Original Article

The role of the maximal first derivative of the radial pulse wave (Rad dP/dtmax) in monitoring cardiac function

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Background: This study aimed to assess the clinical significance of the maximal first derivative of the radial pulse wave (Rad dP/dtmax) in monitoring cardiac function with different perioperative patients by researching the relationship between Rad dP/dtmax and cardiac output (CO).

Methods: Patients with non-pump coronary artery bypass grafting (CABG) and open liver tumor resection (OLTR) were enrolled in this study (n=10). CO was measured using the thermodilution Swan-Ganz catheter method and Rad dP/dtmax was acquired by the analysis of patients' left radial artery pressure waveform through the PowerLab data acquisition device. CO, Rad dP/dtmax, heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure, central venous pressure, mean pulmonary arterial pressure, pulmonary artery wedge pressure (PAW), and body surface area was recorded. Data were analyzed using a mixed linear model of time-dependent covariates to duplicate the data.

Results: The bivariate correlation coefficients of Rad dP/dtmax and CO were 0.526 and 0.413. The result of the multivariate mixed linear model analysis showed that compared with other indicators, Rad dP/dtmax had the greatest standardized coefficient with CO in CABG patients. While in OLTR patients, HR, SBP, PAW, and DBP had larger standardized coefficients.

Conclusions: Rad dP/dtmax could be a useful indicator to reflect and predict the acute changes in cardiac function in perioperative patients, especially for patients with cardiac dysfunction or contractility abnormality.

Keywords: Arterial waveform; Rad dP/dtmax; Cardiac output; Swan-Ganz catheter; perioperative

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Introduction

The ultimate purpose of perioperative cardiac function monitoring and hemodynamic treatment is to ensure adequate perfusion and oxygenation (1). Advanced cardiovascular monitoring tools are useful to ensure the hemodynamic stability of patients, especially the critical ones (2). Among these tools, cardiac output (CO), which is measured with the Swan-Ganz catheter, has been accepted as the clinical "golden standard" (3). CO is significantly meaningful in estimating hemodynamic changes and cardiac function in critical patients (4). However, CO could be influenced by many factors such as myocardial contractility, cardiac preload, and afterload, etc. (5). There are still difficulties in quickly and accurately estimating the myocardial contractility when CO declines abruptly in clinical practice and this delayed judgment will affect treatment.

Furthermore, arterial pressure consists of cardiac stroke volume, intravascular blood volume, and arterial wave tension. The wave intensity theory is defined as (dP/dt)·(dU/dt) at any site of the circulation. In this theory, dP/dt is the derivative of blood pressure with respect to time (6). According to this theory, researchers discovered and confirmed that the maximal first derivative or slope of the radial pulse wave (Rad dP/dtmax) is related to the change of left ventricular developed pressure (7). Rad dP/dtmax is a peripheral indicator of the left ventricular contractility that would not be affected by the load status or vascular compliance to patients with coronary heart disease (CHD) (8). Its value change is usefully referential for heart failure patients to evaluate the left ventricular contraction performance (7). In this study, we simultaneously recorded changes in CO and Rad dP/dtmax during the surgeries, aiming to find the feasibility of using Rad dP/dtmax to assess the left ventricular systolic performance and its guiding value for the acute changes of CO with different heart function conditions in the preoperative period.

Methods

Study subjects

This study was conducted at the Xiangya Hospital of Central South University and approved by the Ethics Committee of the Xiangya Hospital. Hospitalized patients with coronary heart disease (CHD) and hepatoma were consecutively enrolled in this study (n=10). All patients signed informed consent preoperatively. Patients taking cardiovascular drugs did not have to stop taking their medication until the morning of the surgery.

The inclusion criteria of CHD and hepatoma patients

CHD patients were enrolled when they met all the following criteria: (I) patients who have accepted preoperative diagnostic coronary angiography and were diagnosed with CHD; (II) The American Society of Anesthesiologists (ASA) classification grade is III–IV. The enrolled patients underwent-elective off-pump coronary artery bypass grafting (CABG).

Patients with hepatoma were enrolled when they met all the following criteria: (I) patients were diagnosed with hepatoma by examination with preoperative abdominal B ultrasound, abdominal CT, and pathologic diagnosis; (II) Patients with structural heart disease were excluded; (III) The ASA grade was II–III. The enrolled patients underwent elective open liver tumor resection (OLTR).

The exclusion criteria for all patients

Exclusion criteria: (I) existing radial artery contraindications, aortic valve reflux continuously, significant arrhythmias; (II) patients who were equipped with intra-aortic balloon pump; (III) patients who were applied with PEEP ventilation considering the possibility of interference with cardiac output and central venous pressure and other indicators.

Data collection

Patients were anesthetized intravenously. During the surgery, an intravenous infusion pump, as well as an intermittent injection of dopamine, phenylephrine, and nitroglycerin were given in order to maintain stable hemodynamics. Dopamine and nitroglycerin were allocated according to the weight of patients. Dopamine was continuously pumped at the rate of 3–5 μg/(kg·min) throughout the operation. All the data were measured at the beginning of the surgical incision. The experimental design used the same interval time points of one patient for data acquisition, which mixed the “time factor” of the relationship between the variables, A Swan-Ganz catheter was applied for monitoring CO, pulmonary artery pressure, and other related parameters. The patients’ radial pulse wave was recorded with the PowerLab data acquisition (DAQ) device (ADInstruments, Australia) (9). For the collection of arterial blood pressure waveform, the conventional clinical arterial pressure transducer was adopted. A tee was set in the pressure transducer, one side was connected to monitor for intraoperative observation and control of blood pressure. The other side was connected to the Powerlab data acquisition. The arterial blood pressure value was transformed into a corresponding voltage value and the analog voltage value was recorded. Rad dP/dtmax was automatically calculated using the instrument built-in LabChart 7.0 system to analyze each period of time corresponding to the pulse waveform. The largest value of Rad dP/dtmax was measured by monitoring CO for 90s. Heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), central venous pressure (CVP), mean pulmonary arterial pressure (PAM), pulmonary artery wedge pressure (PAW),

Table 1 Baseline characteristics of the two groups of patients undergoing surgery

Parameters	CABG	OLTR	P
N	10	10	
Age, years	59±7	45±6	0.002
Sex (female), %	40	40	NS
Height, cm	160.3±8.7	161.9±5.5	NS
Weight, kg	61.6±8.6	58.1±7.8	NS
BMI, $kg \cdot m^{-2}$	24.0±1.9	22.1±2.9	NS
ASA class II or III, %	90	90	NS
Hypertension	4	3	NS
Diabetes	3	2	NS
ACEI/ARB	4	3	NS
β-blockers	1	0	NS
Diuretics	0	0	NS
Calcium antagonists	0	0	NS
Aspirin	1	0	NS
Digoxin	0	0	NS

NS, non-significant.

and body surface area (BSA) were repeatedly measured for every 5 minutes and recorded 20 times. Additionally, when the automatic measurement of Rad dP/dtmax failed then the data was excluded.

Statistical analysis

Statistical analyses were conducted using SAS statistical software. The single factor mixed linear model and time-dependent multivariable mixed linear model were applied. Time-dependent multivariable mixed linear model was essentially multiple regression analysis. The general information and hemodynamic parameters changed over time in CABG and OLTR group were considered as variables, which would be included into the regression model. Regression analysis wasn't conducted until intra-group correlation coefficient (ICC) was greater 0.3. The variables with a significant difference would be eventually incorporated into each group by the multi-factor mixed linear model. The time-dependent indexes were adopted. All data were tested for normality by Shapiro-Wilk test. All data were expressed as mean ± SD. The statistical significance was P<0.05.

Table 2 Clinical characteristics and Rad pressure analysis data of the study subjects

Parameters	CABG		OLTR	
	Mean ± SD	r value	Mean ± SD	r value
CO (L/min)	3.6±1.0		5.9±1.8	
Rad dP/dtmax (mmHg/s)	701±229	0.526	802±243	0.413
HR (beats/min)	67±17	0.323	82±14	0.230
SBP (mmHg)	102±14	0.345	122±19	−0.069
DBP (mmHg)	60±10	0.246	77±14	−0.240
MAP (mmHg)	74±11	0.307	95±17	−0.113
CVP (mmHg)	8±4	−0.258	11±3	0.235
PAM (mmHg)	16±3	−0.039	21±4	0.373
PAW (mmHg)	11±3	−0.195	16±4	0.338
BSA (m^2)	1.6±0.1	−0.233	1.6±0.1	0.111

CABG cases =196, missing value =4; OLTR cases =165, missing value =35. r value is simply bivariate related with CO to the variables of the correlation coefficient. Confidence level (bilateral) 0.01.

Results

Baseline characteristics

The general characteristics of patients and their current situation of regular medication used were shown in *Table 1*. Interestingly, we found that age was the only factor with a significant difference between the groups (P=0.002). Thus, in the following multivariate model analysis, age was involved.

Rad dP/dtmax and hemodynamic parameters

A total of 196 data from the CABG group and 165 data from the OLTR group were collected (*Table 2*). Four data were excluded in the CABG group and 35 data from the OLTR group. The excluded data lacked in accuracy because of the occurrence of a severe arrhythmia, which was caused by moving the heart during cardiac surgery or the signal of the instrument itself. Rad dP/dtmax analyzing each period of time corresponding to the pulse waveform was showed in *Figure 1*. The value of ICC was 0.5, which meant that the reliability of repeated measurement data was high. In the univariate analysis, it showed that the correlation coefficient (r) of Rad dP/dtmax and CO (r=0.526 in CABG group, and

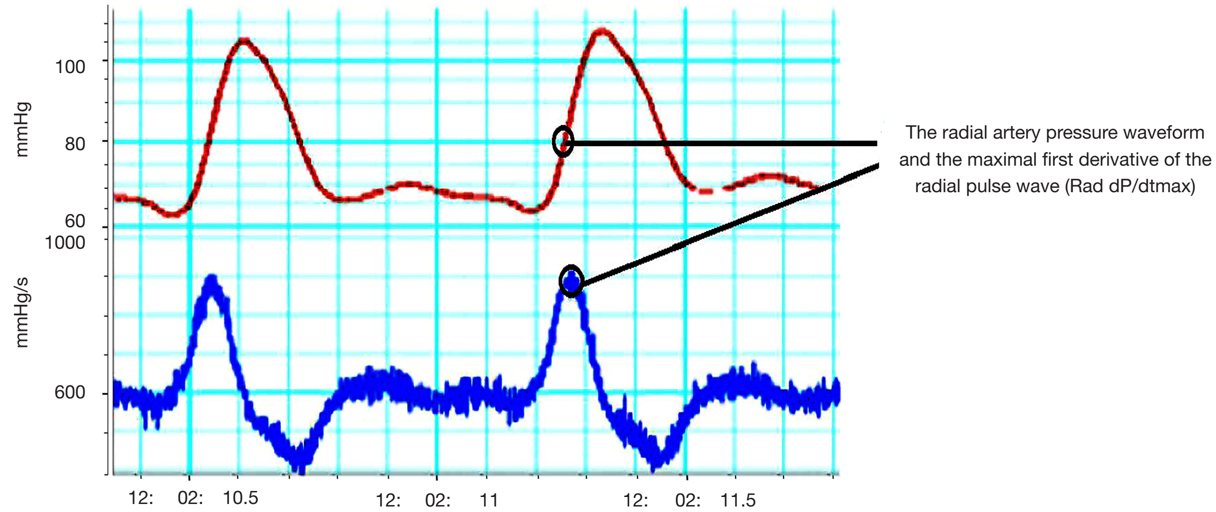

Figure 1 Rad dP/dt was automatically calculated by the instrument built-in LabChart 7.0 system as radial ejection duration.

Table 3 Baseline characteristics related with CO in CABG and OLTR patients by single factor mixed linear model

Parameters	CABG		OLTR	
	r value	P value	r value	P value
AGE	−0.2317	0.0130	−0.2161	0.0524
SEX	−0.2066	0.3677	0.4076	0.0908
HEIGHT	−0.0905	0.4300	0.0730	0.5426
WEIGHT	−0.1524	0.1421	0.0566	0.6654
BSA	−0.9830	0.2097	0.4322	0.7353
TIME	−0.0044	0.6377	−0.0013	0.0921

CABG group: only age is included in the final multivariate mixed linear model for analysis; OLTR group: all the basic indicators are not included in the final multivariate mixed linear model.

r=0.413 in OLTR group) were larger than other indicators. According to these results, we could safely speculate that Rad dP/dtmax and CO always have better consistency whether the heart function is normal or not. Moreover, the changes of Rad dP/dtmax might partly reflect and predict the tendency of CO.

Factors that influence the relationship between Rad dP/dtmax and CO

The results were showed in *Table 3* and *Table 4*. In the CABG group, age (P<0.05), Rad dP/dtmax, Rad dP/dtmax * TIME, HR, HR * TIME, SBP * TIME, MAP * TIME, CVP * TIME, PAM, PAM * TIME, and PAW * TIME were included in the final multivariate mixed linear model for analysis. In the OLTR group: Rad dP/dtmax, Rad dP/dtmax * TIME, HR, HR * TIME, SBP, DBP, MAP, CVP, PAM, and PAW were all included (P<0.05).

In the CABG group, Rad dP/dtmax had the largest standardized coefficient (r=0.2049, P<0.001, *Table 5*) compared with other indicators. However, in the OLTR group, the Standardized coefficient of Rad dP/dtmax had no statistical significance (P=0.1827, *Table 6*). By contrast, HR, SBP, PAW, and DBP had a larger standardized coefficient in this group.

Discussion

It was the first study that explored the relationship between Rad dP/dtmax and CO. In this study, it could be found that compared with other indicators, Rad dP/dtmax could reflect the change of CO, especially when heart function of patients was insufficient. As a classic hemodynamics factor, CO can effectively evaluate patients' cardiac function (2). It is the product of stroke volume (SV) and HR (2). Ventricular systolic performance is the determinant factor of SV. To quantify it, researchers put forward the concept of myocardial mechanics, which regarded the heart as a muscle organ (10). Myocardial mechanics studied the tension, the length, and the shortening or lengthening speed and simultaneously found the variation and relationships among these three mechanical parameters in the myocardial mechanical activity. In animal experiments,

Table 4 Baseline characteristics related with CO in CABG and OLTR patients by the mixed linear model of time-dependent covariates duplicate data

Variable	CABG		OLTR	
	r value	P value	r value	P value
Rad dP/dtmax	0.143	0.0021	0.2429	<0.0001
Rad dP/ dtmax*TIME	0.003	0.0015	0.0017	0.0208
HR	−0.2303	0.009	0.0161	<0.0001
HR*TIME	0.004108	0.0005	−0.0007	<0.0001
SBP	0.006197	0.899	0.2726	<0.0001
SBP*TIME	0.00284	0.0012	−0.0038	0.4926
DBP	−0.01869	0.7339	0.2445	0.0011
DBP*TIME	0.001744	0.0526	−0.0005	0.2405
MAP	0.01964	0.7048	0.1593	0.0009
MAP*TIME	0.00207	0.0188	−0.0010	0.7176
CVP	−0.01801	0.7664	0.1579	0.0003
CVP*TIME	−0.00354	0.0002	−0.0003	0.7355
PAM	0.1705	0.0211	0.1489	<0.0001
PAM*TIME	−0.00296	0.0047	0.0002	0.0821
PAW	0.124	0.0987	0.1670	<0.0001
PAW*TIME	−0.00316	0.002	0.0011	0.1995

CABG patients had 10 variables (Rad dP/dtmax, Rad dP/dtmax * TIME, HR, HR * TIME, SBP * TIME, MAP * TIME, CVP * TIME, PAM, PAM * TIME, PAW * TIME) P value <0.05, to be included in *Table 5* of multivariate mixed linear model analysis. OLTR patients had 10 variables (Rad dP/dtmax, Rad dP/dtmax* TIME, HR, HR * TIME, SBP, DBP, MAP, CVP, PAM, PAW) P value <0.05, to be included in *Table 6* of multivariate mixed linear model analysis.

Table 5 The analysis of variables related with CO for CABG patients by multivariate mixed linear model

Variable	Standardized coefficient	t value	P value
AGE	−0.1438	18.68	0.1138
Rad dP/dtmax	0.2049	−1.59	<0.0001
Rad dP/dtmax*TIME	−0.0010	4.64	0.2754
HR	0.0190	−1.09	0.8052
HR*TIME	0.0006	0.25	0.4187
SBP*TIME	0.0051	0.81	<0.0001
MAP*TIME	−0.0047	4.24	0.0002
CVP*TIME	−0.0045	−3.85	<0.0001
PAM	0.1250	−5.33	0.0298
PAM*TIME	0.0008	2.19	0.5236
PAW*TIME	−0.0005	0.64	0.5926
TIME	−0.0007	−0.54	0.3295

Statistical results are shown that Rad dP/dtmax has the largest standardized coefficient, compared to other indicators, it can better reflect the trends of CO.

Table 6 The analysis of variables related with CO for OLTR patients by multivariate mixed linear model

Variable	Standardized coefficient	t value	P value
Rad dP/dtmax	0.06385	1.34	0.1827
Rad dP/dtmax * TIME	0.001187	2.09	0.0384
HR	0.2215	4.65	<0.0001
HR*TIME	−0.00166	−2.9	0.0043
SBP	0.1827	3.75	0.0003
DBP	−0.179	−3.8	0.0002
MAP	0.0256	0.81	0.4199
CVP	−0.00201	−0.07	0.9481
PAM	0.0242	0.54	0.5872
PAW	0.1044	2.56	0.0114

Statistical results showed that Rad dP/dtmax * TIME, HR, HR * TIME, SBP, DBP, PAW P values <0.05, including HR, SBP, PAW, DBP has a large standardized coefficients compared to other indicators, they can better reflect the trends of CO.

scientists revealed that the maximum rate of left ventricular pressure pressure rise (LV dP/dtmax) has a good linear relationship with cardiac contractility (11). LV dP/dtmax can be regarded as a remarkable indicator of myocardial contractility (12). Subsequently, it was confirmed that the first peak of carotid arterial wave intensity is closely related to LV dP/dtmax (6). The magnitude of this first peak could be derived as $(dP/dt)^2/\rho c$ and it can be concluded from the formula (where ρ is blood density and c pulse wave velocity) that the first peak of the wave intensity is mostly determined by the values of dP/dt (13). The pulse wave morphology is persistently transformed along the arterial tree by the local viscoelastic properties and the increase of the reflected wave, which leads to a steeper slope of the maximal first derivative (14). This phenomenon leads to a systematic addition of the arterial dP/dt with the distance from the aortic root increasing. Thus, its ability to characterize the LV contractility is not changed (15). Therefore, Rad dP/dtmax could be used as a peripheral indicator reflecting the cardiac contractility.

Our previous study has testified that Rad dP/dtmax is one of the best peripheral indexes to reflect left ventricular myocardial contractility to a certain extent during laparotomy through epidural anesthesia (16). In the present study, we further found that it's more meaningful for monitoring Rad dP/dtmax when patients' heart function was not normal. According to the result of the study, we can speculate that the numerical changes of Rad dP/dtmax may partly reflect and predict the tendency of CO. A previous study proposed that myocardial contraction performance is the main factor influencing cardiac function (10,17). Our results are in keeping with this current point of view.

For the analyzes of relatively independent standardized coefficient about each variable in the two groups of patients, it showed that Rad dP/dtmax had the largest standardized coefficient (0.2049, *Table 5*) with CO compared with other indicators in the CABG group. It meant that when Rad dP/dtmax changed by 1 unit, then CO changed 0.2049 units. However, it had no statistical significance in the OLTR group. In the OLTR group, HR, SBP, PAW, DBP had larger standardized coefficients (*Table 6*). All these results suggested that Rad dP/dtmax which estimated the left ventricular systolic performance could be one of the factors to decide the change of CO in patients with cardiac dysfunction. For patients with cardiac dysfunction, positive inotropic drug myocardial contraction could be applied to improve patients' cardiac contractility performance when CO decreased during the process of operation. The changes of Rad dP/dtmax may provide a strong basis for our judgment before and after the treatment. By contrast, changes of CO in patients with normal heart function are mainly affected by four factors: HR, PAW, SBP (positively correlated) and DBP (negatively correlated). The value of Rad dP/dtmax reflecting the intrinsic properties of left ventricular contractility is relatively stable in normal range when patients' heart function was normal and myocardial contraction performance was in good condition.

Our study verified that some relationship could exist between Rad dP/dtmax and CO. However, whether other indicators could influence the correlation and whether the stability of this correlation will change over time needs further analyses. The results of this study suggested that Rad dP/dtmax, which estimates the left ventricular systolic performance, is the main factor in deciding the change of CO in patients with cardiac dysfunction or if their CO is lower than normal. For patients with cardiac dysfunction, positive inotropic drug myocardial contraction can be applied to improve patients' cardiac contractility performance when CO decreased during the process of the operation. Then, observing the changes of Rad dP/dtmax may provide a strong basis for our judgment before and after the treatment. By contrast, in patients with normal heart function, changes of CO are mainly affected by four factors: HR, PAW, SBP (positively correlated), and DBP (negatively correlated) (18). This conclusion is consistent with the results of other studies (19,20). The value of Rad dP/dtmax reflecting the intrinsic properties of left ventricular contractility is relatively stable in the normal range when patients' heart function was normal and myocardial contraction performance was in good condition.

Several limitations still existed in this study. Firstly, the sample size was relatively small and there existed the homogenous nature of the population. Those subjects selected in this study were only patients with heart bypass and liver resection. Therefore, the results could only explain these two types of patients, which couldn't be explained and applied universally in clinic. Although the radial artery was selected in this study, which was more commonly used in clinical practice and had less trauma, this should be further verified in the femoral artery and dorsal foot artery. In the future, further study should be carried out to better convince and verify the significance of Rad dP/dtmax in evaluating cardiac function. Besides, there were no statistical analysis of the dosage of vasoactive medications in the two groups. More statistical methods should be applied, such as scatter plots. All these indeed provided a new direction and idea for our future experimental research.

Conclusions

In this study, it could be concluded that Rad dP/dtmax would an independent and sensitive clinical indicator. Moreover, Rad dP/dtmax could be a useful indicator to reflect and predict the acute changes of cardiac function in perioperative patients, especially for patients with cardiac dysfunction or contractility abnormality.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at http://dx.doi.org/10.21037/jtd-19-3161). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This study was conducted at the Xiangya Hospital of Central South University and approved by the Ethics Committee of the Xiangya Hospital. All patients signed informed consent preoperatively.

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