APPARATUS

Continuous Assessment of Right Ventricular Ejection Fraction: New pulmonary artery catheter versus transoesophageal echocardiography

W. Zink,[1] J. Nöll,[1] H. Rauch,[1] H. Bauer,[1] R. DeSimone,[2] E. Martin[1] and B. W. Böttiger[1]

1 Department of Anaesthesiology, 2 Department of Cardiac Surgery, University of Heidelberg, Im Neuenheimer Feld 110, 69120 Heidelberg, Germany

Summary

In 25 cardiac surgical patients, right ventricular ejection fraction was continuously measured with a new pulmonary artery catheter and transoesophageal echocardiography, scanning the 'fractional area change' in a standardised transatrial cross section area. Measurements were recorded at three predefined time points (pre-, intra-, and postoperatively). Both methods were compared using the Bland-Altman analysis. Comparing right ventricular ejection fraction values obtained from the pulmonary artery catheter with those assessed by transoesophageal echocardiography, bias was −3.7%, with a precision of 30.9%. Bias and precision significantly improved when the heart rate was less than 100 beats.min^{-1}, pulmonary artery pressures were low and cardiac performance adequate. In conclusion, the new continuous pulmonary artery catheter system appears to be a valid and useful bedside monitoring device in the haemodynamic management of critically ill patients.

Keywords *Right ventricle*; ejection fraction. *Monitoring*; pulmonary artery catheter, transoesophageal echocardiography.

Correspondence to: Bernd W. Böttinger
E-mail: bernd_boettiger@med.uni-heidelberg.de
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The impact of right ventricular function on haemodynamics is increasingly recognised [1–7]. Recent studies have impressively demonstrated its importance for global cardiac performance, resulting in the 'modern' physiological concept of ventricular interdependence [8,9]. Furthermore, right ventricular function is associated with patients' outcome after cardiac surgical procedures and major trauma [10–12].

Recently, specific volume parameters like the right ventricular ejection fraction have been evaluated while monitoring right ventricular and global cardiac function at the bedside [1,13–15]. Due to the crescent shape and geometry of the right ventricle, correct assessment of its function has been, and still remains, difficult. Presently, four different methods are clinically available: (i) 'classical' biplane angiography, (ii) radionuclide angiography, (iii) two-dimensional (transthoracic or transoesophageal) echocardiography and (iv) thermodilution volumetric measurements using fast response thermistor pulmonary artery catheters [2,6,16–19]. As angiographic procedures cannot be used in the operating room or intensive care unit, modified pulmonary artery catheters and echocardiography are more suitable to monitor right ventricular volumes at the bedside.

A major limitation of both techniques was that no continuous assessment of right ventricular parameters was possible: all data had to be obtained by intermittent bolus injection or calculation of the right ventricular fractional area change [6,15,20–23]. To overcome this problem, a new modified pulmonary artery catheter which continuously assesses right ventricular parameters has recently been introduced [24].

Therefore, the aim of this study was to compare continuous assessment of right ventricular ejection fraction using the new modified pulmonary artery catheter with intermittent measurements obtained by transoesophageal echocardiography. Furthermore, the influence of other haemodynamic changes on right ventricular ejection fraction was also assessed.

Methods

With approval of the local Ethics Committee and written informed consent, 25 patients undergoing elective coronary artery bypass grafting were enrolled in this study. Patients were premedicated with 1–2 mg flunitrazepam orally after fasting overnight. Sufentanil (1–1.5 $\mu g.kg^{-1}$) and etomidate (0.2–0.3 $mg.kg^{-1}$) were used for induction of anaesthesia. Tracheal intubation was performed after topical anaesthesia of the glottic region and muscle relaxation with pancuronium (0.1 $mg.kg^{-1}$). Anaesthesia was maintained with isoflurane (0.4–0.8%) and sufentanil (0.5–1 $\mu g.kg^{-1}$). During cardiopulmonary bypass, anaesthesia was maintained with a continuous propofol infusion (0.05–0.075 $mg.kg^{-1}.min^{-1}$).

New modified pulmonary artery catheter system

Prior to induction, an arterial catheter was placed in the left radial artery, with pressure transducers being positioned at mid-thoracic level. Additionally, the new pulmonary artery catheter (7.5F CEDV-Pulmonary Artery Catheter, model 744H, Baxter Healthcare Corporation, Irvine, CA, USA), which interfaced with a computerised monitoring system (Vigilance^{TM} CCO/SvO_2/CEDV Monitor, Baxter Healthcare Corporation, Irvine, CA, USA) was inserted. The ECG was recorded to assess RR-intervals.

A modified pulsed warm thermodilution technique is used with this new pulmonary artery catheter. A computer-controlled thermal filament, mounted on the catheter, is placed in the right ventricle and randomly heats the blood (limited to 7.5 Watt and 44.0 °C). The resulting changes in blood temperature are recorded with a distally mounted fast response thermistor. Based on simultaneously assessed RR-intervals, diastolic plateaus of the thermodilution curve are identified. This is necessary as the total end-diastolic heat mass in the right ventricle is the result of the heat mass at the end of the previous systole and of cooling effects due to the influx of colder blood during diastolic filling. These relations are summarised in the equation:

$$\begin{aligned} RVEF &= (EDV - ESV)/EDV \\ &= 1 - [(T_{B2} - T_{B0})/(T_{B1} - T_{B0})] \end{aligned}$$

T_{B0}, blood temperature before heat application; T_{B1}, blood temperature at T_1 (during systole 1); T_{B2}, blood temperature at T_2 (during systole 2); RVEF, right ventricular ejection fraction; ESV, end-systolic volume; EDV, end-diastolic volume.

Right ventricular ejection fraction can be calculated by measuring blood temperature before heat application and the decrease in blood temperature during a predefined period (T_1 to T_2). The value presented at the monitor screen is the average of right ventricular ejection fraction measurements from the previous 6–10 min.

Another feature of this new device is the continuous measurement of cardiac index. The monitoring system computes a cross-correlation between the filament input sequence and the thermistor response to changes in blood temperature. Based on this sequence, cardiac output is calculated using a modified Stewart-Hamilton equation. Again, the value presented at the display is the average cardiac output measurement over the previous 6–10 min. Additionally, intermittent cardiac index measurements are possible with this system.

Transoesophageal echocardiography

Two-dimensional echocardiographic data were obtained using a 5.0 MHz multiplane transoesophageal echo-probe (Model 21369 A, connected to SONOS 5500 Imaging System, Hewlett Packard, Andover, Massachusetts, USA). The probe was advanced to mid-oesophageal level to visualise a standard transverse four-chamber view. At each measurement, three cardiac cycles were recorded for later evaluation.

To determine end-systolic and end-diastolic cross-sectional areas, right ventricular contours were digitally visualised and manually traced [19,25–27]. Based on the fractional area change principle, right ventricular ejection fraction was estimated according to the equation [19,25–27]:

$$RVEF = (EDA - ESA)/EDA \times 100\%.$$

Mean values of the three results per time point were documented and statistically compared with respective right ventricular ejection fraction values assessed with the pulmonary artery catheter.

Study protocol

Measurements were carried out at three predefined time points: pre-operatively before skin incision, intra-operatively 30 min after weaning from cardio-pulmonary bypass, and postoperatively 2 h after admission to the intensive care unit.

Heart rate, mean arterial blood pressure, mean pulmonary artery pressure, central venous pressure, systemic and pulmonary vascular resistance, continuously and intermittently measured cardiac index, and intermittently measured stroke volume index were recorded.

Statistical analysis

Regression analysis as described by Passing and Bablok evaluated the reliability of transoesophageal measurements [28]. The echocardiographic and pulmonary artery catheter measurements of right ventricular ejection fraction were compared using the Bland-Altman analysis [29].

In order to assess the influence of haemodynamic changes on measurements of right ventricular ejection fraction, differences between values assessed with both methods were plotted against further haemodynamic parameters, and Pearson's correlation coefficient was calculated. In the linear regression analysis, the following subgroups were used:

Heart rate: < 60 beats.min^{-1}; 60–100 beats.min^{-1}; > 100 beats.min^{-1}

Mean pulmonary artery pressure: < 15 mmHg; 15–20 mmHg; > 20 mmHg

Pulmonary vascular resistance: < 50 dynes.s.cm^{-5}; 50–100 dynes.s.cm^{-5}; 100–150 dynes.s.cm^{-5}; > 150 dynes.s.cm^{-5}

Cardiac Index: < 2.5 l.min^{-1}.m^{-2}; > 2.5 l.min^{-1}.m^{-2}

Stroke Volume Index: < 20 ml.m^{-2}; 20–60 ml.m^{-2}; > 60 ml.m^{-2}.

All results are presented as means and standard deviations (SD), and *p*-values less than 0.05 were considered statistically significant.

Results

Patients

The mean age of patients (19 male, 6 female) was 64 years, with a mean body weight of 74.1 kg (SD 11.6). The time on cardio-pulmonary bypass averaged 94 min, with a mean aortic cross-clamping time of 51 min.

Pulmonary artery catheter vs. transoesophageal echocardiography and right ventricular ejection fraction

Regression analyses of echocardiographic results were carried out between data assessed at different time points. There was no statistically significant deviation from linearity, indicating good reliability of these measurements. Mean right ventricular ejection fraction using the new pulmonary artery catheter was 32.7% (SD 8.2; range 14–55), whereas transoesophageal echocardiography measurements resulted in a mean right ventricular ejection fraction of 37.2% (SD 6.4; range 27–59). The bias of pulmonary artery catheter was −3.7%, with a precision of 30.9% (Fig. 1).

Influence of different haemodynamic parameters on the assessment of right ventricular ejection fraction

The difference of mean right ventricular ejection fraction values measured with pulmonary artery catheter and transoesophageal echocardiography were explored for a possible dependency on other haemodynamic parameters

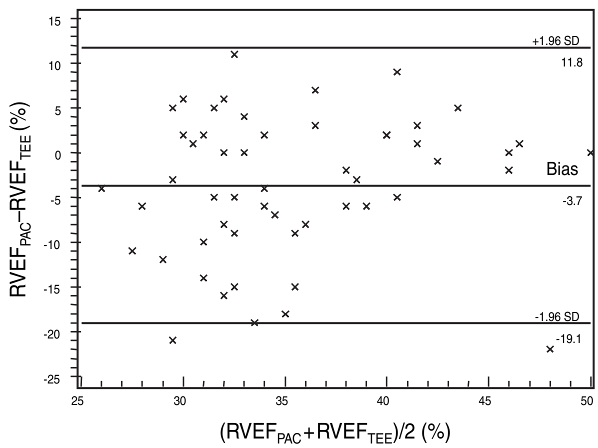

Figure 1 Bland and Altman plot comparing transoesophageal echocardiography (RVEF$_{TEE}$) and pulmonary artery catheterisation (RVEF$_{PAC}$) in the assessment of right ventricular ejection fraction. Bias was −3.7%, with a precision (± 1.96 SD) of 30.9%. SD: standard deviation.

Table 1 Haemodynamic parameters assessed at three predefined time points. All values are means and standard deviation.

	preincision	intra-operative	postoperative
Heart rate; beats.min^{-1}	60 (7)	89 (13)	92 (15)
Stroke Volume Index; ml.m^{-2}	39 (9)	36 (9)	31 (8)
Continuous Cardiac Index; l.min^{-1}.m^{-2}	2.3 (0.5)	3.1 (0.8)	2.8 (0.4)
Intermittent Cardiac Index; l.min^{-1}.m^{-2}	2.1 (0.6)	2.9 (0.6)	2.7 (0.7)
Mean Arterial Pressure; mmHg	68 (9)	80 (13)	86 (15)
Mean Pulmonary Artery Pressure; mmHg	15 (4)	19 (6)	21 (6)
Pulmonary Vascular Resistance; dynes.s.cm^{-5}	102 (31)	150 (41)	166 (36)
Right Ventricular Ejection Fraction (pulmonary artery catheter); %	35 (7)	35 (8)	31 (6)
Right Ventricular Ejection Fraction (transoesophageal echocardiography); %	39 (5)	38 (6)	34 (6)

(Table 1). Significant differences between both techniques were found only with regard to heart rate, mean pulmonary artery pressure, pulmonary vascular resistance and continuous cardiac index (Table 2). With regard to mean arterial pressure, systemic vascular resistance and central venous pressure, the bias of measurements did not change significantly with variations in these parameters.

The correlation between mean pulmonary artery pressure and difference between both techniques is shown in Fig. 2. At mean pulmonary artery pressure < 15 mmHg, there was no statistical difference between both methods (bias −0.2%; precision 10.7%). With a mean pulmonary artery pressure of 15–20 mmHg

Table 2 Influence of haemodynamic changes on right ventricular ejection fraction measurements with the pulmonary artery catheter and transoesophageal echocardiography (*p <0.05).

	range	bias (%)	precision (%)
Heart Rate; beats.min^{-1}	<60	−0.3	12.4
	>100	−9.3	13.3*
Mean pulmonary artery Pressure; mmHg	<15	−0.2	10.7
	15–20	−5.1	17.4*
	>20	−8.2	15.9*
Pulmonary Vascular Resistance; dynes.s.cm^{-5}	<50	1.5	12.4
	50–100	−0.6	10.8
	100–150	−3.2	15.4
	>150	−10.5	15.6*
Continuous Cardiac Index; l.min^{-1}.m^{-2}	<2.5	−7.3	14.1*
	>2.5	−1.1	13.5
Intermittent Cardiac Index; l.min^{-1}.m^{-2}	<2.5	−6.3	17.6*
	>2.5	−1.3	12.3
Stroke Volume Index; ml.m^{-2}	<20	−14.0	13.9*
	>60	−1.1	4.7

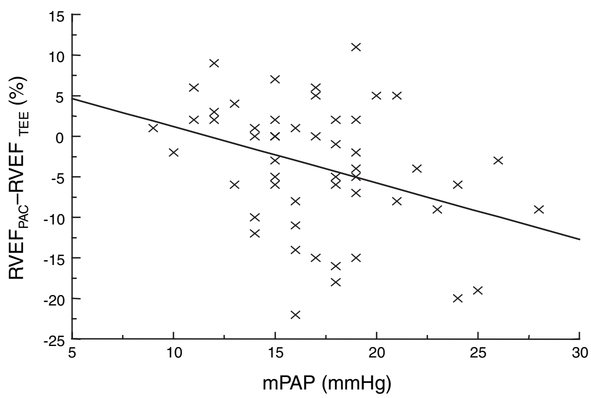

Figure 2 Differences between right ventricular ejection fraction (RVEF) values assessed with both methods (RVEF$_{PAC}$–RVEF$_{TEE}$) plotted against mean pulmonary artery pressure (mPAP) (r = −0.36; p < 0.05).

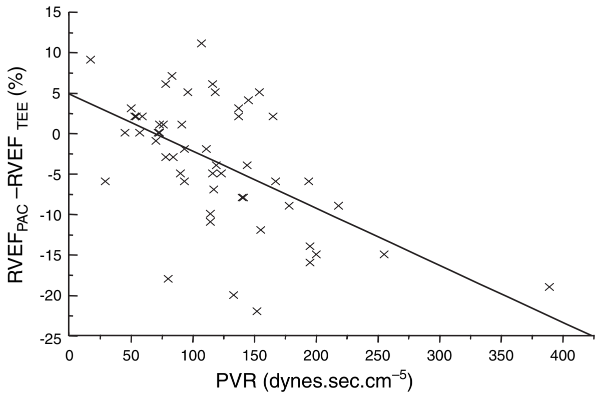

Figure 3 Differences between right ventricular ejection fraction (RVEF) values assessed with both methods (RVEF$_{PAC}$–RVEF$_{TEE}$) plotted against pulmonary vascular resistance (PVR) (r = −0.56; p < 0.05).

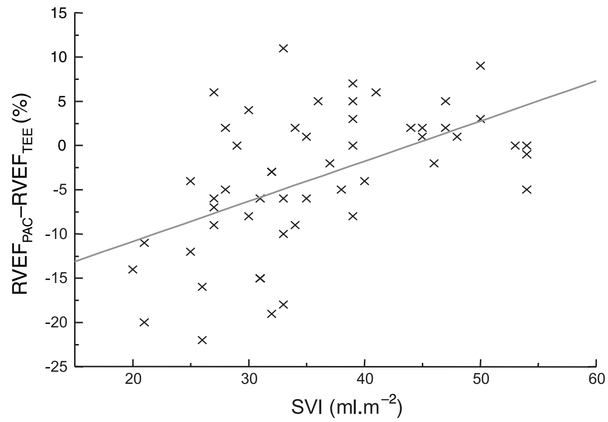

Figure 4 Differences between right ventricular ejection fraction (RVEF) values assessed with both methods (RVEF$_{PAC}$–RVEF$_{TEE}$) plotted against stroke volume index (SVI) (r = −0.53; p < 0.05).

and > 20 mmHg however, bias increased significantly to −5.1% (precision 17.4%; p < 0.05) and to −8.2% (precision 15.9%; p < 0.05), respectively (Table 2).

Physiologically, there is an inverse relationship between right ventricular ejection fraction and mean pulmonary artery pressure. With regard to pulmonary artery catheter measurements, there was a significant negative correlation between mean pulmonary artery pressure and right ventricular ejection fraction (r = −0.31; p < 0.05). However, in contrast, there was no correlation (r = 0.09; p > 0.05) between mean pulmonary artery pressure and right ventricular ejection fraction assessed with transoesophageal echocardiography.

The correlation between pulmonary vascular resistance and differences between both techniques in right ventricular ejection fraction is shown in Fig. 3. At pulmonary vascular resistance index < 50 dynes.s.cm^{-5}, bias was 1.5% (precision 12.4%), whereas between 50 and 100 dynes.s.cm^{-5}, bias was −0.6% (precision 10.8%). With a pulmonary vascular resistance index of 100–150 dynes.s.m^{-5}, bias changed to −3.2%, with a precision of 15.4% (p > 0.05). At values > 150 dynes.s.cm^{-5}, however, there was a significant difference between the examined methods (bias −10.5%, precision 15.6%; p < 0.05).

With stroke volume index > 60 ml.m^{-2}, there was no obvious difference between both methods (bias 1.5%, precision 4.7%; p > 0.05). At values < 20 ml m^{-2}, a bias of −14.0% with a precision of 13.9% was calculated (p > 0.05) (Fig. 4).

Discussion

With the introduction of this modified pulmonary artery catheter, continuous assessment of right ventricular ejection fraction at the bedside is feasible for the first time. In order to evaluate this new monitoring system, this study compared this device with intermittent trans-oesophageal echocardiography in cardiac surgical patients. Our data show that both methods are consistent with good reliability and precision.

Radionuclide and ventriculographic techniques are still considered to be the 'gold standard' for assessing right ventricular parameters [6]. However, due to their technical complexity, these methods can not be used peri-operatively or in the intensive care unit. Therefore, alternative techniques have been developed for bedside use. In this respect, fast response thermistor pulmonary artery catheters have been an important milestone in right ventricular monitoring.

Pulmonary artery catheterisation *per se* is an invasive method, with specific risks and mortality [30,31]. In addition, the lack of definite evidence that pulmonary artery catheters improve patients' outcome is awaited. A criticism was that haemodynamic data were obtained intermittently, which may be inadequate for monitoring over a long period. Consequently, pulmonary artery catheters have been modified for continuous cardiac output monitoring. As right ventricular parameters are increasingly recognised as important in the management of critically ill patients, the introduction of the pulmonary artery catheter system for continuous assessment of right ventricular ejection fraction is an important development.

In comparison with pulmonary artery catheterisation, transoesophageal echocardiography is a less invasive, but technically more complex technique. Qualified users are necessary in order to display standardised cross-sections and to interpret findings [32,33]. Because of its crescent shape, ultrasonographic evaluation of right ventricular function is complex [18]. Therefore, simplified geometry has to be assumed in order to estimate right ventricular ejection fraction; two-dimensional fractional area change is assumed to represent contractility of the entire ventricle [18,19,25–27]. Another problem of transoesophageal echocardiography application is the absence of continuous monitoring: no quantitative online evaluation of right ventricular function is available, and only sporadic right ventricular ejection fraction values can be obtained.

Nevertheless, our regression analyses showed that transoesophageal echocardiography provided reliable right ventricular ejection fraction values at all measurement points. Consequently, transoesophageal echocardiography appears to be a most suitable and valid bedside reference method.

The comparison of both methods resulted in a good consistency of right ventricular ejection fraction values, with a clinically acceptable precision. The negative bias suggested that average right ventricular ejection fraction values generated by the pulmonary artery catheter are slightly smaller than those from transoesophageal echocardiography.

These results agree with findings of other studies with intermittent, but not continuous right ventricular ejection fraction measurements: In cardiac surgical patients, Koorn compared intermittent measurements of right ventricular ejection fraction using bolus thermodilution with two-dimensional transoesophageal echocardiography [34]. Bias of the two methods was 11.5%, with a precision of 39.6%, and he concluded that there was a good consistency of both techniques. There was also a tendency towards smaller right ventricular ejection fraction values generated with pulmonary artery catheters in comparison with those from transoesophageal echocardiography.

Rafferty intermittently assessed right ventricular ejection fraction values in 20 cardiac surgical patients using bolus thermodilution techniques and transoesophageal echocardiography [35]. He also concluded that there was no clinically relevant discrepancy. Again, right ventricular ejection fraction values from pulmonary artery catheters were on average smaller than the results of echocardiographic measurements. Jardin compared intermittent pulmonary artery catheter measurements with two-dimensional transthoracic echocardiography in patients with acute respiratory distress syndrome. He also found good correlation between both methods ($r = 0.74$; $p < 0.001$) [18].

Another aim of this study was to evaluate the influence of other haemodynamic changes on the bias between techniques. With regard to a heart rate up to 100 beats.min^{-1}, both methods showed good consistency. With a further increase in heart rate, however, bias also increased, with right ventricular ejection fraction values from pulmonary artery catheter measurements being markedly smaller than those from transoesophageal echocardiography.

The influence of tachycardia on intermittent thermodilution based measurements is a well known phenomenon- and has been extensively investigated [30,36]. Because of decreasing RR-intervals, diastolic plateaus can not precisely be detected by pulmonary artery catheter systems, which often results in incorrect measurements [6,30,36]. Consequently, it has been recommended to limit the use of intermittent right ventricular ejection fraction catheters to a heart rate of less than 100–120 beats.min^{-1} [30]. Our data show that tachycardia has a negative impact on the precision of continuous measurement of right ventricular ejection fraction.

Changes in mean pulmonary artery pressure and pulmonary vascular resistance also influenced bias: increasing pulmonary vascular resistance and mean pulmonary artery pressure increases bias. In health, there is a negative reciprocal correlation between right ventricular ejection fraction and mean pulmonary artery pressure [37]. This relationship was also found in our study. Comparing right ventricular ejection fraction values from transoesophageal echocardiography and mean pulmonary artery pressure, however, no significant correlation was found. In critically ill patients, moderate tricuspid valve regurgitations – which are regularly caused by pulmonary artery catheters *in situ* – become more prominent with increasing mean pulmonary artery pressure and pulmonary vascular resistance [37,38]. Due to their technical configuration, thermodilution based pulmonary artery catheters measure temperature changes in the forward flowing blood stream only, and thus are likely to estimate the 'true' effective ejection fraction [16]. Increased tricuspid valve regurgitations prevent correct thermodilution measurements, and thus limit the use of thermodilution catheters. Transoesophageal echocardiography, in contrast, estimates right ventricular fractional area change without assessing the direction of blood flow. Thus, with increased pulmonary artery pressure and pulmonary vascular resistance, tricuspid valve regurgitations may be responsible for an apparently unaffected fractional area change. Tricuspid valve regurgitation is supposed to have a greater impact on right ventricular ejection fraction values measured with echocardiography than on pulmonary artery catheter measurements, which may explain the discrepancy of both methods during episodes of elevated mean pulmonary artery pressure and pulmonary vascular resistance.

With unaffected cardiac performance (stroke volume index > 50 $ml.m^{-2}$; continuous/intermittent cardiac index > 2.5 $l.min^{-1}.m^{-2}$), there was a good correlation between right ventricular ejection fraction values assessed with the pulmonary artery catheter and transoesophageal echocardiography. In periods of poor global cardiac performance, however, discrepancy between both methods significantly increased.

In cardiac surgical patients, haemodynamic changes often occur quickly and sometimes require immediate therapeutic interventions. In our study, the monitoring system displayed mean right ventricular ejection fraction values derived from randomised measurements during the previous 6–10 min.

Such delay is a well known problem. In 1995, Haller compared continuous and intermittent assessment of cardiac output using modified pulmonary artery catheters [39]. The bias of both methods significantly increased in situations requiring therapeutic interventions to restore cardiac performance. He concluded that these systems were not fast enough to precisely assess sudden haemodynamic changes. With regard to our findings, the latency of the pulmonary artery catheter system might be responsible for the increased bias during periods of poor cardiac performance.

In conclusion, the present data show that there was a good consistency between right ventricular ejection fraction measured with the modified pulmonary artery catheter and transoesophageal echocardiography, with a clinically acceptable precision. Bias of both methods, however, significantly increased during severe tachycardia, with increased mean pulmonary artery pressure and pulmonary vascular resistance, and during episodes of poor cardiac performance. These restrictions must be kept in mind when interpreting continuously assessed right ventricular ejection fraction values. Despite these limitations, the examined pulmonary artery catheter system appears to be a useful bedside monitoring device.

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