI was also found to be afterload dependent, mainly due to prolongation of IVRT, whereas no changes could be identified with increased preload, which is in agreement with the findings of Kjaergaard et al. [19]. This might be due to its heightened load dependency, as we demonstrated, with a significant correlation between IVRT and SPAP, PVR and RA area. These findings are consistent with the results of Lindqvist et al. [35], who found that IVRT was also a marker of right pressure, with a significant correlation with SPAP and RA pressure.

Study limitations

Our results were not validated against MRI, which is regarded as the gold standard for RV function assessment. Aside from the limitations discussed, previous studies have already dealt with this issue [6,36]. Consequently, we intentionally focused our evaluation on the use of recent echocardiographic guidelines that are applied widely in everyday practice.

RA area as a marker of preload could be questionable in chronic atrial fibrillation and/or with significant TR. In our study, 34 patients (8%) had chronic atrial fibrillation. When these patients were excluded, the statistical analysis did not change significantly. Similarly, 98% of patients had only mild TR.

Although IVT is a diastolic parameter, it was evaluated in the present work as a systolic marker. As myocardial function deteriorates, ejection time is shortened and IVRT is lengthened. Indices of left ventricular systolic function and IVRT are strongly related [37]. Moreover, IVT is an integral part of the right myocardial performance index that reflects the global function of the RV.

Assessing PVR is questionable in patients with RV dysfunction, as it has not been studied in this specific population. However, patients with RV dysfunction have been included in different studies dealing with this issue [17,38].

The receiver operating characteristic analyses were performed in the same population of patients used to derive RV dysfunction thresholds. Further studies are therefore necessary to further validate the performance of the various cut-off levels. We used EchoPAC software for 2D strain analysis, although this programme has not yet been validated for RV strain. We did not evaluate three-dimensional volumetric echocardiography for RV EF measurement, which has been recently proposed but not recommended for routine use by recent guidelines. Finally, evaluation of clinical outcome was not included in our study, but is part of an ongoing analysis to assess the short- and long-term clinical prognostic value of these parameters.

Conclusion

In a large population of 413 patients, RV FAC and S’, validated in recent ASE guidelines for the diagnosis of RV dysfunction, were sometimes discordant. For this reason, a single parameter cannot be used to characterize RV function. Among seven other parameters, we found that IVA and basal 2D
strain both had good diagnostic value. Moreover, unlike 2D strain, IVA was not influenced by loading conditions, which adds to its diagnostic value. Including these parameters in a multiparametric approach could improve the diagnostic accuracy of RV dysfunction detection.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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Echocardiographic assessment of right ventricular systolic function


