



# Severe loss of right ventricular longitudinal contraction occurs after cardiopulmonary bypass in patients with preserved right ventricular output

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## Abstract

Assessment of right ventricular (RV) function is crucial since RV failure with a reduced cardiac output (CO) is associated with compromised outcome in cardiac surgery. Echocardiographic evaluation of RV function is commonly used, but a reduction in tricuspid annular plane systolic excursion (TAPSE) and tricuspid annulus tissue Doppler imaging (S') have been observed independently of clinical signs of RV failure. This has led to uncertainty of these variables' validity in cardiac surgery. To describe transesophageal echocardiographic (TEE) measures of RV function during coronary artery bypass graft surgery with detailed haemodynamic assessment using pulmonary artery catheter (PAC) measurements to describe “natural” changes in the absence of RV failure. We prospectively studied 30 patients with concomitant PAC and TEE measurements at four time-points, namely after: anaesthesia induction, sternotomy, cardiopulmonary bypass (CPB) and upon arrival in the intensive care unit. TAPSE and S' were significantly reduced by 43% ( $p < 0.0001$ ) and 22% ( $p = 0.006$ ), respectively after CPB without any change in stroke volume (SV). RV ejection fraction (RVEF), RV fractional area change (RVFAC) and global longitudinal strain (RV-GLS) remained unchanged. SV measured with 3D echocardiography correlated with PAC measured SV ( $r = 0.66$  [95% CI 0.50; 0.78],  $p < 0.0001$ ), but 3D showed a minor, but statistically significant underestimation of SV (8.5 ml (95% CI 2.7 ml; 14 ml,  $p = 0.004$ )). TAPSE and S' were both reduced after CPB despite maintained CO. RVFAC, RVEF and RV-GLS remained stable, however, these measures were unable to detect minor changes in SV. 3D-echocardiography showed a strong correlation with SV measured by thermodilution, but with a consistent underestimation of approximately 10%.

**Keywords** Right ventricle · Tricuspid annular plane systolic excursion · Three-dimensional echocardiography · Global longitudinal strain · Coronary artery bypass graft surgery

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## Introduction

Right ventricular (RV) function is a key determinant of outcome after cardiac surgery [1–3]. The occurrence of RV dysfunction is highly dependent on how it is defined but an incidence up to 30% is reported after coronary artery bypass graft (CABG) surgery [3]. Since longitudinal contraction contributes with 80% of RV output in the normal heart echocardiographic evaluation has traditionally focused on longitudinal contraction [4]. Echocardiography is a cornerstone in diagnosing RV dysfunction, but there is no consensus on which variable is optimal for the diagnosis, especially in cardiac surgery. One of the common measures of longitudinal contraction is tricuspid annular plane systolic excursion (TAPSE), but studies have shown that TAPSE and other measures evaluating longitudinal contraction (i.e.

tissue Doppler imaging of the tricuspid annulus ( $S'$  and longitudinal strain) decrease during cardiac surgery despite no change in global echocardiographic parameters i.e. RV ejection fraction (RVEF) and RV fractional area change (RVFAC) [5–8]. We have shown that TAPSE decreases after cardiopulmonary bypass (CPB) for both CABG and surgical aortic valve replacement and that the decrease is present up to one year after aortic valve replacement [5, 9], but without any clinical signs of RV dysfunction. In the former CABG study, a pulmonary artery catheter (PAC) was not applied so RV output was evaluated with velocity time integral of the pulmonary artery, with the inborn limitations of velocity and flow correlation [9].

Guidelines suggest that alternatives to TAPSE in RV evaluation include RVFAC and  $S'$  [10]. Both measures have shown acceptable correlations with magnetic resonance imaging (MRI) RVEF in non-cardiac surgery populations [11, 12]. RVFAC has also shown reasonable correlation with RVEF from 3D echocardiography performed before CPB [13]. The gold standard for non-invasive RV stroke volume (SV) measurement is MRI, but that is not possible for intraoperative, continuous monitoring. Instead, the thermodilution technique is preferred [14, 15]. We wanted to study if the reduction in TAPSE reflected RV SV changes, measured by the most validated method possible or occurred independently. We therefore used a thermodilution PAC to measure RV SV with the aim to describe the relation between changes in RV SV and TAPSE as well as additional echocardiographic variables, including 3D estimation of RV SV, during CABG surgery. The purpose of the present study was to obtain knowledge on echocardiographic changes in patients with preserved RV output in low risk patients undergoing CABG. It is a prerequisite to identify “natural” changes prior to identification of echocardiographic alterations in patients with RV failure. This is the first study to use 2D and 3D transesophageal echocardiography (TEE) measurements alongside PAC evaluation during and immediately after CABG surgery.

## Materials and methods

### Design

This was a prospective, single-centre, observational study conducted at a tertiary university hospital between May 4th and October 5th, 2017. The study was approved by the Regional Ethics Committee (Journal suite H-17005565) and patients gave informed consent. This paper describes the intraoperative endpoints from the Right Ventricular Echocardiography in cardiac SurgEry (ReVERSE) study ([www.clinicaltrials.gov](http://www.clinicaltrials.gov) identifier NCT03301571).

### Patients

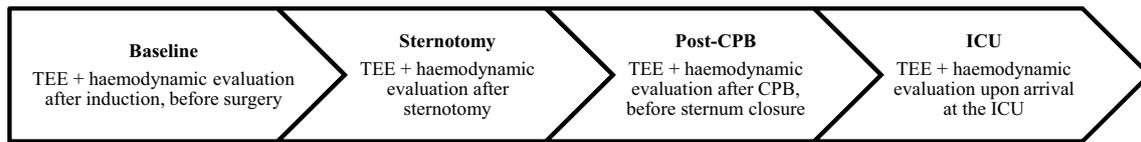
Eligible patients were approached and included before the day of surgery. Inclusion criteria were: adult ( $\geq 18$  years) patients scheduled for elective on-pump CABG surgery and left ventricular ejection fraction of 50% or more on the preoperative transthoracic echocardiography (TTE). Exclusion criteria were: preoperative RV impairment, pulmonary hypertension (estimated RV systolic pressure  $> 25$  mmHg), non-sinus rhythm, aortic, mitral, or tricuspid valve stenosis or severe regurgitation on the preoperative TTE or the first intraoperative TEE. Five patients with physiological/mild tricuspid regurgitation were not excluded. Patients with intracardiac shunts or contraindications to TEE and/or PAC placement were excluded.

### Procedure

Patients were monitored with electrocardiogram and intra-arterial blood pressure measurement. All patients received general anaesthesia, tracheal intubation and were ventilated with tidal volumes of 6–10 ml/kg. Anaesthesia induction was achieved with propofol, midazolam and fentanyl and afterwards a TEE probe was inserted into the oesophagus (Philips X7-2t connected to Philips Epiq 7C ultrasound system, Philips Healthcare, Andover, MA, USA) and a 7.5 French PAC (Edwards Lifesciences, Irvine, CA, USA) was placed in the pulmonary artery via the right internal jugular vein. Anaesthesia was maintained with sevoflurane, propofol and remifentanyl at the choice of the treating anaesthetist. At this time a baseline TEE was performed, and PAC haemodynamic measurements were recorded. Cardiac output (CO) was measured using the thermodilution technique with 10 ml tepid saline and SV was calculated as CO/heart rate (HR). Triple CO measurements with less than 20% variation were performed and mean value of the three measurements were used. Haemodynamic measurements were taken again after sternotomy, after CPB (defined as complete separation after heparin reversal, but before sternal closure) and repeated upon arrival in the intensive care unit (ICU) (Fig. 1).

### Echocardiography

At the same timepoints of haemodynamic evaluation a TEE evaluation was performed. Images and haemodynamic evaluations were acquired when the patient was haemodynamically stable. This was defined as mean arterial pressure with  $\leq 5$  mmHg variation and central venous pressure with  $\leq 3$  mmHg variation and stable HR with  $\leq 10$  beats/min variation and no boluses of vasopressors or inotropes given prior to image acquisition (assessed for 5 min prior). The



**Figure 1** Time points for echocardiographic and haemodynamic measurements. *CPB* cardiopulmonary bypass, *ICU* intensive care unit, *TEE* transesophageal echocardiography

surgeon refrained from bipolar coagulation and manipulation of the heart during image acquisition. TEE TAPSE with anatomical M-mode and S' were both acquired in the transgastric view. These views and the use of anatomical M-mode were chosen because it has previously been shown that these views have high availability and agreement with corresponding TTE measures [16, 17]. RVFAC and RV-GLS were measured on four-chamber 2D images using speckle tracking (TomTec 2D cardiac performance analysis, TomTec Imaging Systems, Unterschleissheim, Germany). We used automated border delineation and afterwards borders were reviewed and manually fitted to minimize errors. RV SV and RVEF were acquired from full-volume 3D images using TomTec 4D-RV-Function software (TomTec Imaging Systems, Unterschleissheim, Germany). 3D images were acquired over five cardiac cycles to improve frame rate. In the protocol we intended to include Tei index, but this was abandoned because we could not achieve reliable pulsed-wave Doppler measurements across the tricuspid valve. Mitral annular plane systolic excursion was also abandoned due to time constraints intraoperatively. The TEE probe was left in situ when the patient was transported to the ICU to perform the postoperative TEE.

## Statistics

Continuous variables are presented as mean (SD) or median [IQR] depending on distribution. Categorical variables are presented as counts and proportions. No generally validated sample size calculation method exists for random effects in mixed models. Our sample size estimation was based on a previous study where we found a baseline TAPSE of 2.4 cm (SD 0.5) [5]. For repeated measures ANOVA 24 patients would be required to detect a 20% reduction/increase in TAPSE with a power of 0.8 and a risk of type I error of 5% and an estimated correlation of 0.4. For a paired t-test with the same prerequisites 13 patients would be required. Because adequate echocardiographic images can be difficult to obtain in cardiac surgery and to account for the estimation in our sample size calculation we decided to include 30 patients. After the study we performed a post hoc power calculation for a repeated measures fixed effects model with the observed correlation pattern from TAPSE and this yielded a power of 0.94 [0.91–1.00].

To assess changes over time in haemodynamic and echocardiographic variables we fitted repeated measures mixed models using restricted maximum likelihood with time as fixed effect and random intercepts for each patient. Covariance structures and models were compared with log-likelihood ratio statistics and unstructured covariance structure was used if it provided the best fit. Overall significance was established with F-statistics. We used Dunnett's correction to adjust for multiple comparisons within each model and Holm–Bonferroni to correct for multiple F-tests. To compare SV from thermodilution and 3D echocardiography and determine overall bias between the methods, we constructed a mixed model with time and measurement method as fixed effects and random intercepts for each patient and unstructured covariance structure. For all regression models, we performed model control by evaluating residual plots. We calculated the within-subject correlation coefficient of SV from thermodilution and echocardiography, using a repeated measures analysis of covariance method with random intercepts for each patient as described in detail previously [18]. For correlation coefficient statistics our sample size was large enough to detect a medium effect size of 0.3 with a power of 0.8 and an alpha of 5%.

All tests were two-sided and p-values after correction for multiple comparisons < 5% were considered significant. Statistics were performed with R (version 3.5.1, 2018, Boston, MA).

## Results

### Clinical characteristics

Thirty patients scheduled for elective CABG were included. Patient characteristics are shown in Table 1. They were low risk patients (EuroSCORE II 0.98 [0.80–1.34]). The majority (57%) had three vessel coronary artery disease while 43% had two vessel disease. Three patients (10%) received norepinephrine for weaning from CPB and six patients (20%) received a nitroglycerine infusion. Eleven patients (36%) required epicardial pacing during weaning from CPB due to sinus bradycardia, but none required pacing upon arrival in the ICU. Time between weaning from CPB and ICU measurements was 76 min

**Table 1** Baseline characteristics

	N = 30
<b>Patient characteristics</b>	
Age (years), mean $\pm$ SD	61 $\pm$ 9.6
Gender (female), n (%)	4 (13)
Weight (kg), mean $\pm$ SD	91 $\pm$ 15
BMI (kg/m <sup>2</sup> ), mean $\pm$ SD	29.3 $\pm$ 4.7
EuroSCORE II (%), median [IQR]	0.98 [0.80–1.34]
COPD, n (%)	5 (17)
Current smoker (within 1 month), n (%)	12 (40)
Pack years for smokers (current and previous) <sup>a</sup> , median [IQR]	37 [30–44]
Two vessels disease, n (%)	13 (43)
Three vessels disease, n (%)	17 (57)
Right coronary artery diseased, n (%)	24 (80)
Hypertension, n (%)	21 (70)
Peripheral vascular disease, n (%)	6 (20)
Previous myocardial infarction, n (%)	10 (33)
Previous percutaneous coronary intervention, n (%)	5 (17)
CCS class I, n (%)	9 (30)
CCS class II, n (%)	12 (40)
CCS class III, n (%)	7 (23)
CCS class IV, n (%)	2 (6.7)
Diabetes type I, n (%)	3 (10)
Diabetes type II, n (%)	9 (30)
Preoperative creatinine (mmol/l), mean $\pm$ SD	90 $\pm$ 16.5
<b>Medication</b>	
Preoperative beta-blocker, n (%)	14 (47)
Preoperative ACE/ATII inhibitor, n (%)	12 (40)
Preoperative calcium channel blockers, n (%)	6 (20)
Nitroglycerine, n (%)	18 (60)
Diuretics, n (%)	10 (33)
Statins, n (%)	23 (77)
Acetylsalicylic acid, n (%)	24 (80)
<b>Preoperative echocardiography</b>	
LVEF (%)	57 $\pm$ 4.7
LVIDd (cm) <sup>a</sup>	4.8 $\pm$ 0.45
LV mass index (g/m <sup>2</sup> ) <sup>a</sup>	86.3 $\pm$ 22.5
TAPSE (cm) <sup>a</sup>	2.6 $\pm$ 0.46

ACE angiotensin converting enzyme, ATII angiotensin II receptor, BMI body mass index, CCS Canadian Cardiovascular Society, COPD chronic obstructive pulmonary disease, LV left ventricular, LVEF left ventricular ejection fraction, LVIDd left ventricular internal diameter in diastole, TAPSE tricuspid annular plane systolic velocity

<sup>a</sup>Missing pack years: 7 patients. LVIDd: 11 patients, LV mass index: 13 patients. TAPSE: 7 patients [these patients had preoperative TAPSE registered as “normal (> 1.8 cm)” in the patient medical journal. Original images were not available]

(SD 18). One patient was re-operated the same day due to bleeding. Another patient was re-operated the following day because the left internal mammary artery (LIMA) graft to the left anterior descending artery was kinking intermittently, which was identified by performing a coronary angiography the day after surgery, because creatine

kinase-MB increased to 107  $\mu$ g/l and the patient developed ST-segment elevation in ECG lead aVL and I. The right coronary artery was not grafted during the primary operation, and since LIMA did not supply the RV, patient data were not excluded from analysis. All patients were discharged home after a median hospital stay of 6 days [5–7].

## Haemodynamic characteristics

Table 2 displays haemodynamic and echocardiographic data. CO increased 44% following CPB, mainly due to an increase in HR compared to baseline, and CO remained significantly increased despite a decrease in SV of 15% compared to baseline upon arrival in the ICU. Systemic vascular resistance (SVR) was significantly reduced immediately after CPB (26% decrease,  $p < 0.0001$ ). Pulmonary vascular resistance (PVR) decreased by 15% immediately after CPB which was not significant, and overall there was no significant change in PVR. Both vascular resistances returned to baseline level in the ICU. The PVR/SVR ratio was constant throughout the study.

## Echocardiographic results

Echocardiographic results are shown in Table 2 and Fig. 2. TAPSE decreased by 43% after CPB (2.0 cm SD 0.43 vs. 1.2 cm SD 0.39,  $p < 0.0001$ ) and continued to decrease in the ICU (59% decrease from baseline,  $p < 0.0001$ ). The same pattern was seen in  $S'$  decreasing by 22% after CPB ( $p = 0.006$ ) and 29% in the ICU ( $p < 0.0001$ ) compared to baseline. RVFAC, RVEF and RV-GLS did not change significantly. In the ICU SV from 3D echocardiography decreased by 15% ( $p < 0.0001$ ). SV from 3D echocardiography demonstrated a reasonable correlation with SV measured by PAC ( $r = 0.66$  (95% CI 0.50; 0.78),  $p < 0.0001$ ) (Fig. 3), but 3D echocardiography underestimated SV by on average 8.5 ml (95% CI 2.7 ml; 14 ml),  $p = 0.004$ . The changes in SV were driven by changes in end-diastolic volume, whereas end-systolic volume did not change significantly throughout the observation period. SV assessed with PAC had statistically significant, although low correlations with TAPSE, RV-GLS and RVEF, but not with RVFAC and  $S'$ .

## Discussion

It is essential in cardiac surgery to quantify RV function pre-, peri- and postoperatively to identify patients at risk of developing RV failure [19]. However, a prerequisite to identify abnormalities is to know what can be characterised as normal changes in a setting with uncomplicated surgery, without any haemodynamic compromise. Study inclusion was therefore based on low-risk patients with normal preoperative RV and LV function undergoing isolated CABG. Haemodynamic measurements from PACs were used to validate normal RV function during the study. This study demonstrates how longitudinal contraction was significantly and uniformly reduced in all patients after CPB in CABG surgery and further reduced in the immediate postoperative period despite a preserved CO, making assessment of

longitudinal contraction as a single variable unsuitable for RV assessment in cardiac surgery. After weaning from CPB, SV measured by PAC was unchanged compared to baseline, and at the same time TAPSE was reduced by 43% and  $S'$  was reduced by 22%. This is in agreement with previous studies demonstrating a reduction in TAPSE by approximately 50% in CABG surgery without other echocardiographic or clinical indications of RV dysfunction [9, 20]. The current study is, to our knowledge, the first to report a full haemodynamic assessment based on PAC measurement along with 2D and 3D echocardiographic evaluation assuring that RV output is preserved despite the marked changes in longitudinal contraction. Studies have shown that TAPSE is reduced postoperatively after both aortic valve replacement and mitral valve replacement while RVEF is unaffected [7, 21]. In contrast a high correlation coefficient of 0.86 has been found between RVEF and TAPSE in pulmonary hypertensive patients, when used for consecutive assessment of RV function [22, 23], indicating that after heart surgery the contribution of longitudinal contraction is reduced without change in overall RV function. This observation is supported by studies showing a change in contraction pattern after cardiac surgery, where the decrease in longitudinal contraction is partly compensated by increased transverse contraction [7, 20, 24]. For TAPSE to be a valid surrogate for RV function, the longitudinal contraction must be the main contributor of RV output and collisions between echocardiographic modalities can be explained by a change in contraction pattern. We used SV measurements based on thermodilution and found a weak, but significant correlation between TAPSE and SV [ $r = 0.38$  (95% CI 0.18; 0.56),  $p = 0.0005$ ]. This is very similar to a study by Tousignant where the correlation coefficient between SV and TAPSE was 0.48 [25]. In contrast, a recent study showed that TAPSE had a good correlation with RVEF from PAC after cardiac surgery ( $r = 0.73$ ,  $p < 0.001$ ). However, in the latter study, there were no preoperative TAPSE or RVEF stated, so it is not known if the patients had preoperative RV dysfunction. Patients differed from our cohort in having low postoperative RVEF (26.2%, SD 9.7) and elevated mean pulmonary pressure (29.5 mmHg, SD 7.9), even though TAPSE was comparable to what we observed (11.4 mm, SD 4) [26], implying that TAPSE can be low irrespective of whether RVEF is reduced. SV remained unchanged throughout surgery, but decreased in the ICU, whereas RVEF and RVFAC were unchanged during the entire study. Normal RV contraction involves an inwards bowing of the free wall and further contribution from the outflow tract. The advantage of using RVEF and RVFAC is that they include the radial components of contraction and RVEF also includes the contribution from the outflow tract [27]. However, both methods require a high image quality to trace the endocardium, which can interfere with the modalities' precision and can explain why minor changes in SV are not

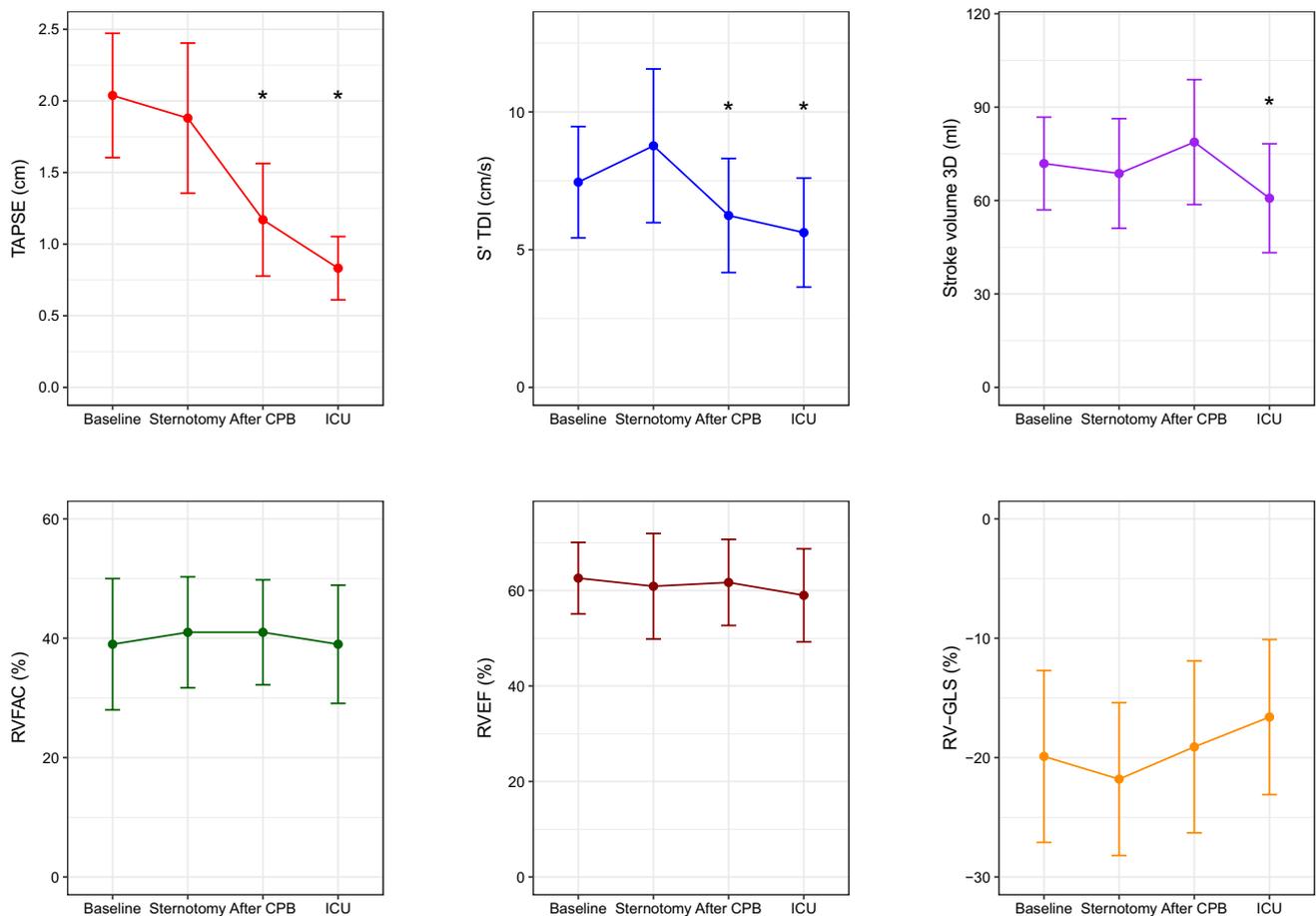
**Table 2** Change in haemodynamic and echocardiographic variables during surgery

Variables <sup>a</sup>	Baseline	SD	Sternotomy	SD	p-values	Post-CPB	SD	p-values	ICU	SD	p-values	F-statistics
HR (beats/min)	55	±8.9	61	±9.8	< 1 × 10 <sup>-4</sup>	80	±7.3	< 1 × 10 <sup>-4</sup>	74	±12	< 1 × 10 <sup>-4</sup>	<b>F<sub>3,87</sub> = 81.3, p &lt; 1 × 10<sup>-4</sup></b>
PAC SV (ml)	81	±17	78	±19	0.84	81	±20	0.84	69	±20	<b>0.001</b>	<b>F<sub>3,86</sub> = 7.40, p = 0.001</b>
CO (l/min)	4.47	±1.02	4.65	±1.12	0.18	6.40	±1.34	< 1 × 10 <sup>-4</sup>	5.04	±1.67	<b>0.012</b>	<b>F<sub>3,86</sub> = 36.8, p &lt; 1 × 10<sup>-4</sup></b>
SVR (dynes s cm <sup>-5</sup> )	992	±287	970	±313	~ 1	730	±194	< 1 × 10 <sup>-4</sup>	1031	±406	~ 1	<b>F<sub>3,86</sub> = 17.2, p &lt; 1 × 10<sup>-4</sup></b>
PVR (dynes s cm <sup>-5</sup> )	148	±49	154	±52		126	±77		145	±47		<b>F<sub>3,86</sub> = 1.66, p = 0.91</b>
PVR/SVR ratio	0.15	±0.050	0.17	±0.051		0.17	±0.07		0.15	±0.050		<b>F<sub>3,86</sub> = 1.22, p ≈ 1</b>
PAPm (mmHg)	18.0	±4.5	19.9	±5.2	<b>0.028</b>	19.6	±5.4	0.17	17.1	±4.2	0.17	<b>F<sub>3,86</sub> = 6.28, p = 0.004</b>
TAPSE (cm)	2.04	±0.43	1.88	±0.52	0.16	1.17	±0.39	< 1 × 10 <sup>-4</sup>	0.83	±0.22	< 1 × 10 <sup>-4</sup>	<b>F<sub>3,76</sub> = 98.4, p &lt; 1 × 10<sup>-4</sup></b>
TDI S' (cm/s)	7.95	±2.02	8.77	±2.79	0.15	6.24	±2.07	<b>0.006</b>	5.62	±1.98	< 1 × 10 <sup>-4</sup>	<b>F<sub>3,74</sub> = 9.52, p &lt; 1 × 10<sup>-4</sup></b>
RVFAC (%)	39	±11	41	±9.3		41	±8.8		39	±9.9		<b>F<sub>3,66</sub> = 0.38, p ≈ 1</b>
3D SV (ml)	72	±15	69	±18	0.67	79	±20	0.12	61	±18	< 1 × 10 <sup>-4</sup>	<b>F<sub>3,67</sub> = 19.2, p &lt; 1 × 10<sup>-4</sup></b>
EDV (ml)	116	±25	117	±38	0.36	128	±29	<b>0.035</b>	108	±30	<b>0.034</b>	<b>F<sub>3,67</sub> = 6.92, p = 0.003</b>
ESV (ml)	44	±16	48	±27		49	±16		46	±21		<b>F<sub>3,67</sub> = 0.76, p ≈ 1</b>
RVEF (%)	63	±7.5	61	±11		62	±9.0		59	±9.7		<b>F<sub>3,67</sub> = 1.04, p ≈ 1</b>
RV-GLS	-19.9	±7.2	-21.8	±6.4		-19.0	±7.2		-16.6	±6.5		<b>F<sub>3,66</sub> = 3.09, p = 0.20</b>

CO cardiac output, CPB cardiopulmonary bypass, ICU intensive care unit, RV-GLS right ventricular global longitudinal strain, HR heart rate, PAPm mean pulmonary artery pressure, PVR pulmonary vascular resistance, RVEF right ventricular ejection fraction, RVFAC right ventricular fractional area change, SVR systemic vascular resistance, TAPSE tricuspid annular plane systolic velocity, S' TDI tissue Doppler tricuspid annulus peak systolic velocity, SV stroke volume

Mean ± SD. p-values adjusted for multiple comparisons. F-statistics establish any overall significance

<sup>a</sup>Missing values: baseline/sternotomy/CPB/ICU:TAPSE: 1/5/3/2. TDI S': 1/7/3/5. RVFAC: 2/10/10/1. 3D SV: 3/9/8/2. EDV: 2/10/10/1. ESV: 3/9/8/2. RVEF: 3/9/8/2. RV-GLS: 2/10/10/1. 1 patient was missing baseline PAC measurements due to difficulty getting the PAC into the pulmonary artery

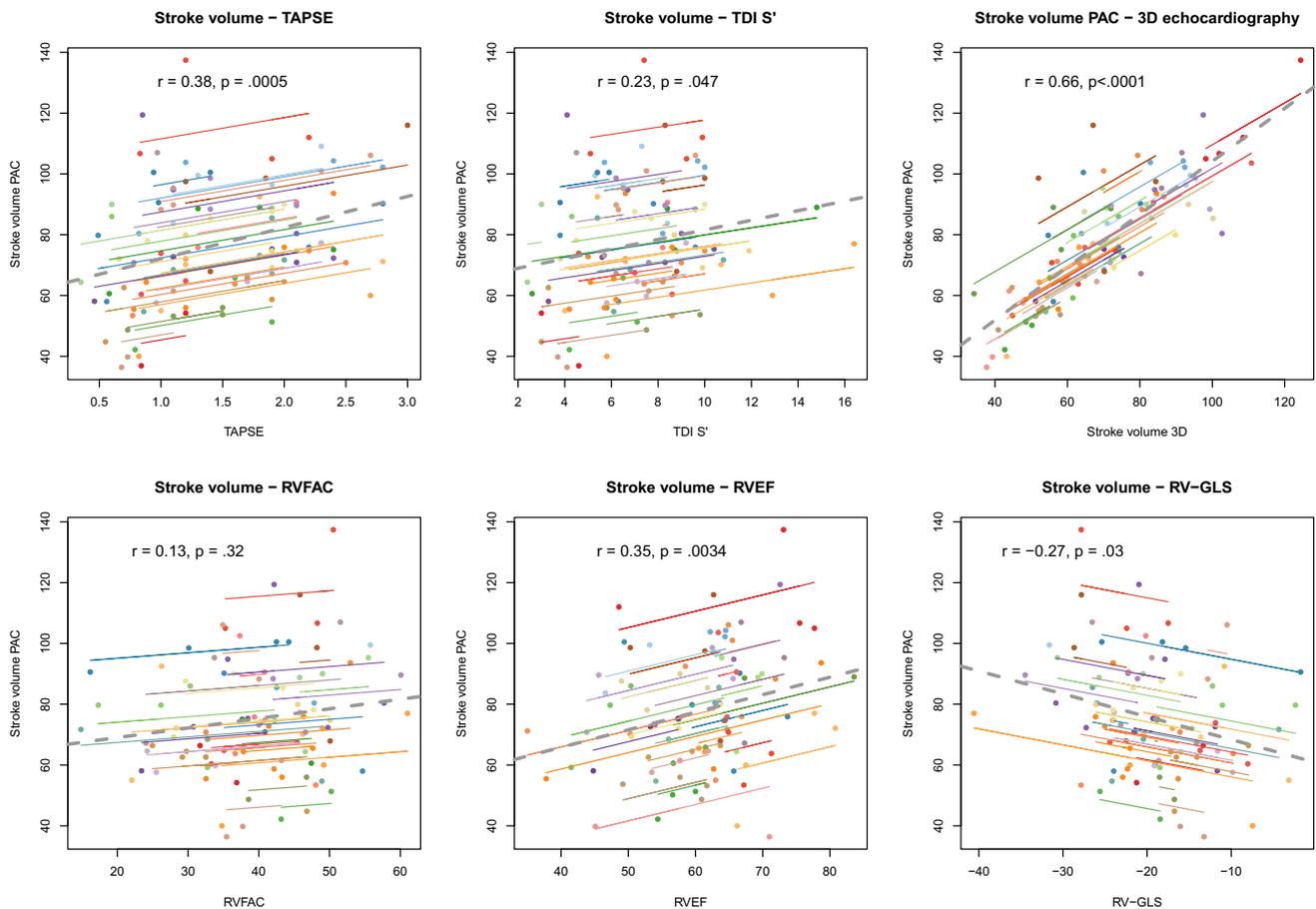


**Figure 2** Echocardiographic measurements of RV function during and after uncomplicated CABG surgery. Error bars represent SD. \*Indicates significant difference from baseline after adjustment for multiple comparisons. CPB cardiopulmonary bypass, ICU intensive

care unit, RVEF right ventricular ejection fraction, RVFAC right ventricular fractional area change, TAPSE tricuspid annular plane systolic velocity, TDIS' tissue Doppler tricuspid annulus peak systolic velocity

detected [5, 28]. Especially in cardiac surgery where good quality images can be difficult to obtain due to the open sternum, air in the field and manipulation of the heart. RV-GLS did not change significantly during the study although it did show a minor decrease in ICU, indicating that it may track SV better than RVFAC and RVEF. SV from 3D echocardiography and SV from thermodilution, showed similar trends at all time points, but echocardiography systematically underestimated SV. Several studies have compared SV assessment based on 3D echocardiography of the LV and thermodilution, but results are conflicting [29, 30]. In agreement with the present study, 3D echocardiography demonstrated clinically acceptable agreement, but 3D echocardiography was unable to track dynamic changes in SV [31]. Our study is the first to compare 3D echocardiography of SV from the RV with thermodilution. Despite the minor absolute difference between 3D and thermodilution SV measurements, the difference cannot be considered clinically negligible. However, the imprecision associated with

both methods can explain the previously observed discrepancy between the two applied methodologies. Thermodilution can overestimate SV when using tepid saline [32, 33], which may have contributed overestimation of RV volumes. Importantly, one study showing overestimation of RV volumes with thermodilution found that RVEF was comparable between the two modalities. [34]. The fact that TAPSE and S' decreased significantly when PVR was reduced after weaning from CPB is counterintuitive since RV emptying is facilitated by a low PVR, but SV was unchanged at the same time-point. However, it should be emphasized that this does not necessarily apply to patients with high PVR as the reduction in PVR from an elevated state may influence RV function differently. In contrast, during the increase in PVR in the ICU, TAPSE, S' and SV decreased concomitantly, which is more in agreement with a normal physiological understanding of contractility, but we cannot make any firm conclusion based on these observations, since there are several potential confounders such as stunning of the myocardium



**Figure 3** Repeated measures correlations between stroke volume from thermodilution and echocardiographic parameters and between RVEF and RVFAC.  $r$  overall repeated measures correlation coefficient,

$RVEF$  right ventricular ejection fraction,  $RVFAC$  right ventricular fractional area change,  $TAPSE$  tricuspid annular plane systolic velocity,  $TDIS'$  tissue Doppler tricuspid annulus peak systolic velocity

and electrolyte disturbances. RV-GLS was not significantly decreased in the ICU, indicating that contractility was not affected during the observation period.

### Strengths and limitations

The strength of this study is that we used several 2D and 3D echocardiographic modalities and compared them to the longitudinal measures TAPSE and S' in low-risk patients with preserved CO. This enabled us to show that the changes in TAPSE and S' occur irrespective of CO changes or signs of RV dysfunction. Another strength is that we are the first to use TEE both peri- and postoperatively to ensure comparability of methodology whereas previous studies have switched to TTE postoperatively [26]. A limitation is that we did not use cardiac MRI pre- and postoperatively to quantify RVEF and SV. Another limitation is that we used room temperature saline for thermodilution measurements which could cause overestimation of CO [32, 33]. Finally, this study was performed in a clinical setting, so variation in

patient treatment can contribute to an increase in variation in measurements. Since RVEF and RVFAC did not decrease we suspect that an increase in transverse motion of the free wall and/or reversed septal motion can contribute to maintain SV. Quantification of the inwards motion of the free wall and septum should be investigated in future studies.

### Clinical implications

Assessment of longitudinal contraction after cardiac surgery is insufficient to detect RV dysfunction. After cardiac surgery we suggest that TAPSE and S' are only used in combination with global measures to assess RV function. Our results suggest that 3D echocardiography is better at tracking RV output than other echocardiographic modalities, however, the clinician should be aware that 3D echocardiography underestimate SV compared to thermodilution. If 3D echocardiography is not accessible we suggest obtaining RVFAC and RV-GLS from 2D B-mode images.

## Conclusion

In uncomplicated CABG surgery with no indications of RV dysfunction, TAPSE and  $S'$  were uniformly depressed in all patients, despite a preserved CO. Global measures of RV function, such as RVFAC, RVEF, RV-GLS and 3D SV all remained stable throughout the study period. RVEF, RVFAC and RV-GLS, however, did not provide sufficient precision to detect subtle changes in SV. 3D echocardiographic assessment of SV demonstrated a decent correlation with PAC SV and could be used to track changes in SV over time, although it systematically underestimated SV.

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## Compliance with ethical standards

**Conflict of interest** The authors declare no conflict of interest.

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