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Echocardiographic evaluation of right heart function and pulmonary vascular bed

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Abstract The aim of this review was to describe the different ultrasonic modalities to non-invasively evaluate right cardiac chambers and pulmonary vascular bed function. M-Mode, 2-D, conventional pulsed doppler, tissue doppler imaging (TDI), strain rate imaging (SRI) and 3D echocardiography are illustrated in order to obtain both regional and global right heart and pulmonary function. The results have a good correlation with other invasive and non-invasive diagnostic techniques, as magnetic resonance imaging (MRI). All these echocardiograpic techniques can be employed to evaluate the morphologic and functional pictures of right heart and pulmonary circulation in presence of pulmonary hypertension (PH). The hemodynamic profile obtained consent to anatomically and functionally characterize PH. But, other experiences performed on more wide range of healthy and PH patients are necessary to confirm the described results.

Keywords Right ventricular function ·
M-D echocardiography · RV myocardial performance index · Tissue doppler imaging · Strain rate imaging ·
3D echocardiography · Pulmonary hypertension (PH)

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Introduction

For long time, right heart chambers were judged such as cavities without any active function, placed between the venous systemic blood flow and the pulmonary vascular bed. But, recently both collected action and propulsive push of the right heart were remarked [1, 2]. Right ventricular cavity exhibits reduced walls' thickness, as consequence of reduced loading in respect to the left ventricle (pulmonary resistances are about 1/6 towards these induced by systemic circulation). This cavity shows an inflow way (sinus) and an outflow tract (infundibulum), similarly to the left ventricle. Two ventricular parts are divided by the supraventricular crest and are connected respectively to the blood coming from the venous circulation (sinus) and the blood drawing to the pulmonary circulation (infundibulum). As consequence, in early systole the inflow tract contracts whereas its outflow tract expands and vice versa happens in late systole [3].

Microscopically, right ventricular walls predominantly consist of longitudinal fibers present in the epicardial zone, and radial fibers constituting the endocardial zone. This unlike orientation of myocardial fibers produces longitudinal motion (see in long-axis approach) and radial motion (see in short axis view) during systole [4]. The morphological (irregular shape and trabeculations) and functional complexity of right ventricle give rather difficult their volumes and EF% calculation. These parameters are

Table 1 Some echocardiographic indexes of right cavities

RVEDD mm	24.3 ± 5
RVOT s mm	3.3 ± 10
TAPSE mm	20.2 ± 4.7
RA area cm^2	13 ± 2
RV wall thickness mm	4.0 ± 07
RVEF% (Simpson)	46 ± 7

RVEDD right ventricle end-diastolic diameter, RVOT right ventricular outflow tract, TAPSE tricuspid annular plane systolic excursion, RA area right atrium area, RVEF% right ventricle ejection fraction%

usually evaluated by echocardiography. The normal echocardiographic values of main indexes of right structures (atrium and ventricle) are reported in Table 1 [5].

M-Mode echocardiography performed in parasternal long or short axis view, is used to measure RVEDD in mm. and walls' thickness of RV in mm. The normal RV is approximately two thirds of the LV size. RVOT is evaluated by 2D echocardiography in parasternal short-axis view alone, by measuring the distance between the aortic root and the wall of the pulmonary truncus [6, 7]. Tricuspid annular plane systolic excursion (TAPSE) is a relatively new echocardiographic RV parameter, indicating the displacement of tricuspid annular plane in systole. It is obtained in long-axis view in M-Mode echocardiography, placing the sample-volume at level of lateral tricuspid annulus under B-Mode echocardiography's guidance (Fig. 1a, b). TAPSE is related to

RVEF% obtained with radionuclide methods. A value >15 mm indicates the normal systolic RV function, whereas a value <8 mm is connected with the significant RV dysfunction [8]. The degree of TAPSE approximately corresponds with RVEF%; 5 mm = 20% EF; 10 mm = 30% EF; 15 mm = 40% EF; 20 mm = 50% EF. The correspondence between TAPSE and RVEF% calculated from radionuclide angiography (judged as the standard method for assessing the right ventricular ejection fraction) depends of ability of the radionuclide method to evaluate the complex geometry of the right ventricle. In a recent study comparing TAPSE and radionuclide angiography, Ueti and colleagues confirm that this diagnostic technique can be considered the "gold standard" for assessing RVEF, because the obtained values not depend on the complex geometry of the right ventricle [9].

RA area is obtained in apical 2D-four chamber view, as the product between longitudinal and transverse side. Its normal value is equal to 13 ± 2 cm^2, but it also depends for right atrial pressure, BMI, and age or sex.

Right atrial pressure is appraised from the inferior vena cava (IVC) diameter and its inspiratory collapse [10], detected by subcostal view. The diameters of IVC, % of inspiratory IVC collapse and the corresponding values of RA pressure are reported (Fig. 2).

From the matched values of IVC diameter and its inspiratory collapse, it is possible to estimate RA pressure. Right atrial pressure must be added to calculated value of tricuspid insufficiency (eventually

Fig. 1 TAPSE detection with 2-D (a) and M-Mode (b) echocardiography
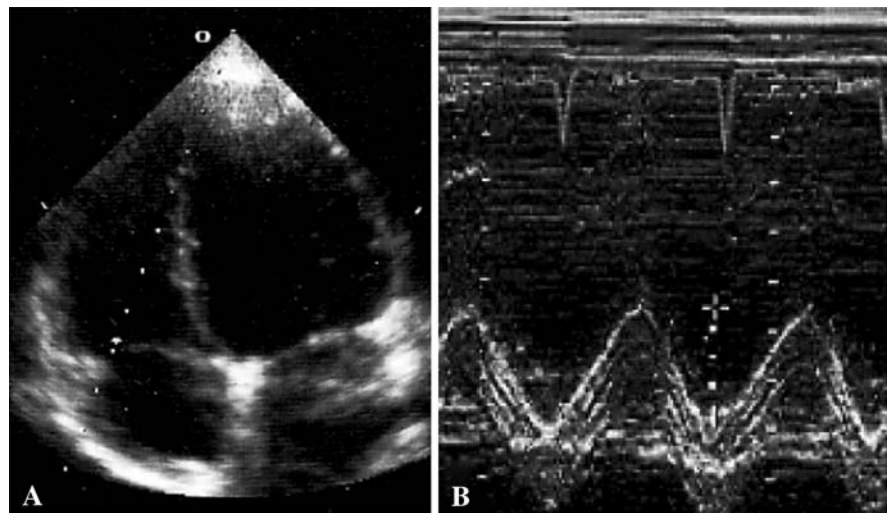
INFERIOR VENA CAVA		
Diameter	Inspiratory collapse	**R.A. PRESSURE**
< 1.7 cm	>/=50%	**0-5 mmHg**
>/=1.7 cm	>/=50%	**6-10 mmHg**
>/= 1.7 cm	<50%	**10-15 mmHg**
>/= 1.7 cm	0%	**>15 mmHg**

Fig. 2 Diameter of inferior vena cava recorded by subcostal view; % of its inspiratory collapse and corresponding values of right atrial pressures

present), for estimate systolic pulmonary pressure (PAPs).

Usually, atrial filling happens from the point of minimal atrial volume until the onset of atrial systole. This phase starts at tricupid valve opening. On the contrary, atrial empying happens from maximal to minimal right atrial volume. Two phases of atrial emptying were described: passive emptying, occurring during ventricular diastole, and active emptying, occurring during atrial contraction. Emptying times progressively change with increasing age in healthy subjects. In fact right atrial passive emptying volume and passive emptying fraction decrease with age, whereas active empting volume and active right atrial ejection fraction increase with advancing age. This could indicate that with increasing age right ventricular diastolic function deceases [11].

These results are not without any impact in patients with pulmonary arterial hypertension (PH) and are important in the impact of age with some diseases, as chronic pulmonary diseases, pulmonary embolism, right ventricular infarction, chronic heart failure, atrial fibrillation, etc.

The main echocardiographic parameters evaluated in the pulmonary artery are:

Systolic pressure in pulmonary artery (PAPs), obtaining in presence of tricuspid valvular incompetence only, adding PARm to velocity of tricuspid insufficiency (corrected by Bernoulli formula):

$$PAPs = PARm + 4V^2 \text{Tricuspid. Max}$$

in which: PAPs = systolic pressure in pulmonary artery; PARm = mean pressure in right atrium (estimated by IVC); $4V^2$ tricuspid max, i.e. velocity^2 of tricuspid regurgitant jet $\times$ 4 (in accordance with modified Bernoulli equation). Doppler-derived PAPs critically depends upon age, body mass index and

right atrial pressure. A value >30 mmHg indicates a condition of pulmonary hypertension (PH).

Diastolic arterial pressure (PAPd) can be calculated when the pulmonary valvular regurgitation is present, from the formula:

$$PAPd = PARm + 4V^2 \text{PR end diast.}$$

where PAPd = diastolic arterial pulmonary pressure; PR end diast. = end diastolic pulmonary regurgitant jet detected with continuous wave Doppler. It is obtained as the pulmonary regurgitant flow at end-diastole (Fig. 3).

Mean pulmonary artery pressure (PAPm), evaluated as:

$$PAPm = 2/3 \, PAPd + 1/3 \, PAPs$$

where the values of PAPd and PAPs are previously reported.

A value of PAPs > 35 mmHg at rest, of PAPd > 15 mmHg and PAPm = 25 mmHg corresponds to PH.

Among the pulmonary pressures (systolic, diastolic, mean), PAPs is more frequently evaluated for its importance in to estimate maximal systolic pulmonary
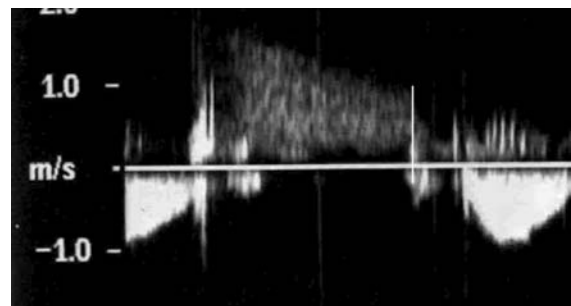

Fig. 3 Pulmonary flow: measurement of end-diastolic pulmonary regurgitant jet

pressure. In a study investigating the relationship between PAPs and age, Ueda et al. [12] in healthy aged subjects found an increased value compared with that recorded in younger healthy subjects. This different behaviour seems to be reported to the changes of the senile lungs, characterized by a homogeneous enlargement of the alveolar airspaces without fibrosis or destructions of alveolar walls [13, 14]. Elevated PAPs in the elderly are also correlated with the thickness of the RV outflow tract wall. This is also attributed to an increase in pulmonary vascular resistance and decrease LV compliance. Usually, PAPs increases of 0.8 mmHg per decade in over 50 years of age controls. In connection to sex, McQuillan et al. indicated that PAPs is significantly higher in men than in women. BMI and obesity also induce an increase of PAPs in absence of any condition of pulmonary hypertension. Finally, a positive association between PAPs and posterior wall thickness was described [15].

Mean PAP (mPAP) > 25 mmHg at rest or >30 mmHg during exercise truly indicates pulmonary hypertension (PH). This condition corresponds to sPAP > 36 mmHg. Friedberg et al. [16] hypothesized that sPAP correlates with dPAP and mPAP. This correlation can be used to estimate diastolic and mean PAP from Doppler data (PAPs).

The previously reported mPAP formula:

$$mPAP = 2/3 \ dPAP + 1/3 \ sPAP$$

implies that knowing the minimal and maximal values of the pressure signal allows a precise estimation of the mean pressure. In the formula: dPAP may reflect vascular tone, whereas sPAP depends on pulmonary artery compliance, and right ventricular ejection.

An invasive study also demonstrated that sPAP alone may estimate mPAP, without the need to include dPAP, for a linear relationship between mPAP and sPAP [17]. This implies that sPAP obtained by doppler flow (in presence of tricuspid regurgitation) may directly estimate mPAP and so a condition of PH.

In addition, increasing evidence from clinical studies emphasizes the importance of evaluating pulmonary artery flow and RV function during 2-D stress echocardiography. Stress echo can be performed with bicycle or treadmill test; hypoxia or pharmacologic tests can also be employed. In healthy individuals, the adaptation to exercise includes an increase in stroke volume, heart rate, and cardiac output, with minimal increase in PAPm and PVR. Values of doppler-derived systolic PAP have been reported to be <40–45 mmHg in healthy individuals [18]. Exercise echocardiography may uncover abnormal increases in pulmonary pressure and cardiac output. These parameters are further impaired in patients with resting pulmonary hypertension (PH), such as in scleroderma [19] and in thrombo-embolic pulmonary disease. It is also important in patients with right coronary artery disease, for evaluate right ventricular wall motion in ischemic patients. In these individuals, stress induces a decrease in RV function or RV asynergy [20, 21]. In detail, patients with inferoposterior MI have 50% RV involvement. In patients with acute RV infarction, severe hemodynamic compromise arises when both RV free wall and septum are involved. In turn, RV dysfunction leads to an elevated RV end-diastolic pressure, that shifts the septum toward the left in systole, thereby further limiting left-sided filling and compliance.

Right ventricular function

Unlike left ventricle, the anatomically complex right ventricle and its crescentic shape with both the infundibulum and some trabeculations is very difficult to assess in one manner its volumes and ejection fraction%. An additional condition rendering difficult to detect RV volumes is its variable shape with different loading conditions [22, 23]. A number of echocardiographic methods have used for evaluating RV volumes and %RVEF. Of these: two-dimensional echocardiography includes: the Simpson's rule method and the biplane area-length method. Two dimensional echocardiography Simpson's rule method requires computer calculations and was been used in a number of echocardiographic studies. The most frequently views utilized are: the apical four-chamber view or the subcostal approach [24–26]. RV volumes are recorded in diastole and in systole by subcostal approach, as reported in Fig. 4.

The area-length method, putted to subcostal outflow tract or to apical four-chamber view, is another 2-D echocardiographic method to evaluate RV volumes [27, 28].

Fig. 4 Two-dimensional subcostal approach to record right ventricular volumes in diastole (*right*) and systole (*left*) with the Simpson's rule method
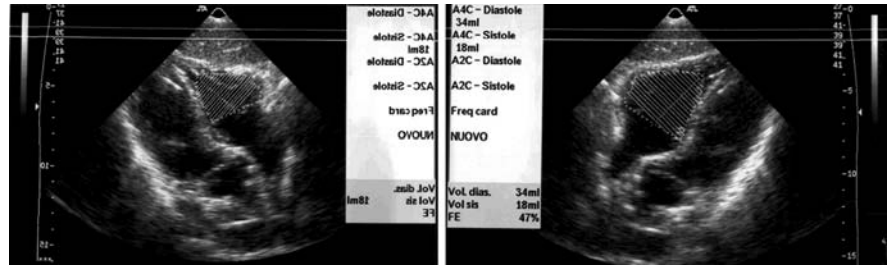
RV myocardial performance index

Right ventricular myocardial performance index (MPI) has been demonstrated to be clinically useful to define RV function. The most frequently employed ultrasonic technique is pulsed doppler echocardiography (PDE). It is the result of (isovolumetric contraction time + isovolumetric relaxation time)/ ejection time (Fig. 5). The RV mean reported value of MPI in healthy adults is = 0.25 ± 0.05 [29]. Its comparison with invasive measurements makes the index a sensitive indicator of RV function. This index, also named Tei index, is not influenced by heart rate, body weight, and aging and is correlated with %RVEF obtained by nuclear ventriculography [30]. Tei index can be also obtained using tissue doppler imaging (TDI) [31].
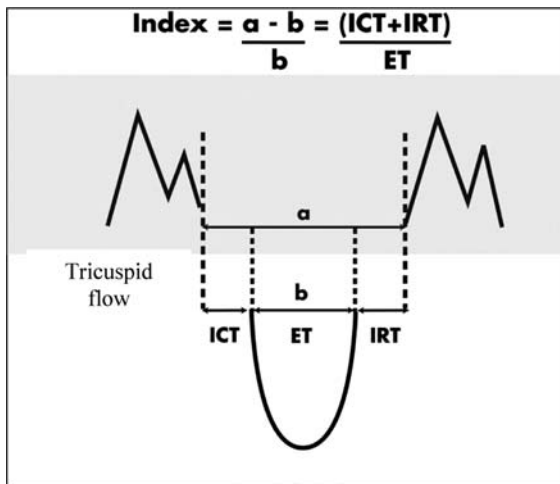

Fig. 5 Calculation of myocardial performance index (MPI) of RV. The interval *a* was obtained in apical for chambers view at the tips tricuspid leaflets. The interval *b* was recorded from the parasternal short axis view, with doppler sampling site positioned just below the pulmonary valve, by pulsed doppler echocardiography. *ICT* Isovolumetric contraction time, *IRT* Isovolumetric relaxation time, *ET* Ejection time

MPI is prolonged in patients with primary pulmonary hypertension compared with normal subjects. In using this index to discriminate COPD patients with impaired diastolic function, El-Damarawy et al. [32] recently found the index had high efficacy, sensitivity and positive predicted values but low specificity and negative predicted values in to define RV dysfunction.

Tissue doppler imaging

Tissue doppler imaging (TDI) allows quantitative assessment of RV systolic and diastolic function by the measurement of myocardial velocities. Usually, sample volume is placed at level of lateral or septal tricuspid annulus (Fig. 6). Peak velocity <11.5 cm/s identifies RV dysfunction with a sensitivity and specificity of 90 and 85% respectively [33]. Using this technique, Lindqvist and coll demonstrated that RV isovolumic contraction velocity is a reproducible and an easily obtaining non-invasive parameter correlated with invasive measurements of RV referring to intrinsic contractility (dP/dt) and its filling pressures [34, 35]. Recently, Meluzin et al. [36] showed that the peak systolic velocity of RV myocardial free wall correlated to EF%. An advantage of using TDI to assess RV function is that measurement is independent of geometric assumptions and endocardial border tracing. Its main limitation is that it does not distinguish between active and passive wall motion both in animals and in humans [37, 38].

Strain and strain rate imaging

The strain rate imaging (SRI) have made more assessment of global and regional systolic and diastolic RV function [39, 40]. But, while the assessment of longitudinal strain from apical view

Fig. 6 TDI (systolic and diastolic times) of RV recorded at level of lateral tricuspid annulus
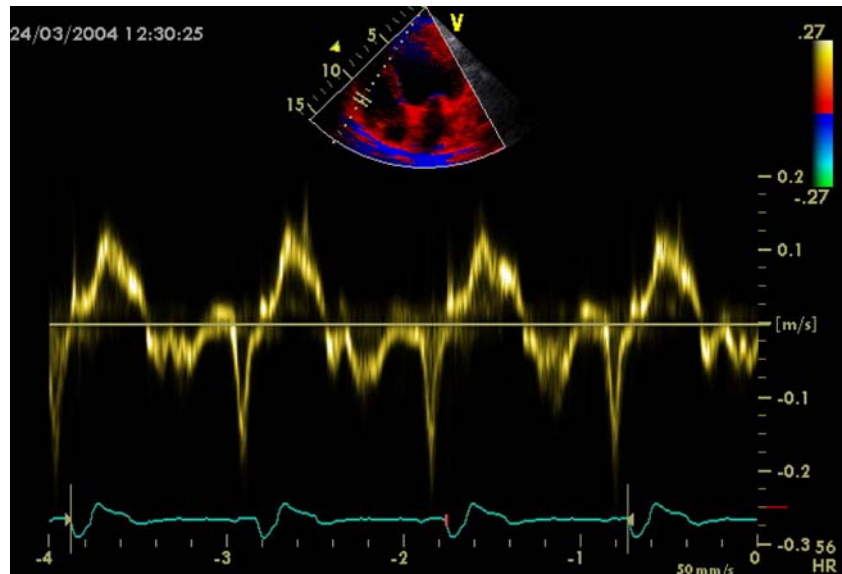
is feasible, the analysis of RV radial deformation from the parasternal window turned out to be difficult. In healthy individual, RV longitudinal velocities demonstrated a baso-apical gradient with higher velocities at the base; also RV velocities are higher as compared to the LV. Contrary to LV, the strain rate and the strain values of the RV are in homogeneously distributed. This pattern can be explained by the complex RV geometry. In a recent study RV strain demonstrated a good correlation between the peak systolic ε (this is the maximal deformation of the myocardium) recorded in the basal segment of the RV free wall and other prognostic markers of chronic heart failure, such as BNP concentration, peak VO_2 or slope of the VE/VCO_2 ratio. Some data recorded in patients with pulmonary hypertension suggested that in compensated patients, peak systolic strain rate correlated with peak systolic pulmonary artery pressure, with depression in the smooth inlet portion of RV [39].

Strain/strain rate values were reduced in all segments of RV free wall and interventricular septum in patients with PAPs > 35 mmHg compared with control group (<35 mmHg). A significant relationship was also found between peak systolic SR at basal free wall and radionuclide RVEF% [40]. Furthermore, in contrast to other ultrasound-based methods, SRI allows the quantification of longitudinally systolic and diastolic function for each segment of RV. The study demonstrates the utility of SRI for the

evaluation of right ventricular function in chronic obstructive pulmonary disease patients and is correlated with severity of pulmonary disease.

But, strain measurements are angle dependent, therefore the strain interpretation should be performed with caution if tissue direction deviates more than 30° from the beam direction. On the contrary, speckle-tracking is a new, non-invasive method for the assessment of global and regional ventricular function for tracking every point on the 2D echocardiography [41]. With this method it is possible to detect myocardial coordinates in every frame, allowing a myocardial strain to be detect in any direction. In addition, RV function cannot easily appraisable because RV is a triangle-shaped chamber composed of the inlet portion, the outlet portion, and the apical portion with rough trabeculations having a complex architecture. For these reasons, RV global and regional function can be more entirely evaluated with speckle-tracking method [42].

Two works have been evaluated the behaviour of RV free wall and interventricular septum in healthy subjects and in patients with pulmonary hypertension. In the first, RV free wall longitudinal myocardium deformation, myocardial systolic peak strain, systolic peak strain rate (SRs), early diastolic peak strain rate (SRe), late diastolic peak strain rate (SRa), the ratio of SRe/SRa were measured in the basal, middle and apical segments of right ventricular free wall in healthy volunteers from the apical

4-chamber view. The results obtained shown that RV longitudinal strain and strain rate are highest in the basal and middle segments than in the apical of the free wall [43]. This study also shows that in normal subjects there was no difference between the contractile timing in the strain along the posterior wall and that of the pulmonary valvular annulus shortening. In another study, in patients with pulmonary hypertension, peak systolic myocardial velocities, strain rate, and strain resulted significantly impaired compared with controls and resulted most altered in patients with severe pulmonary arterial hypertension [44].

3-D echocardiography

3-D echocardiography (3DE) has been proposed to evaluate RV function in spite of its complex geometry. Contrary to two-dimensional echocardiography, 3DE provides volumetric measurements without geometric assumptions and allows us to measure right ventricular volumes irrespective of the RV irregular shape [45]. The values of RV volumes and ejection fraction obtained with 3DE resulted closely correlated with magnetic resonance imaging (MRI) and radionuclide ventriculography (RNV) [46–48]. A close correlation was also found between radionuclide ventriculography and transesophageal 3DE. 3DE images of RV can be obtained from a modified apical window. Endocardial tracing and the calculation of volumes may be hindered by trabeculations and the presence of the moderator band. Contrary to 2D echocardiography that underestimates RV cavity, real-time 3D echocardiography (RT3D) slightly overestimated RV end-diastolic and end-systolic volumes, although this overestimation was not statistically significant [49]. In normals, the mean times for 3D acquisition are of few minutes and the imaging quality is good in 85% of cases. RVEF is negatively correlated with pulmonary arterial systolic pressure and positively correlated with TAPSE, peak systolic velocity, and fractional shortening area. In patients with pulmonary hypertension RV volumes were larger than in normals and RVEF appear lower than in these. In addition, data obtained by 3D evaluation are well correlated with those obtained by 2D and Doppler methods and can differentiate normal subjects and pulmonary hypertensive patients [50].

Conclusive remarks

All right heart and pulmonary indices are useful to non-invasively define the hemodynamic profile both of healthy subjects and patients with primary or secondary PH, such as those with COPD . This condition is favoured by some diseases provoking PH with consequent RV dysfunction [51, 52]. In turn, the functional RV derangement induces an elevation of PAP and PVR, as adaptive mechanism, leading to RV enlargement and hypertrophy. When the adaptive mechanisms of RV dilatation and hypertrophy cannot compensate for the hemodynamic burden, right heart failure associated with poor prognosis occurs.

The conventional echocardiographic methods are important to non-invasively define right ventricular function and estimate pulmonary pressures. The new echocardiographic techniques, as TDI, SRI or 3DE, appear more accurate and sensitive in to detect both regional and global RV function in healthy and in RV dysfunctioning patients. The results achieved with these same have a good correlation with radionuclide angiography (that is considered as "gold standard") in to accurately define RV function in spite of the RV complex features, its myoarchiytecture, and coarse trabeculations of the apex. But, further researches on large of healthy and diseased populations are needed to definitely validate the echocardiographic results obtaining both with new and conventional techniques.

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