

# Comparison of Doppler Flow Tei-Indexes With Pulmonary Artery Thermodilution Measurement of Cardiac Output in an Experimental Porcine Model

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## Summary

The objective of our study was to compare Doppler echocardiography imaging with pulmonary artery thermodilution measurement during mechanical ventilation. Total 78 piglets (6 weeks old, average weight 24 kg, under general anesthesia) were divided into 4 groups under different cardiac loading conditions (at rest, with increased left ventricular afterload, with increased right ventricular preload, and with increased afterload of both heart ventricles). At 60 and 120 min the animals were examined by echocardiography and simultaneously pulmonary artery thermodilution was used to measure cardiac output. Tei-indexes data were compared with invasively monitored hemodynamic data and cardiac output values together with calculated vascular resistance indices. A total of 224 parallel measurements were obtained. Correlation was found between values of right Tei-index of myocardial performance and changes in right ventricular preload ( $p < 0.05$ ) and afterload ( $p < 0.01$ ). Significant correlation was also found between left index values and changes of left ventricular preload ( $p < 0.001$ ), afterload ( $p < 0.001$ ), stroke volume ( $p < 0.01$ ), and cardiac output ( $p < 0.01$ ). In conclusion, echocardiographic examination and determination of the global performance selectively for the right and left ventricle can be recommended as a suitable non-invasive supplement to the whole set of methods used for monitoring of circulation and cardiac performance.

## Key words

Myocardial performance • Tei-index • Pulmonary artery thermodilution • Cardiac output • Piglets

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## Introduction

Cardiopulmonary interaction plays an essential role in critically ill pediatric patients. Accurate assessment of cardiac output and myocardial function has been considered vital in the successful treatment of any such patients. There are several techniques for monitoring cardiac output in seriously ill patients. The use of thermodilution for cardiac output measurements via in-dwelling pulmonary arterial catheter is considered one of the most reliable methods of haemodynamic monitoring in pediatric patients. However, its invasive nature is not without inherent risks (Takano 1997, Carmosino *et al.* 2007).

Non-invasive methods of cardiovascular functional monitoring are therefore particularly appealing in children. The Tei-indexes of myocardial performance (IMP) has been demonstrated to fulfill criteria as a non-invasive, easily obtainable, and reproducible tool for myocardial performance assessment in both adult and pediatric patients (Williams *et al.* 2000, Pratap *et al.* 2004, Lavine *et al.* 2008). The technique is based on Doppler derived time intervals within the cardiac cycle and used to assess global, systolic and diastolic

myocardial function. It also allows for separate assessment of the left and right ventricular function and its increasing value represents myocardial dysfunction (Tei *et al.* 1995).

Given the persistent controversy about load dependence of IMP (LaCorte *et al.* 2003, Teschima *et al.* 2007, Murphy *et al.* 2007), we compared hemodynamic parameters achieved using invasive monitoring with values of myocardial performance indexes in an experimental setting.

## Materials and Methods

The study was conducted with the approval of a multidisciplinary institutional ethics committee in an EU accredited experimental center of the Faculty of Medicine of Charles University in Pilsen, Czech Republic. Respecting the principles of Helsinki Declaration this study was part of an ongoing experimental studies.

Seventy-eight clinically healthy piglets (aged 6 weeks, mean weight 24 kg with range between 18-27 kg, male to female ratio 1:3) anesthetized, endotracheally intubated, catheterized and divided into 4 groups: Control Group A (n=34) included spontaneously breathing animals without surgical intervention nor changes in hemodynamics. After completing the measurements in this control group, the animals were generally anesthetized, mechanically ventilated with neuromuscular block, and divided into two groups according to further surgical interventions: Group B animals (n=17) formed the hemodynamic model of animals with cross clamping of the abdominal aorta above the origin of renal arteries (Treska *et al.* 2003), and Group C (n=17) comprised of animals with partial occlusion of the portal bed via right portal vein embolization (Liska *et al.* 2009). In the normal course of events the high volume of venous blood from the digestive tract of unpaired organs arises through the portal circulation to the liver on the basis of a pressure gradient. Acute occlusion of half of the entire portal venous bed causes early portal hypertension and transient changes in regional hemodynamics. Immediate adaptation after surgery leads to a reduction in liver flow lasting several hours, and conversely increases flow through the natural porto-systemic venous connections into the lower vena cava (Sinderman *et al.* 1978, Sheen *et al.* 2000). Temporary increase in-flow in the lower vena cava was used to create an experimental hemodynamic model of increased right ventricle preload and diastolic

filling (Karunanithi *et al.* 1992, Khan *et al.* 2009). Group D (n=44) animals underwent abdominal aortic tight banding 3 weeks before study commencement (Molacek *et al.* 2009), and were ventilated by high tidal volume strategy. The combination of flow-limiting abdominal aorta and increasing pressure in the chest created a hemodynamic model of the increase afterload of the both heart ventricles.

The internal jugular vein was cannulated for central venous access using the Seldinger percutaneous technique and a Swan-Ganz thermodilution pulmonary catheter was introduced. The femoral artery was used for direct arterial blood pressure monitoring via the arterial catheter. The animals were examined by echocardiography to acquire data for Tei-indexes calculations, invasively monitored hemodynamic data were recorded, and thermodilution technique was used to parallel measure cardiac output via pulmonary artery catheter.

### *General anesthesia and ventilator support*

Premedication was given by intramuscular administration of atropine 0.07 mg/kg and azaperone 5.0 mg/kg. General anesthesia was induced by intravenous administration of thiopental 10 mg/kg and all animals were orotracheally intubated. Combined general anesthesia was maintained by intravenous ketamine 1.5-3.0 mg/kg or fentanyl 0.5-1.0 microg/kg with azaperone 3.0-4.0 mg/kg and peripheral muscle paralysis by pancuronium 0.1-0.2 mg/kg (Jacson *et al.* 2007).

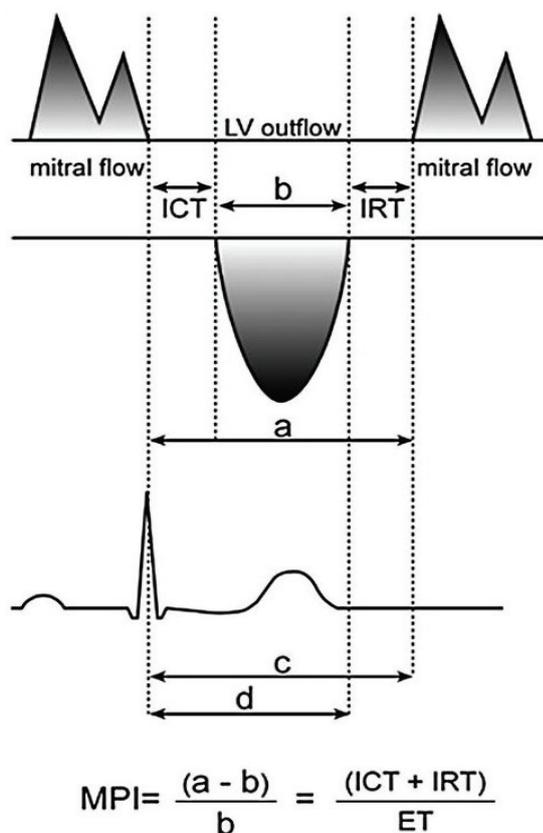
Animals in Group A were breathing spontaneously with continuous positive airway pressure support at 2 cmH<sub>2</sub>O and FiO<sub>2</sub> 0.21. Animals in Groups B, C, and D were mechanically ventilated using a servo-ventilator (Siemens Elema900C, Germany) in pressure controlled mode with the following settings: P<sub>insp</sub> 15 cmH<sub>2</sub>O, rate 24 breath/min, PEEP 6 cmH<sub>2</sub>O, I:E 0.7, FiO<sub>2</sub> 0.21 in Groups B, C. Group D settings were P<sub>insp</sub> 30 cmH<sub>2</sub>O, rate 30 breath/min., PEEP 0 cmH<sub>2</sub>O, I:E 1.0, FiO<sub>2</sub> 0.21.

### *Study protocol*

Experimental work in all piglets utilized tracheal intubation and establishing invasive entry under general anesthesia. Following a 60-min recovery period the first measurement reading was taken and echocardiographic imaging performed (time-1). After a further sixty minutes, all measurements were repeated (time-2).

### Echocardiographic assessment and Tei indexes calculations

A transthoracic echocardiogram was performed using 3.5-5.0 MHz probe (Sonoline Siem, Siemens; Germany). A two-dimensional echocardiogram and pulse wave Doppler were used in apical four-chamber view to acquire data from blood flow through atrioventricular and in a left parasternal view of the semilunar valves, respectively. Care was taken to align the transducer beam as closely as possible to the blood flow axis. Doppler signals for the left and right ventricular valves were not acquired simultaneously. No angle correction was made. Doppler and ECG tracings were recorded and stored digitally.



**Fig. 1.** Schema for measurements of Doppler time intervals and calculations. Interval *a*, the interval between cessation and onset of the tricuspid or mitral inflow (AVCO); interval *b*, the ejection time (ET) of right or left ventricular outflow; interval *c*, the interval between the R wave and the cessation of right or left ventricular outflow; interval *d*, the interval between the R wave and the onset of mitral inflow; MPI, myocardial performance index; ICT, isovolumic contraction time (obtained by subtracting IRT from *a-b*); IRT, isovolumic relaxation time (*c-d*)

The blood flow time intervals were measured by taking the three most distinct Doppler trace in a frozen template. The time interval from the cessation to the

onset of mitral or tricuspid inflow (AVCO) was measured. This interval is equal to the sum of isovolumic contraction time, ejection time, and isovolumic relaxation time. Left and right ventricular ejection time (ET) was measured in the ascending aorta or main pulmonary artery just above the corresponding valve. Myocardial performance index was then calculated using formula (AVCO – ET) / ET selectively for the right (RIMP) and left (LIMP) heart ventricle (LaCorte *et al.* 2003, Eidem *et al.* 1998). Diagram representing the measurement and calculation of MPI figures are documented in Figure 1 (Pattoneri *et al.* 2007). Real display pulse Doppler flow in the pulmonary ejection time measurement in experimental animals in our study is shown in Figure 2.

Thus the calculated value was divided by the current value of the R-R interval of simultaneously recorded electrocardiogram to exclude the impact of variations in heart rate on the measurement result. This method was used to calculate the myocardial performance index for each of the three measurements. The average value of these three indices was stored in a database. This data was used for statistical processing.



**Fig. 2.** Real pulse Doppler flow measurements in the pulmonary ejection time. The top figure shows the morphology of the right heart, right ventricular outflow tract, the semilunar valve and the pulmonary trunk. The bottom diagram shows the pulse Doppler flow in the pulmonary artery and crosses marked with the value of right ventricular ejection time.

### Measurement of cardiac output and hemodynamic data acquisition

Cardiac output was measured by intermittent pulmonary artery thermodilution. Under ultrasound guidance a Swan-Ganz thermodilution catheter was positioned in the pulmonary artery. The average temperature of 38.5 °C measured in the pulmonary artery allowed for adequate thermal difference with the test

solution (0.9 M sodium chloride at 21 °C). Standard technique was used to assess cardiac output by rapid injection of test solution into proximal port of pulmonary artery catheter and subsequent temperature monitoring at the catheter tip (Takano *et al.* 1997). Moreover, no fluid replacement bolus or any other therapeutic intervention was performed at the time of all data acquisition.

The following hemodynamic data were acquired, calculated and recorded: heart rate, mean central venous pressure, right heart ventricle pressure, pulmonary arterial

pressure, pulmonary arterial occlusive (capillary wedge) pressure, mean arterial pressure (MAP), stroke volume, cardiac output and cardiac index, systemic vascular resistance (MAP-CVP/CO), pulmonary arteriolar-vascular resistance (PAP-PAoP/CO). Body surface area of animals was calculated using the following Meehe's formula:  $0.087 \times \text{weight} / 0.66 \text{ (m}^2\text{)}$  (LaCorte *et al.* 2003). Each parameter was expressed as mean value from the five consecutive measurements in 30 second intervals.

**Table 1.** Data values obtained in groups and the differences between Groups B, C, D and control Group A (n=244).

Variables	Group A	Group B	P<	Group C	P<	Group D	P<
	n=68	n=34		n=34		n=88	
	Mean ± SD (95 % CI)	Mean ± SD (95 % CI)		Mean ± SD (95 % CI)		Mean ± SD (95 % CI)	
RIMP	0.20 ± 0.03 (0.18 - 0.21)	0.23 ± 0.02 (0.22 - 0.24)	0.05	0.24 ± 0.03 (0.23 - 0.25)	0.01	0.24 ± 0.03 (0.23 - 0.25)	0.01
LIMP	0.28 ± 0.02 (0.27 - 0.29)	0.38 ± 0.06 (0.36 - 0.40)	0.05	0.38 ± 0.06 (0.36 - 0.40)	0.01	0.41 ± 0.07 (0.39 - 0.43)	0.01
HR	158.00 ± 19.40 (148.07 - 165.13)	161.02 ± 19.42 (150.07 - 163.45)	NS	160.05 ± 19.12 (149.22 - 173.30)	NS	161.11 ± 19.60 (145.07 - 179.10)	NS
CVP	1.81 ± 2.17 (1.00 - 2.00)	2.80 ± 2.61 (3.31 - 4.91)	0.05	5.60 ± 2.42 (4.81 - 6.50)	0.01	3.60 ± 2.33 (2.90 - 4.31)	0.01
RVP	9.04 ± 1.87 (8.03 - 9.01)	9.45 ± 1.74 (9.23 - 12.33)	0.05	14.43 ± 3.04 (13.43 - 15.41)	0.01	14.12 ± 2.30 (13.41 - 14.81)	0.01
PAP	16.02 ± 3.13 (14.02 - 17.82)	16.50 ± 2.53 (14.70 - 17.80)	NS	17.21 ± 5.30 (15.31 - 19.07)	0.05	18.04 ± 4.73 (14.90 - 20.20)	NS
PAoP	6.91 ± 5.87 (7.04 - 10.01)	10.64 ± 2.33 (9.82 - 11.31)	0.01	13.53 ± 2.44 (12.72 - 14.33)	0.01	12.60 ± 2.72 (11.81 - 13.40)	0.01
MAP	75.52 ± 4.30 (73.12 - 78.04)	75.80 ± 3.74 (72.81 - 78.41)	NS	75.22 ± 3.30 (72.61 - 77.30)	NS	74.74 ± 3.50 (71.80 - 78.12)	NS
SV	18.03 ± 2.50 (16.04 - 19.02)	17.93 ± 2.84 (15.61 - 19.51)	NS	15.21 ± 2.62 (14.04 - 17.31)	0.01	16.04 ± 2.60 (15.70 - 17.91)	0.01
CO	2.91 ± 0.98 (1.95 - 3.02)	2.66 ± 0.83 (2.02 - 3.01)	NS	1.94 ± 1.01 (1.46 - 2.72)	0.01	2.04 ± 1.10 (1.64 - 2.77)	0.01
CI	1.34 ± 0.30 (1.11 - 1.53)	1.25 ± 0.28 (1.03 - 1.44)	NS	0.64 ± 0.37 (0.52 - 0.77)	0.01	0.71 ± 0.34 (0.60 - 0.81)	0.01
MAP-CVP	73.71 ± 2.13 (74.31 - 76.29)	74.22 ± 1.78 (73.90 - 75.73)	NS	69.13 ± 3.8 (67.81 - 70.54)	0.01	72.03 ± 3.34 (71.01 - 73.05)	0.05
SVR	1580.03 ± 680.31 (1830.0 - 1920.2)	1595.07 ± 480.01 (1490.4 - 1975.0)	NS	2435.12 ± 130.20 (2210.2 - 2570.1)	0.01	2370.11 ± 392.08 (2260.3 - 2550.1)	0.01
PVR	404.17 ± 52.23 (378.34 - 420.22)	409.02 ± 58.32 (382.11 - 437.40)	NS	440.01 ± 82.24 (411.02 - 469.17)	0.01	429.01 ± 77.31 (405.10 - 452.44)	0.01

RIMP, myocardial performance index of right ventricle; LIMP, myocardial performance index of left ventricle; HR, heart rate (beat/min); CVP, mean central venous pressure (mmHg); RVP, mean right ventricle pressure (mmHg); PAP, mean pulmonary artery pressure (mmHg); PAoP, mean pulmonary artery occlusive pressure (mmHg); MAP, mean artery pressure (mmHg); SV, stroke volume (ml); CO, cardiac output (l/min); CI, cardiac index (l/min/m<sup>2</sup>); MAP-CVP, difference of mean systemic pressures (mmHg); SVR, systemic vascular resistance (dyn.sec/cm<sup>5</sup>); PVR, pulmonary vascular resistance (dyn.sec/cm<sup>5</sup>); NS, not significant; P<, values P

### Statistical analysis

Parametric data were expressed as mean, standard deviation (SD) and 95 % confidence interval (95 % CI). Pearson's analysis and polynomial regression was used to compare the data obtained. Collinearity between variables was tested prior to modelling by computing the correlation of estimates, with a  $R^2 > 0.5$  considered to be significant. For qualitative analysis of accuracy of the variables reference interval dispersion, the linearity, reproducibility agreement were used (Bland *et al.* 1986).  $P$  values  $< 0.05$  were considered statistically significant. All data were analyzed using statistical software (Analyze-it211 Software Ltd.).

## Results

A total of 224 parallels data sets including data on myocardial performance indexes, hemodynamics and cardiac output measurements were acquired. Echocardiographic measurements of myocardial performance indices (IMP;  $n=224$ ) showed excellent reproducibility ( $p < 0.01$ ) and acceptable diversity ( $p = 0.097$ ). The files of all data and differences in quality between the groups were not statistically significant.

Differences between the values of data obtained in the time-1, time-2 of study in groups were not

statistically significant. A summary of all data values obtained in the groups and the differences between Groups B, C, D and control Group A are listed in Table 1.

In all ventilated (Groups B, C and D) RIMP, LIMP, CVP and PAoP were higher compared with spontaneously breathing animals of Group A. In Groups C and D the values of HR, SV, CO, CI, PVR and SVR were higher compared with Group A, while there were no differences between Group B and Group A.

Correlations of the RIMP and LIMP with the values of standard hemodynamic parameters in individual Groups B, C and D are listed in Table 2. The set of all data obtained in the study was used for the overall correlation between RIMP and LIMP and hemodynamic parameters. The results of these correlations are presented in Table 3.

In spontaneously breathing piglets (Group A) LIMP values correlated only with the SVR ( $R^2 = 0.69$ ;  $p < 0.01$ ), but in ventilated animals (Groups B, C and D) correlated with the PAoP, SVR, CO, and MAP-CVP. RIMP values in Groups C, D correlated with the CVP, RVP, MAP, CVP and PVR, but in Group B only with PVR and RVP. When processing all data obtained ( $n=224$ ) values RIMP correlated directly with the CVP and PVR. Values LIMP correlated directly with the PAoP, SVR, and indirectly with SV, CO, and MAP.

**Table 2.** Correlations of myocardial performance indexes with standard hemodynamic parameters in the groups ventilated animals ( $n=120$ ).

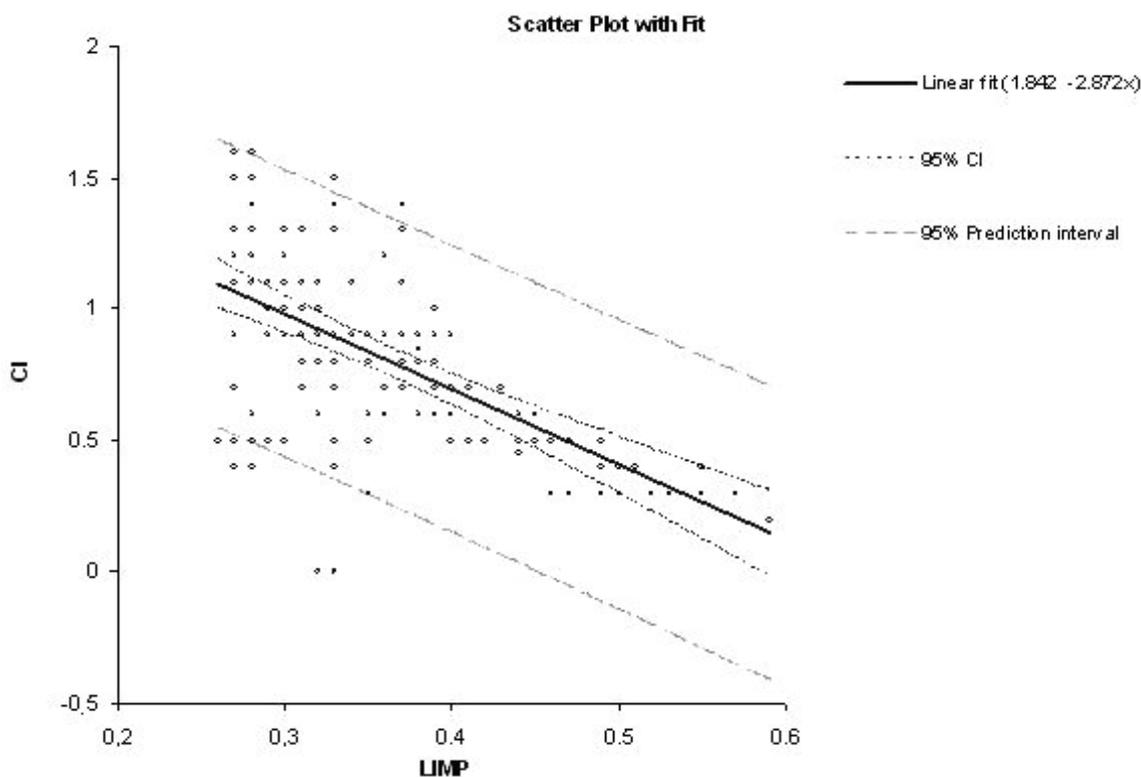
Dependent variables	Independent variables	Group B $n=34$		Group C $n=34$		Group D $n=88$	
		$R^2$	$P <$	$R^2$	$P <$	$R^2$	$P <$
RIMP	PVR	0.78	0.01	0.87	0.001	0.72	0.01
	CVP	0.35	NS	0.83	0.001	0.69	0.01
	MAP-CVP	0.28	NS	0.82	0.001	0.67	0.05
	RVP	0.88	0.001	0.75	0.01	0.81	0.001
LIMP	SVR	0.84	0.001	0.68	0.05	0.75	0.01
	PAoP	0.75	0.01	0.89	0.001	0.82	0.001
	SV	0.66	0.05	0.59	0.05	0.31	NS
	CO	0.78	0.01	0.81	0.01	0.76	0.01
	MAP	0.38	NS	0.35	NS	0.90	0.001
	MAP-CVP	0.57	0.05	0.60	0.05	0.61	0.05

RIMP, myocardial performance index of right ventricle; LIMP, myocardial performance index of left ventricle; HR, heart rate (beat/min); CVP, mean central venous pressure (mmHg); RVP, mean right ventricle pressure (mmHg); PAP, mean pulmonary artery pressure (mmHg); PAoP, mean pulmonary artery occlusive pressure (mmHg); MAP, mean artery pressure (mmHg); SV, stroke volume (ml); CO, cardiac output (l/min); MAP-CVP, difference of mean systemic pressures (mmHg); SVR, systemic vascular resistance (dyn.sec/cm<sup>5</sup>); PVR, pulmonary vascular resistance (dyn.sec/cm<sup>5</sup>); NS, not significant;  $R^2$ , multiple Pearson's residual index;  $p <$ , level of significance

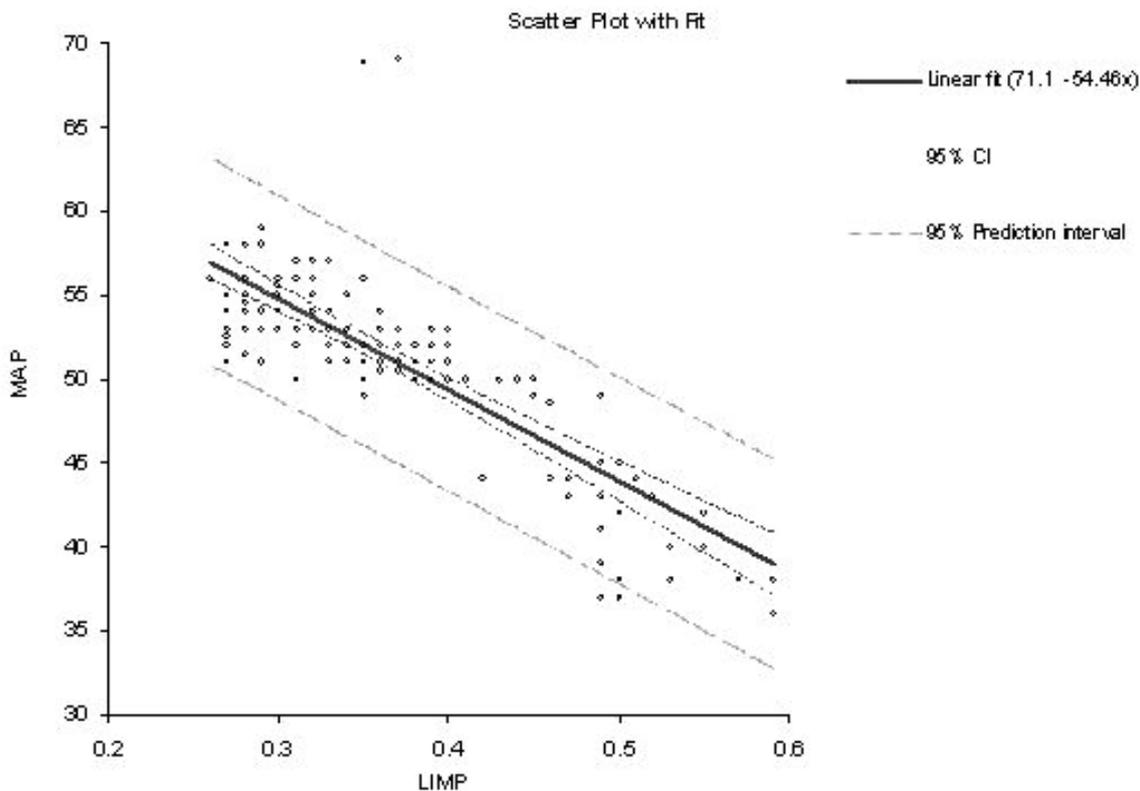
**Table 3.** Correlations of myocardial performance indexes with standard hemodynamic parameters in the set of all data obtained (n=244).

Dependent variables	Independent variables	95 % CI interval	R <sup>2</sup>	P<
<i>RIMP</i>	<i>PVR</i>	0.57 to 0.75	0.67	0.01
	<i>RVP</i>	0.13 to 0.42	0.28	NS
	<i>CVP</i>	0.27 to 0.53	0.51	0.05
	<i>MAP-CVP</i>	-0.46 to -0.17	0.32	NS
	<i>PAoP</i>	0.21 to 0.48	0.35	NS
	<i>CO</i>	-0.37 to -0.07	0.23	NS
<i>LIMP</i>	<i>SVR</i>	0.77 to 0.87	0.86	0.001
	<i>PAoP</i>	0.64 to 0.79	0.72	0.001
	<i>SV</i>	-0.53 to -0.19	0.62	0.01
	<i>CO</i>	-0.73 to -0.54	0.64	0.01
	<i>MAP</i>	-0.86 to -0.75	0.82	0.001
	<i>MAP-CVP</i>	-0.42 to -0.13	0.28	NS
	<i>PVR</i>	0.11 to 0.40	0.26	NS

RIMP, myocardial performance index of right ventricle; LIMP, myocardial performance index of left ventricle; CVP, mean central venous pressure (mmHg); RVP, mean right ventricle pressure (mmHg); PAoP, mean pulmonary artery occlusive pressure (mmHg); PVR, pulmonary vascular resistance (dyn.sec/cm<sup>5</sup>); MAP-CVP, difference of mean systemic pressures (mmHg); CO, cardiac output (l/min); SVR, systemic vascular resistance (dyn.sec/cm<sup>5</sup>); MAP, mean artery pressure (mmHg); NS, not significant; R<sup>2</sup>, multiple Pearson's residual index; p<, level of significance



**Fig. 3.** Chart polynomial regression data of the left myocardial performance index vs cardiac index. The "x" axis of the graph are plotted the data values left myocardial performance index and on the axis "y" values of cardiac index data.



**Fig. 4.** Chart polynomial regression data of the left myocardial performance index vs mean arterial pressure. The "x" axis of the graph are plotted the data values left myocardial performance index and on the axis "y" values of mean arterial pressure data.

After analyzing the entire data set ( $n=224$ ) polynomial regression revealed significant correlations between the values of LIMP versus CI ( $p<0.001$ ) and LIMP vs. MAP ( $p<0.001$ ). Graphical representation of those regressions are given in Figures 3 to 4.

## Discussion

Echocardiographic index of global myocardial performance has been used in non-invasive assessment of cardiac function for more than 10 years (Takano *et al.* 1997). Wide experience was gained with its use both in experimental (LaCorte *et al.* 2003, Teshima *et al.* 2007, Treska *et al.* 2003, Liska *et al.* 2009, Molacek *et al.* 2009, Cheung *et al.* 2004, Hori *et al.* 2007) and adult clinical practice (Lavine *et al.* 2008, Tei *et al.* 1995 and 1997, Murphy *et al.* 2007), respectively. It also appears to be a useful prognostic tool in adult patients with dilated cardiomyopathy (Koga *et al.* 2008, Dujardin *et al.* 1998), anthracyclin induced myocardial toxicity (Peltier *et al.* 2002), chronic lung disease (Senju *et al.* 2007), amyloidosis (Tei *et al.* 1996), and Chagas disease (Borges *et al.* 2002). This index of myocardial performance has been validated in paediatric patients with various

congenital heart defects (Williams *et al.* 2000, Eidem *et al.* 1998 and 2000, Yacoub *et al.* 2003), and with pulmonary hypertension (Pratap *et al.* 2004). It has been found useful in the acute setting of paediatric cardiac intensive care as well (Harada *et al.* 2002, Patel *et al.* 2009). Controversy has persisted about its load independence. In their original description of the index, found it independent of the degree of mitral valve regurgitation. They subsequently found the index correlated closely with parameters of systolic and diastolic myocardial function measured invasively (Takano *et al.* 1997, Tei *et al.* 1996). However, further experimental testing of the index against acute changes in both preload and afterload conveyed some evidence about significant impact of these changes on the index values (Hori *et al.* 2007). Results from our experimental study show a correlation between indices of myocardial performance for the right ventricle and its invasively measured preload (central venous pressure) and afterload (pulmonary vascular resistance). Left ventricular index of myocardial performance also correlated with its preload (pulmonary arterial occlusion pressure) and afterload (systemic vascular resistance). Both indices then inversely correlated with cardiac output. These results support load dependence of the index. It has to be stressed that all data in our study

were obtained in an acute setting of experimental kidney transplantation or liver surgery. It is perhaps not surprising that myocardial function as assessed by global myocardial performance index closely mirrors acute changes in ventricular loading conditions and afterload in particular. Experimental studies of Cheung *et al.* (2004) and Lavine *et al.* (2006, 2008) are of particular interest here. They all show dependence of the index on loading conditions in pigs and dogs, respectively. Positive and negative inotropic agents were used to assess the index sensitivity to altered myocardial function. Interesting results were obtained showing improvement of the index values (lower values) in the setting of mildly chronically decreased left ventricular function with acute administration of dobutamine infusions (2.0-2.5  $\mu\text{g}/\text{kg}/\text{min}$ ) or following one month of digoxin treatment (Duggal *et al.* 2005). No such improvement was observed with dobutamine administration (5.0  $\mu\text{g}/\text{kg}/\text{min}$ ) in pigs with normal left ventricular function despite improved  $\text{dP}/\text{dt}$  in the study of Cheung *et al.* Any such results and their extrapolation into clinical human physiology have to be treated with caution as inter-species and even intra-species differences are likely (Cheung *et al.* 2004, Patel *et al.* 2009). Nevertheless the index of myocardial performance being dependent on loading conditions follows changes in myocardial function and it appears to have predictive value mainly in myocardial dysfunction. This probably reflects changes in isovolumic contraction time and ejection time most likely to be affected by disease states leading to myocardial systolic dysfunction and increased afterload. Treatment interventions altering myocardial systolic function and afterload with concomitant shortening of isovolumic contraction time and lengthening of ejection time will lead to improved values of the index (Lavine *et al.* 2006).

At our centre we obviously prefer minimally invasive techniques. In critically ill children we assess the global performance of each ventricle. Over the last approximately ten years we have had excellent experience with echocardiography. Repeated echocardiographic evaluation and calculations of Tei-indices with shortening fraction in combination with continuous monitoring of systemic pressures we checked the effectiveness of pharmacological circulatory support. Quality testing is for all methods of monitoring hemodynamics depend on the hands-on investigator experience. The basic levels of cardiologic morphological orientation, measurement and control of the sonographic apparatus may be achieved over an intensive course lasting several days. However, good technique using invasive thermo-dilution methods does

take considerably longer. At our PICU, 75 % of physicians are trained in echocardiography, whilst only 5 % are experienced in thermo-dilution techniques. It was a logical step for us to scientifically confirm that the global preferred trend of minimally invasive techniques in determining cardiac performance, are comparable to the so-called gold standard in monitoring haemodynamics via a pulmonary catheter.

The authors of this work are aware that echocardiographic imaging does have its limitations, most of which are investigator dependent (e.g. angle of spread of the doppler wave). Measurement of the time interval between the opening and closing of the atrioventricular valves (AVCO), however, is not investigator dependent. This measurement is imprecise during tachycardia where this interval is significantly shortened. We feel that any potential inaccuracies of this method are counterbalanced when the same investigator performs all the measurements in each subject. The clinical assessment of each subject does not depend upon absolute values, but rather the trend of the measured parameters.

Additional limitations of study may include the fact that the study duration took place over 6 years. As the fundamental aim of the study was to achieve the greatest amount of data from a very large number of haemodynamically compromised animals, it was a logistical problem to achieve this in a shorter period of time. As the investigator, apparatus and experimental conditions throughout the entire length of the study remained constant, we feel that the end result is minimally influenced by bias. Echocardiographic cardiac imaging in piglets is hampered by the morphological uniqueness of their chest anatomy, not least by the narrow intercostal spaces. Echocardiography, introduction of pulmonary artery catheter and all measurements were performed by the same investigator in all test animals.

In the statistical processing of large amounts of data ( $n=224$ ) was more accurate calculation of correlation and assessment different than the processing of data in each group.

All the above limitations do not detract from the importance of the Tei-index as a non-invasive, easily obtainable, and reproducible tool for assessment of biventricular myocardial performance in the setting of experimental work and clinical intensive care. Based on our experience and the experience of others serial measurements of this index are likely to be a valuable tool in close monitoring of cardiovascular function in critically ill patients.

## Conflict of Interest

There is no conflict of interest.

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