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Right ventricular function after cardiac surgery: the diagnostic and prognostic role of echocardiography

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Abstract

Cardiac surgical techniques and circulatory supports have strongly evolved in the last years. Right ventricular (RV) function during the post-operatory period is still subject of study, although its relevant prognostic impact has been variably described in different papers. RV post-surgical dysfunction's underlying mechanisms are still not clear and include a different hypothesis. Echocardiography, with both first and second level parameters, offers the possibility to accurately analyze the right ventricle and optimize these patients' management. This paper describes the pathophysiology of the right ventricle, the most used echo indexes of RV function, whether they alter after surgery, the different supposed mechanisms of RV dysfunction and its role in the prognosis of patients undergoing cardiac surgery.

Keywords Right ventricular function · Echocardiography · Cardiac surgery · Prognosis

Background: pathophysiology of the right ventricle

Not much time has passed since right ventricle (RV) was just considered an auxiliary of the left ventricle (LV), mainly consequently to old animal experiments in which ablation or replacement of RV free wall seemed to be quite well tolerated [1, 2]. Recently, RV assessment has gained great relevance in many cardiac diseases and in patients undergoing cardiac surgery, also thanks to the advanced imaging techniques that allow a better evaluation of its anatomy and function. RV has only about one-sixth of LV mass and roughly has the shape of triangular pyramid. In its thin walls, longitudinal myocardial fibers are more represented than circular ones. Surface-to-volume ratio is elevated, and end-diastolic and end-systolic volumes are higher than those of the LV. RV retrosternal position makes its evaluation complex with transthoracic echocardiography (TTE), so it is fundamental to complement different dimensional and functional indexes. Currently, there is no unanimous viewpoint whether RV is always altered during cardiac surgery or regarding which weight should be given to each index during a post-operative routine evaluation. The aim of the present paper is to analyze different characteristics of the main surgical techniques, to comment upon different hypothesis regarding the impact of cardiac surgery on RV function and to describe which parameters can be reduced and their prognostic impact.

Contractility, preload, and afterload

RV output depends on three components: ventricular contractility, preload, and afterload. RV contraction has many peculiarities. Systolic contractility is composed of two sequential phases: in the first, the inlet contracts while the outflow tract broadens, the tricuspid valve plane moves towards the apex, but no RV ejection takes place; in the second, the infundibulum contracts with subsequent RV ejection. In healthy subjects, right-sided pressures are lower than left-sided ones

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and, given the smaller afterload, RV pressure loop displays an early peaking and a rapid decrease. Differently from LV, RV isometric contraction is much shorter, as it quickly reaches the pressure threshold needed for the ejection. Moreover, RV ejection phase is quite longer than that of LV. RV preload is mostly affected by vascular volume status, heart rate, left-side filling pressure, intra-pericardial pressure, and RV ventricular compliance [3]. RV complies with Frank Starling law: in a healthy heart, an increased RV preload corresponds to improved myocardial contraction and ejection. However, after a compensative phase, persistent volume overload leads to dysfunctional RV filling and contractility, up to RV failure. On the other side, pulmonary vascular resistances are the main determinants of RV afterload. RV can tolerate an increased preload better than an increased afterload. For example, in massive pulmonary embolism, the thin RV walls are not able to adapt to the acute increase of afterload and go through chamber failure due to subendocardial ischemia and subsequent inflammation [4, 5]. On the contrary, a chronic afterload increase, as it occurs in pulmonary hypertension, is followed by RV free wall hypertrophy, the ventricle becomes more rounded-shaped, reducing wall stress in order to maintain an adequate output [6, 7]. However, with time, this compensative process leads to RV dilation and contractile dysfunction.

Ventricular interdependence

About 20–40% of RV stroke volume is dependent on LV contraction [8]. The so-called *ventricular interdependence* can be explained by the basic concept that size, shape, and compliance of one ventricle affect the hemodynamic properties of the other, both in systole and diastole [9]. This interdependence is due to different factors: the pericardium that embraces both ventricles, the shared blood supply, the continuity between RV myocardial fibers, LV muscular layers, and the interventricular septum (IVS). Moreover, LV stroke volume eventually corresponds to RV preload. Notably, diastolic ventricular interdependence is mainly due to the pericardium [10]. In the case of RV volume or pressure overload, RV dilates and intrapleural pressure increases determining a shift of the IVS towards the left. This phenomenon changes LV geometry and causes upward shifting of LV diastolic pressure curve, raise in LV pressure at end diastole, and reduction of LV stroke volume [9, 11]. Systolic interdependence is mainly mediated by IVS [12].

How to assess RV function by echocardiography: from TAPSE to strain

Advanced echocardiographic techniques can integrate standard parameters in order to obtain a complete and satisfying RV evaluation without the need of applying cardiac magnetic resonance (CMR). Table 1 shows normal cutoff values of RV function indexes. RV longitudinal shortening is the main contributor to its ejection and function. Tricuspid annular plane systolic excursion (TAPSE, Fig. 1), measurable by M-mode in apical four-chamber view, is extremely easy to obtain and has low interobserver variability [13, 16]. TAPSE is dependent on the angle of insonation and load conditions. Although being less sensible in presence of important cardiac dysfunction [17], it is the most employed RV parameter and has a key diagnostic and prognostic role in pulmonary hypertension and embolism [18–23] and in heart failure [24, 25]. Systolic velocity of the tricuspid annulus (s', Fig. 2) by tissue Doppler imaging (TDI) in an alternative method for the evaluation of RV longitudinal function. S' is quick and reproducible, but has the same limitations of TAPSE, it is load dependent and affected by cardiac translational motion as well as by tethering by adjacent diseased myocardial segments. It needs correction if the heart rate is < 70 bpm or > 100 bpm, by multiplying s' by 75 and dividing it by the heart rate [26]. The main application of s' is the assessment of RV function in pulmonary hypertension, also in the pediatric population [27]. RV fractional area change (RVFAC) is a quantitative method used to estimate RV systolic function (Fig. 3), which has demonstrated good correlation with RV EF assessed by CMR [28]. In an unselected cohort of more than 400 patients undergoing cardiac surgery [29], RVFAC was more feasible (98% vs 99.3%, respectively), but less reproducible than s' (coefficients of variation 8.6% for intra-observer and 7.4% for interobserver reproducibility). However, s' and RVFAC were concordantly impaired just in 39 patients, while they were discordant in 54 patients [29], showing low reliability if used as the only parameters of RV function in an echo report. The so-called RIMP (right ventricular index of myocardial performance) or Tei Index is an index of both systolic and diastolic function. To assess RIMP, isovolumic relaxation time (IVRT), isovolumic contraction time (IVCT), and ejection time intervals are measured by PW Doppler or TDI at lateral tricuspid annulus (the formula is (IVRT + IVCT)/ejection time). The higher the value, the worse the RV function [13]. RIMP is pre-load dependent, being IVRT reduced with elevated right atrial (RA) pressure. Three-dimensional (3D) echocardiography currently allows a better definition of the RV complex anatomy than 2DE, allowing the evaluation, from an apical four-chamber view, of the base, the apex, and the outflow tract. 3D feasibility is quite high during a routine echocardiography, with medium execution time and good quality of images even if it requires a different transducer [30, 31]. Moreover, it has been widely validated against CMR [32]. 3D RV ejection fraction (EF) is not a direct measure of contractile function, but an index of global ventricular

Table 1 Cutoff values of right ventricular function indexes

Index	Normal cutoff value	Ref.
TAPSE	> 17 mm	Lang [13]
Tricuspid S' velocity	> 9.5 m/s	Lang [13]
RVFAC	> 35%	Lang [13]
RIMP	< .43 by PW Doppler and < 0.54 by TDI	Lang [13]
3D RVEF	> 45%	Lang [13]
RV LS	− 27% ± 2	Fine [14]
Free wall RVLS	− 28.7% ± 4.1	Meris [15]

TAPSE tricuspid annular plane systolic excursion, *RIMP* right index of myocardial performance, *RVEF* right ventricular ejection fraction, *RVFAC* right ventricular fractional area change, *RV LS* right ventricular longitudinal strain

performance, being the result of the interaction between RV contractility and load. Irregular heart rhythm, inadequate acoustic window, abnormal septal motion, and load dependency are the main limitations in addition to the poor availability and the complexity of the software. Speckle tracking echocardiography (STE) is another second level echocardiographic technique for an accurate assessment of global and regional cardiac function, independently of the angle of insonation and in-plane translational motion. Born for a selective evaluation of the LV, RV longitudinal strain (RVLS**,** Fig. 4) has shown good feasibility and reproducibility [15]. The average value of longitudinal deformation of the six segments of the RV represents global RVLS [14, 33]; however, free wall RVLS (Fig. 5) has emerged as an even more accurate parameter in detecting RV dysfunction in some clinical settings, including advanced heart failure [34]. In the absence of second level tools, the combined use of TAPSE, s', and RVFAC is not just considerable as a basic surrogate but allows a good assessment of RV function in a short time and with high availability.

Insights in cardiac surgery: most common surgical approaches, types of cardioplegia, and extracorporeal circulation

Median sternotomy with pericardiotomy has become the gold standard approach since 1957 [35], with low failure rates and excellent long-term outcomes [36]. Pericardial effusion and onset of supraventricular arrhythmias are the most common complications, with differences in size and location according to the type of surgery [37]. For most of the cardiac interventions, myocardial protection by cardioplegic solutions is needed, while systemic arterial perfusion and oxygenation are transferred to a heart-lung machine in an extracorporeal circulation (ECC). Crystalloid cardioplegic solutions are the most used and are historically divided into two types, intracellular-type and extracellular-type solutions. The types of cardioplegia differ also for delivery method and temperature. Retrograde cardioplegia is an established method of myocardial protection [38–40], based on the concept that distribution of an antegrade-delivered cardioplegia might be impaired in

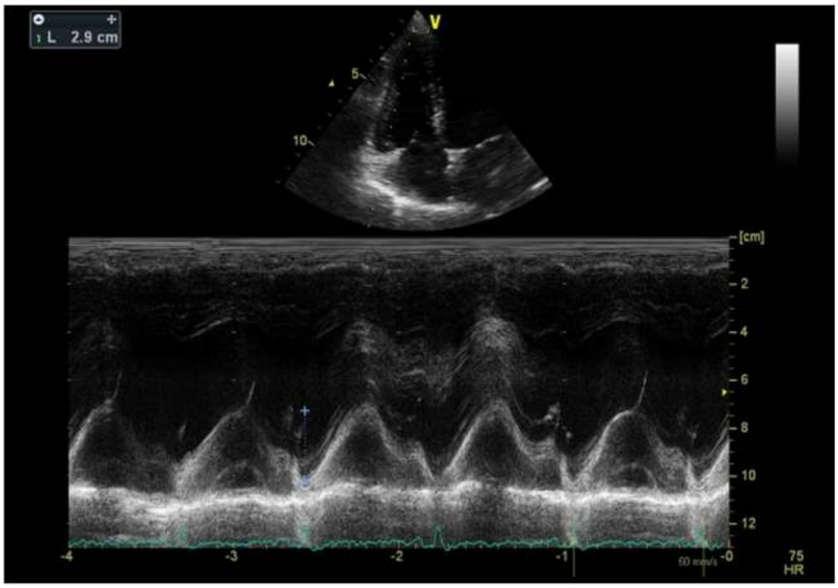


Fig. 1 Tricuspid annular plan systolic excursion (TAPSE). It is assessed by M-mode in apical four chambers view, placing the 2D cursor at the tricuspid lateral annulus and measuring the distance of it excursion along a longitudinal line defining the end of systole as the end of the T wave on the ECG

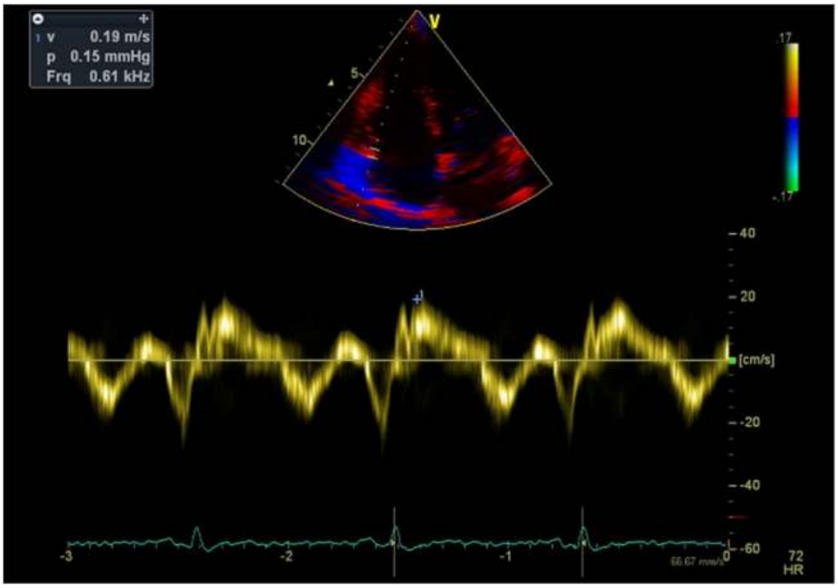


Fig. 2 Systolic velocity of the tricuspid annulus (s') by tissue Doppler imaging. The pulsed wave cursor is placed at the basal segmental level of the RV free wall in an apical four chambers view

case of significant coronary stenosis or ventricular hypertrophy. There are some main concerns, though: the scarce distribution to RV and posterior IVS [41, 42], the extreme variability of cardiac venous system anatomy, and the insufficient capillary flow due to the large amount of cardioplegic solution delivered into the RV through the Thebesian system [43]. Currently, a combined approach is recommended to minimize the potential risk of post-ischemic myocardial damage. Performing surgery at 32–33 °C seems the best compromise to preserve heart and brain metabolism [44, 45]. In fact, tepid cardioplegia seems to overcome the limitations of both cold and warm types, reducing metabolic demands, and allowing an immediate recovery of cardiac function [46]. Cardiopulmonary bypass (CPB) represents the gold standard equipment for ECC in most of the cardiac surgical procedures. It provides optimal conditions (bloodless field and arrested heart) but the blood passage through a foreign, nonendothelial surface and subsequent reintroduction into the body, may lead to an inflammatory response that triggers a powerful thrombotic stimulus and production of vasoactive and cytotoxic substances. A prolonged duration of ECC is correlated to a higher risk of cardiac and non-cardiac damages. To overcome the limitations of standard ECC, a minimally invasive ECC (MECC) has been introduced in clinical practice, with minimized hemodilution and mechanical trauma. In the late 90s, another approach has made inroads in CABG surgery: the beating heart or "off-pump" procedure. As easily perceivable, cardioplegia is not performed, with no need for ECC. Even if patients need a more aggressive anticoagulant therapy in the post-operative period, a lower rate of transfusion or renal failure and improved outcomes after the surgery have been established also in frailty patients [47]. Moreover, off-pump surgery should be the first choice in case of calcified or diseased ascending aorta, where the ECC cannula might put the patient at high risk of dissection or stroke. New thoracic approaches have been developed to reduce the size of the

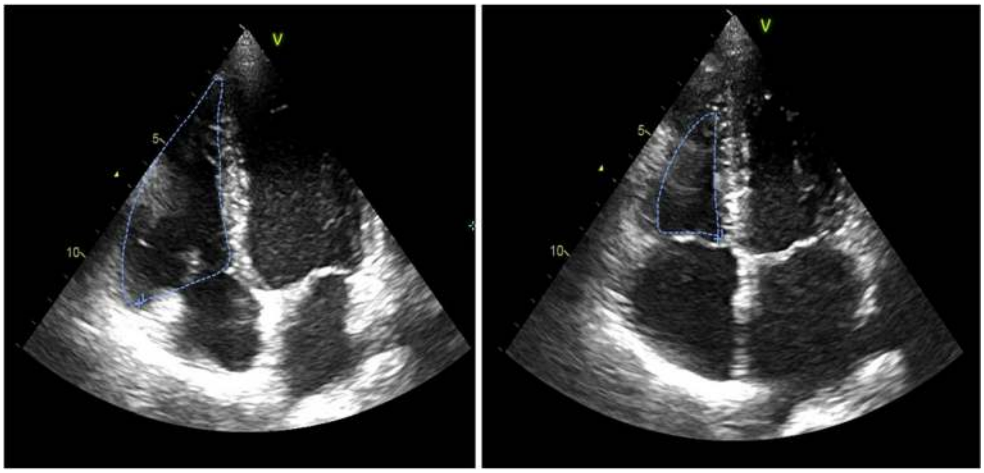


Fig. 3 Right ventricular fractional area change (RVFAC). It is calculated, in apical four chambers view, as the difference between end-diastolic and end-systolic RV area divided by the end-diastolic area and multiplied by 100

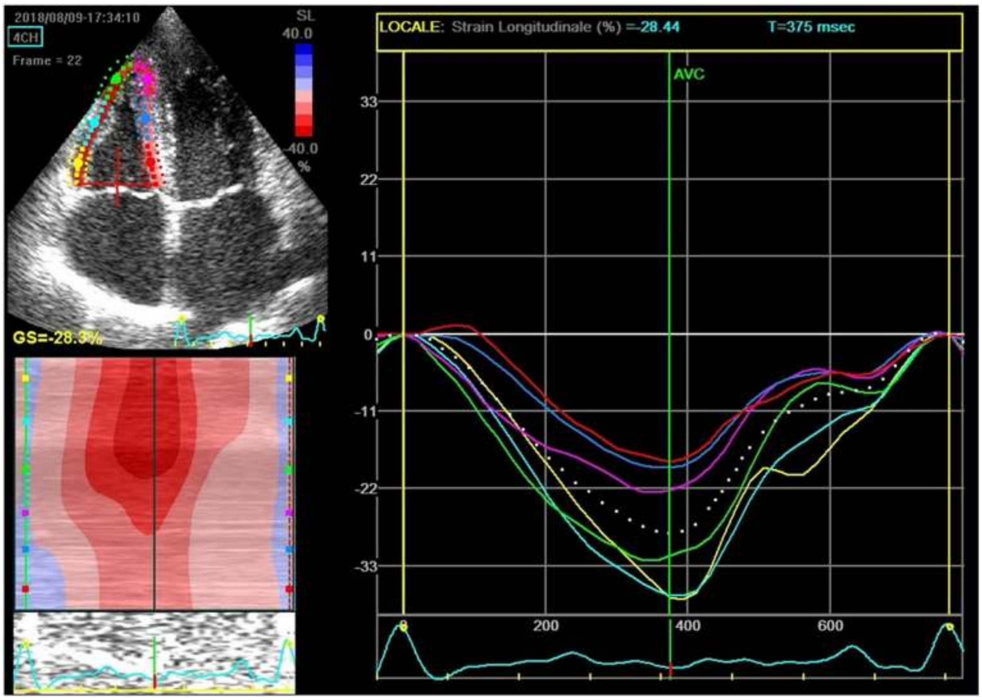


Fig. 4 Global right ventricular longitudinal strain (RVLS). To perform the analysis, an apical four chambers with the complete inclusion of RV wall in the image must be acquired. The operator must accurately trace the endocardial border by a point-and-click approach, obtaining a region of interest composed of six segments (three at interventricular septum, three at free wall). The mean value of the longitudinal deformation of these six segments represents the global RVLS

incision. One of the most currently used approaches is the right anterior mini-thoracotomy for mitral valve surgery. Thanks to the limited heart manipulation and trauma, this is a valuable cost-effect strategy associated with reduced morbidity and mortality and has been established as the routine approach in many centers all over the world [48].

Mechanisms underlying right ventricular dysfunction after cardiac surgery: hypothesis and evidences

Different etiological hypotheses have been raised to explain RV dysfunction in the context of cardiac surgery (Fig. 6). Firstly, a suboptimal myocardial protection during surgery is

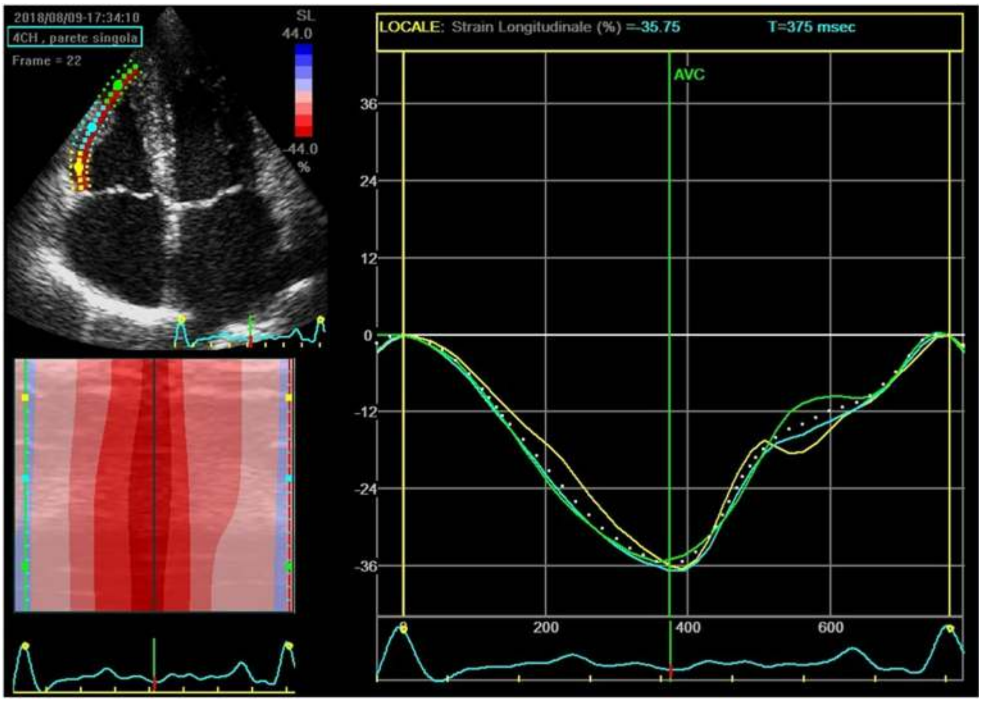


Fig. 5 Free wall right ventricular longitudinal strain (RVLS). By the same point-and-click approach, the region of interest can be focused only at basal, mid, and apical segments of RV free wall

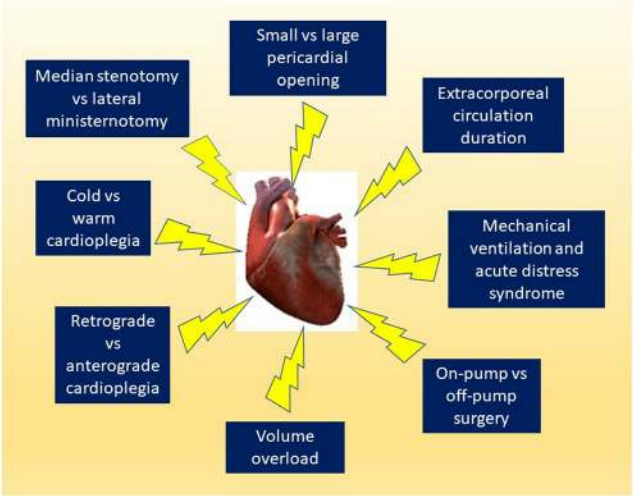


Fig. 6 Imaging illustrating the different hypothesis behind the reduction of RV function after cardiac surgery

included. Several studies have shown a better protection of the RV using warm rather than cold cardioplegia [49, 50], while differences between anterograde or retrograde administration in terms of post-operative dysfunction did not emerge [51]. Also, duration of ECC has a relevant impact on RV function. A retrospective study conducted by Schuuring et al. on more than 400 patients undergoing cardiac surgery for congenital heart disease revealed that a CPB time over 150 min was a strong determinant of clinical RV failure regardless of the site of surgery [52]. The most accredited theory beyond this relationship would lie in the role of cytokines, mostly endothelin-1, that induce a vasoconstrictive effect on pulmonary arterioles with consequent increase in pulmonary pressures and RV afterload [53]. The adherences following pericardiotomy may impair RV filling and lead to its dysfunction [54]. Coronary embolism or graft acute occlusions can represent other risk factors for RV functional alteration [55]. In particular, if the right coronary artery (RCA) is stenotic, a reduced perfusion during surgery might reduce RV contractility. In a small cohort of patients with different degrees of RCA stenosis referring for CABG, RV volumes increased and RV ejection fraction decreased in the group undergoing only circumflex and left anterior descending arteries revascularization (because the RCA stenosis was considered not significant), but not in those undergoing RCA revascularization [56]. Moreover, the development of ventilatory problems or of acute respiratory distress syndrome (ARDS) during the perioperative respiratory assistance adversely affects RV function. Incidence of ARDS in cardiac surgery patients is estimated around 10% [57]. The type of ventilation is crucial in causing these alterations: the use of high tidal volumes elicits compression on alveolar vessels that raises pulmonary vascular resistance and RV afterload [58] and stretch of alveolar walls, responsible for a ventilator-induced lung injury [59], leading to subsequent RV dysfunction. Finally, the hypothesis of volume overload as a possible mechanism of post-operative RV dysfunction has been proposed. Guinot et al. [60] found that RV dysfunction foreruns renal dysfunction in the early post-operative period, and this was correlated with dilated inferior vena cava and increased central venous pressure, but not with an improved cardiac index, suggesting congestion as the responsible.

Changes in RV function after cardiac surgery: which parameters alter?

Several studies addressing the echocardiographic assessment of RV function after cardiac surgery evaluated the abovementioned parameters. TAPSE and s' appear to be reduced in subjects undergoing surgery for both congenital and acquired heart diseases [61–63]. However, when we consider global RV function, results are mostly variable. In 40 patients evaluated at a 3-month follow-up after mitral valve surgery, Tamborini et al. [64] found that TAPSE and s' were significantly reduced (25.3 + 4 vs 15.5 + 3 mm and 17.8 + 4 vs 11.9 + 2 cm/s, respectively, all $p < 0.0001$). On the contrary, 3D echocardiography revealed no differences in RV dimensions and, above all, RVEF did not change accordingly. Interestingly, in this study, at 6- and 12-month follow-up, both TAPSE and s' returned to normal values. 3D assessment of RV function with TAPSE and s' in this setting of patients is recommended, when possible, also by Lang et al. [13]. Data regarding RVFAC are still conflicting [65–67], while RIMP emerges to improve after surgery [67, 68]. To prove that the main culprit of the loss of RV longitudinal function is the pericardial opening, in 2010, Unsworth and colleagues [69] decided to perform not only transthoracic echocardiography with TAPSE analysis before and after CABG, but also transesophageal echocardiography during surgery, with repetitive measurement of s' from the onset of general anesthesia to the end of the operation. Compared with preoperative values, s' was reduced by 44 ± 17% ($p < 0.0001$) in the first 3 min after pericardium opening, by 54 ± 11% ($p < 0.0001$) after 5 min and by 61 ± 11% ($p < 0.0001$) at the time of skin suture, independently of "on-pump" or "off-pump" procedure and cardioplegia. To confirm the hypothesis, successive studies compared parameters of RV longitudinal function in standard sternotomy with anterior pericardiotomy vs mini-thoracotomy with lateral smaller pericardial opening (in which, anyway, CPB and cross-clamp times are quite longer) [66, 70]. TAPSE was lower after surgery but with a systematic greater reduction in the full sternotomy group, again with no changes in 3D RVEF. In 42 patients undergoing cardiac surgery for mitral valve repair, RVLS was evaluated, in addition to the other indexes. With good reproducibility and interobserver agreement, at 6-month follow-up, both free wall RVLS and septal RVLS values were lower than pre-surgical ones (− 26.5% vs − 18% and − 20.8% vs 14.1%, respectively) in

Table 2 Prognostic value of right ventricular parameters after cardiac surgery

Index and cut-off	Number of pts	Population of pts	Results	Ref.
RVFAC < 35%	$n = 60$	Unstable post-operative Pts	RV dysfunction was associated with high mortality rates during ICU stay	Reichert et al. [72]
RVFAC < 35%	$n = 41$	Pts with LVEF < 25% undergoing elective CABG	RV dysfunction was associated with poor early and late outcome	Maslow et al. [73]
RVFAC < 32% and RIMP ≥ 0.50	$n = 50$	Pts undergoing corrective mitral or aortic valve surgery	RV dysfunction was associated with high mortality rate and risk of circulatory failure. RV function correlates with days in ICU and hospital	Haddad et al. [74]
TAPSE < 16 mm	$n = 324$	Pts with HF undergoing surgical ventricular reconstruction after MI	RV dysfunction predicted long-term mortality, incidence of low-output syndrome, inotropic support, and IABP insertion	Garatti et al. [75]
RVFAC < 35% or RVFAC > 25% and RVLS < 21%	$n = 250$	Pts referred for mitral and/or aortic valve surgery and CABG	RV clinical or subclinical dysfunction was associated with high post-operative mortality rate	Ternacle et al. [76]

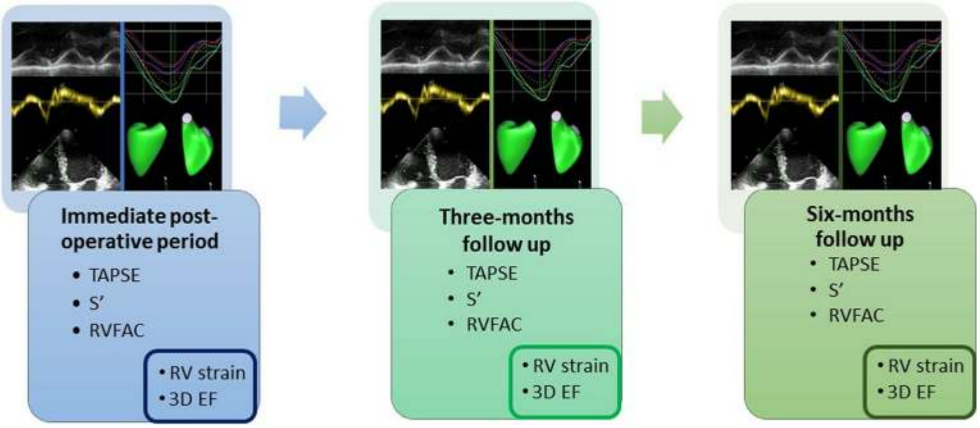
TAPSE tricuspid annular plane systolic excursion, *RIMP* right index of myocardial performance, *RVFAC* right ventricular fractional area change, *RVLS* right ventricular longitudinal strain

accordance with TAPSE and s' reduction [65]. Analogously, RVLS decreased after correction of congenital heart defects in infants compared with baseline (− 10.7% vs − 19.7%, $p < 0.0001$) with good correlation between strain and z-score of TAPSE and s' [71].

Impact of RV dysfunction on prognosis of patients after cardiac surgery

Table 2 lists some of the main papers regarding the impact of RV dysfunction on the short- and long-term prognosis of patients undergoing cardiac surgery. Reduced RV longitudinal or global function is associated with a higher risk of events, mainly of cardiovascular death. In the early post-operative period, incidence of RV dysfunction in patients with hemodynamic compromise was around 50% [77] and a RVFAC below 35% was associated with a high mortality rate [72, 73]. In a population of 50 patients with heart valve disease treated with surgery, both altered RVFAC and RIMP were able to predict a poor long-term outcome, improving risk stratification better than LV function. The composite endpoint included cardiovascular death and circulatory failure and a worse RV function was correlated with the duration of intensive care unit and in-hospital stay [74]. A value of TAPSE < 16 mm predicted 5-year and 8-year mortality rate after ventricular surgical reconstruction in patients with heart failure. Moreover, in the perioperative period, RV dysfunction was associated with higher incidence of low-output syndrome, inotropic support, and intra-aortic balloon pump insertion [75]. The importance of RV longitudinal deformation emerged mostly in the correlation between preoperative RVLS and outcome. In a large cohort of patients referring to different heart diseases, a RVFAC < 35% was associated with the greatest risk of post-operative mortality. In the case of preserved RV global function, mortality rate of patients with a RVLS > − 21% was similar to

Fig. 7 Systematic assessment of right ventricular function after cardiac surgery. A complete echocardiogram including TAPSE, s', and RVFAC should be performed in the early post-operative period and successively at 3 and 6 months. Completing the exam with right ventricular longitudinal strain by speckle tracking echocardiography and the measurement of ejection fraction by 3D echocardiography can be useful, when available



those with RVFAC < 35% (20% vs 32%; $P = 0.12$). At multivariate analysis, after adjustment for CPBP duration and EuroSCORE II, only global RVLS was associated with patients' outcomes [76]. Free wall RVLS has a key role in the selection of patients for the implant of a LV assist device in advanced heart failure as the presence of a pre-implantation reduced longitudinal deformation is indicative of an extremely high risk of developing RV failure in the early or late post-operative period [78, 79].

Echo-guided treatment of RV function after cardiac surgery

In the case of a mild-moderate RV dysfunction without hemodynamic impact, a tailored follow-up of the patient with particular attention on the evolution of biventricular function is indicated. It is not uncommon to find a complete restoration of RV longitudinal deformation with time. In the immediate post-operatory setting, in the case of true RV failure, echocardiography helps the intensivists to validate the diagnosis together with the clinical clues and to guide therapeutic support. Starting from the need for a preload optimization, ultrasounds guide fluids administration in case of low RV filling pressure (i.e., low RA pressure) to optimize cardiac output [80]. Anyways, for the mentioned interventricular interdependence, a rapid fluid overload should be avoided to not reduce LV function. Based on RV dysfunction and pulmonary pressures, inotropic or vasopressor support (e.g., dobutamine, milrinone, norepinephrine) can be required and echocardiography has a key role in their management [81, 82]. Pulmonary embolism should be also excluded and, in addition to vital parameters, arterial blood gas and ECG, evaluation of RV helps in the decision making before a thoracic CT scan.

Conclusions

Right ventricle assumes great importance after cardiac surgery mostly because of its relevant prognostic impact. Beyond all the hypothesized etiologies, a complete assessment of RV size, longitudinal and global function should be performed before and after the intervention to optimize patients' management. Echocardiography, both with standard indexes and second level techniques including 3D and STE, represents a non-invasive and reliable tool for this purpose. Figure 7 shows a proposed algorithm for a step-by-step evaluation of post-operative RV function. A complete exam systematically including TAPSE, s', and RVFAC assessment should be performed soon after the surgery and repeated after 3 and 6 months to verify the possible complete restitution of RV longitudinal function. In the case of available second level echocardiographic tools, evaluation of 3DEF and RV longitudinal strains should complete the screening.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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