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Comparison of two minimally invasive cardiac-output monitoring systems with different algorithms

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Abstract

Objectives: Minimally invasive haemodynamic monitoring is important in goal-directed therapy. The algorithms used by the FloTrac/Vigileo (FV) and lithium dilution cardiac output rapid (LiDCOrapid) (LR) measurement systems for cardiac output (CO) monitoring differ. We examined correlations of FV and LR measurements with thermodilution measurements and determined responsiveness to phenylephrine using both systems.

Methods: The FV system was used as the main arterial pressure line, and a second line was connected to the LR system. First, we measured CO at multiple time points using thermodilution and compared these measurements with those obtained simultaneously using the LR and FV systems. Second, CO, systemic vascular resistance and stroke volume (SV) were simultaneously measured using the LR and FV systems after phenylephrine administration.

Results: Measurements obtained at 38 time points in 3 patients were compared. There were strong correlations of LR and FV measurements with thermodilution measurements. Bland–Altman analysis indicated that LR (percentage error, PE, 29.8%) and FV (PE, 31.6%) system measurements were equivalent to thermodilution measurements. Following phenylephrine administration, the LR system detected an increase in blood pressure following an increase in vascular resistance, with negligible change in SV. Conversely, the FV system detected little change in vascular pressure and a marked increase in SV.

Conclusions: Compared with thermodilution, both the LR and FV systems demonstrated sufficient accuracy and precision for clinical use. The LR system was more accurate than the FV system in reflecting rapid changes in blood pressure, vascular resistance and CO following phenylephrine administration.

Keywords: Minimally invasive haemodynamic monitoring, PulseCO/LiDCOrapid, FloTrac/Vigileo, Thermodilution, Cardiac output, Phenylephrine

Introduction

Excessive fluids are harmful during perioperative fluid management, and the concept of individual fluid optimization is gaining attention. The concept differs from that of uniform conventional management in that it aims to optimize fluid management tailored for individual patients in real-time. To achieve individual fluid optimization, minimally invasive blood-pressure monitoring that measures blood pressure and accurately reflects haemodynamics is crucial. The UK consensus guidelines[1] recommend cardiac output (CO) monitoring to evaluate circulating blood volume during perioperative fluid management.

The FloTrac/Vigileo system (Edwards Lifesciences, Irvine, CA, USA) is widely used in clinics across Japan. However, in relation to fluid loading, the ability of the system to monitor systemic vascular resistance (SVR) is considered poor, and its precision has been questioned.[2,3] In 2012, the lithium-dilution CO rapid (LiDCOrapid) measurement system (distributed by: Nihon Kohden Corporation, Tokyo, Japan), a new non-calibrated device for peripheral arterial analysis, was released in Japan for clinical use. The LiDCOrapid system uses a new algorithm

to calculate CO, which measures changes in arterial volume on the basis of stroke volume (SV), with SV defined as a function of arterial pressure. Therefore, the LiDCOrapid system allows beat-to-beat analysis and provides quick and accurate responses when anaesthesia is induced or cardiovascular drugs are administered. In this study, we examined correlations of values obtained by thermodilution with those obtained by FloTrac/Vigileo, and also with those obtained with the LiDCOrapid system, and determined the responsiveness to phenylephrine using both systems.

The LiDCOrapid and FloTrac/Vigileo systems and their algorithms
1. The LiDCOrapid system

The first-generation LiDCO monitoring system was released in 1999. This system offered intermittent, high-precision CO measurements using the lithium arterial indicator dilution method following an intra venous injection of lithium chloride.[4] In 2002, the PulseCO algorithm enabled continuous CO measurement, with calibrated CO values obtained using a non-morphologically based algorithm (PulseCO autocorrelation) for deriving stroke volume and heart rate from the peripheral arterial blood-pressure signal. The LiDCOplus system, which was introduced in 2005, combined the lithium-dilution method with the PulseCO algorithm. Finally, the LiDCOrapid system was released in 2008 as a non-calibrated system incorporating the PulseCO algorithm and a patient-characteristic nomogram (undisclosed) for improved accuracy by reduction of bias.

The PulseCO algorithm converts arterial pressure waveforms

sampled at 100 Hz into blood volume waveforms (equation 1), defines SV as the change in arterial vascular volume per systole, and calculates CO. The calibration factor (CF) is a patient-specific variable based on patient height, body weight and age.

$$\text{Vascular volume} = CF \times 250 \times (1 \times e^{-k*P}) \qquad (1)$$
(k: unpublished coefficient, P: arterial pressure,
$1 \times e^{-k*P}$: vascular compliance)

Because vascular volume is calculated using pulse power, which is independent of blood pressure waveforms, accurate evaluation is possible even when vascular resistance changes rapidly (e.g. in a hyperdynamic state or after administration of a vasoactive agent). Moreover, the results are minimally affected by arterial pressure measurement, line damping (frequency response), or large changes in resistance.[5]

2. The FloTrac/Vigileo system

The standard deviation (SD) of pulse pressure (PP) values measured at 100 Hz is a reliable method for characterizing PP. Greater SD values indicate a higher PP and a larger area under the curve (AUC). In cadaveric autopsy studies, vascular resistance is calculated on the basis of the elasticity of large arteries, degree of distortion and kurtosis of blood pressure waveforms (left or right deviation of distribution). Therefore, arterial pressure waveforms are extremely important in the FloTrac/Vigileo system. Extending or shortening the FloTrac sensor circuit alters the arterial pressure waveforms, causing inaccurate vascular resistance calculations. The software is updated by incorporating arterial waveform data recorded for various disease pathologies.

Methods

Monitoring circuit used for clinical comparison of the sensors

To maintain similar hydrodynamic properties between the two sensors investigated, a monitoring circuit for clinical comparison of the two sensors was established (the 'test circuit') with the FloTrac sensor circuit as the main circuit

and a secondary circuit connected to a three-way stopcock plugged into the tip of a 30-cm tube connected to the FloTrac sensor. The secondary circuit included the LiDCOrapid arterial pressure sensor and a 30-cm pressure resistance line (Figure 1). This allowed the use of both sensors simultaneously while monitoring from the same radial artery site.

Comparison between the test circuit and the an unmodified FloTrac sensor

To determine whether the test circuits used to compare the two sensors and an unmodified FloTrac sensor (i.e., in the absence of the secondary circuit) were equally precise, we compared the characteristics (amplitude, natural frequency and damping factor) and reproducibility, of simulated radial artery pressure waveforms, among the systems.

*Comparison of precision between thermodilution and the two systems*

Using the test circuit, we compared the precision of CO and SV values derived from the LiDCOrapid arterial pressure sensor, and the values from the FloTrac sensor, with the corresponding values obtained by thermodilution. The subjects included two patients (cases 1 and 2) scheduled for routine liver resection and one patient (case 3) undergoing postoperative management after implantation of an aortic arch prosthesis (Table 1). In all patients, anaesthesia was induced, for which a Swan–Ganz catheter was inserted into the right jugular vein after securing an invasive arterial pressure line for the monitoring circuits. CO was measured simultaneously using thermodilution (CO_{Ther}), LiDCOrapid (CO_{LiDCO}) and FloTrac ($CO_{FloTrac}$) systems at multiple time points.

Responsiveness to phenylephrine administration

Changes in mean arterial pressure (MAP), SV and SVR after intraoperative phenylephrine administration were determined by measuring radial artery pressure using both the LiDCOrapid and FloTrac/Vigileo systems in the test circuit.

The analytical data differed between the two systems because the FloTrac/Vigileo system measured mean values over 20-s periods that were renewed every 20 s, whereas the LiDCOrapid system performed beat-to-beat

Figure 1.
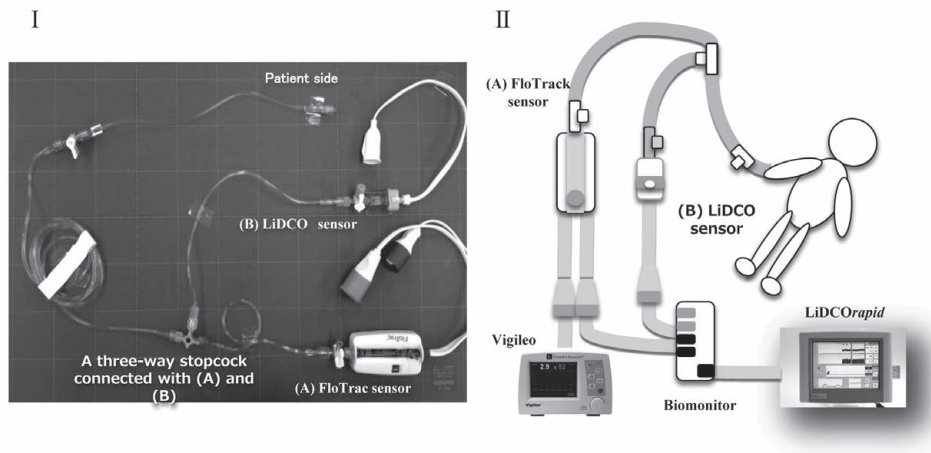
Monitoring circuit for clinical comparison of the two sensors.
I: actual circuit, II: schematic diagram. To maintain the properties of the FloTrac sensor, the monitoring circuit was established with the FloTrac sensor (A) as the main circuit, and a secondary circuit was connected via a three-way stopcock plugged into the tip of a 30-cm tube connected to the FloTrac sensor. The secondary circuit included a LiDCOrapid pulse pressure sensor (B) and a 30-cm pressure-resistant line.

Table 1. Backgrounds of patients used in comparisons among the two sensor systems and thermodilution measurements.

	Case 1	Case 2	Case 3
Age (year)	66	64	69
Sex	Male	Male	Female
Height (cm)	163	159	157
Body weight (kg)	52	53	47
Disease	Liver cell cancer	Metastatic liver cancer	Ascending aortic dissection
Operative method	Liver resection	Liver resection	Total arch replacement
Past history			
Hypertension	-	+	+
Hyperlipidemia	-	+	-
Arrhythmia	-	-	-
Coronary heart disease	-	-	-
Vascular disease	-	-	+
Others	-	-	-

Table 2. Backgrounds of patients used in tests of responsiveness of the two systems to phenylephrine administration.

	Case 4	Case 5	Case 6
Age (year)	65	73	57
Sex	Female	Female	Male
Height (cm)	162	151	166
Body weight (kg)	62	40	66
Disease	Rectal prolapse	Metastatic liver cancer	Rectal cancer
Operative method	Laparoscopic rectal prolapse surgery	Liver resection	Robot-assisted laparoscopic rectal surgery
Past history			
Hypertension	-	-	-
Hyperlipidemia	-	-	-
Arrhythmia	-	-	-
Coronary heart disease	-	-	-
Vascular disease	-	-	-
Others	-	-	-

measurements. Therefore, the LiDCOrapid beat-to-beat data were consolidated and processed with the FloTrac/Vigileo data points by calculating mean values over 20-s periods. For the analysis of LiDCOrapid data, we used LiDCOview, which matched the timing of phenylephrine administration with MAP measurements. We examined the responsiveness to phenylephrine administration in three patients (Cases 4, 5 and 6; Table 2).

Ethics and consent
This observational case study was approved by the ethics committee of the Fujita Health University School of Medicine, Toyoake, Aichi, Japan. All patients or their families provided written informed consent after receiving a verbal explanation of the study.

Results

Comparison between the test circuit and the unmodified FloTrac sensor
Natural frequencies of 21.7, 18.0 and 18.2 Hz, and damping factors of 0.15, 0.15 and 0.16, were observed for the unmodified FloTrac sensor, and for the FloTrac and LiDCOrapid arterial pressure sensors in the test circuit, respectively.

To investigate the reproducibility of the simulated radial artery pressure waveforms, we compared the measurements obtained using a normal unmodified FloTrac sensor, and the FloTrac and LiDCOrapid arterial pressure sensors in the test circuit, with those obtained using a control. The systolic pressure overestimates were +2, +3 and +2 mmHg, respectively. Therefore, our results revealed no difference among circuits, indicating equivalent accuracy.

Comparison of the precision of thermodilution and the two systems

CO was measured in all three patients (Table 1) at 38 time points. These data were analysed with single correlations and Bland-Altman analyses. Single correlation analysis revealed strong correlations between the LiDCOrapid sensor and thermodilution ($r = 0.835$; $p < 0.01$) measurements and between the FloTrac sensor and thermodilution ($r = 0.762$; $p < 0.01$; Figures 2, 3) measurements. The results of Bland-Altman analysis are shown in Table 3.

Responsiveness to phenylephrine administration

Table 2 shows the backgrounds of the three patients in the test for responsiveness to phenylephrine administration. Following phenylephrine administration, the LiDCOrapid sensor measurements of SVR and MAP increased simultaneously, whereas little or no change was detected in SV (Figure 4). In contrast, the FloTrac/Vigileo system measurements of SV and MAP increased simultaneously, whereas little change in SVR was detected (Figure 4).

Table 3. Results of Bland-Altman analysis comparing the precision of the two sensor systems with thermodilution measurements.

|	LiDCOrapid	FloTrac
Bias	0.15	0.28
Standard deviation	0.64	0.68
upper limit of agreement	1.40	1.61
lower limit of agreement	−1.10	−1.05
percentage error (%)	29.82	31.58

Figure 2.
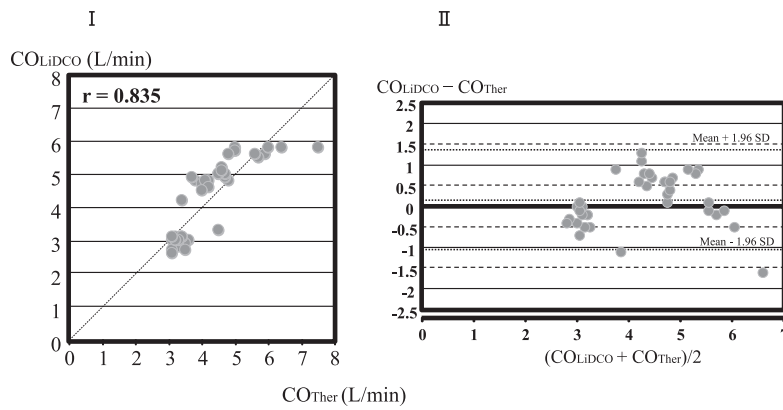
Comparison between the LiDCOrapid sensor and thermodilution.
I: single correlation, II: Bland–Altman analysis. Single correlation analysis indicated a strong correlation ($r = 0.835$, $p < 0.01$).
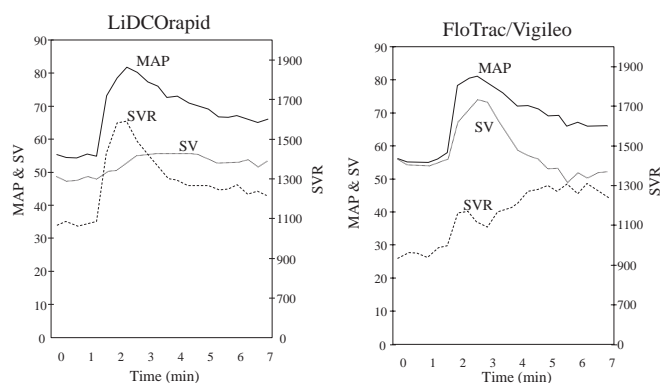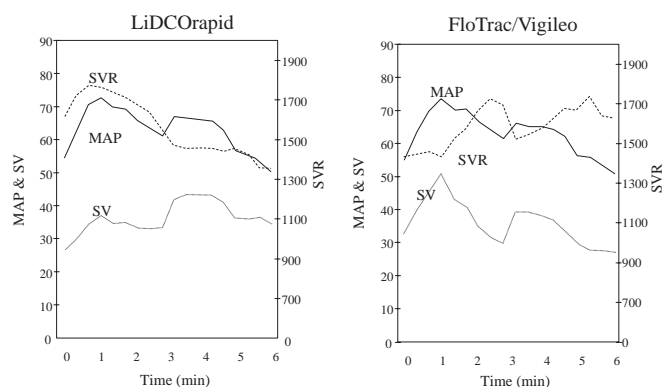CO: cardiac output

Figure 3.
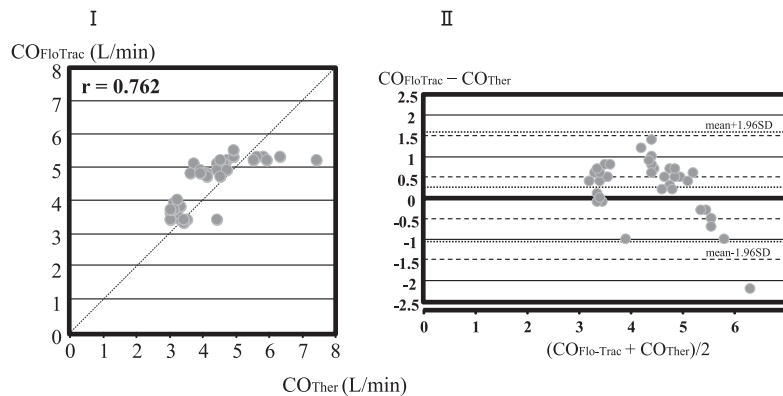
Comparison between the FloTrac sensor and thermodilution.
I: single correlation, II: Bland–Altman analysis. Single correlation analysis indicated a strong correlation ($r = 0.762$, $p < 0.01$).
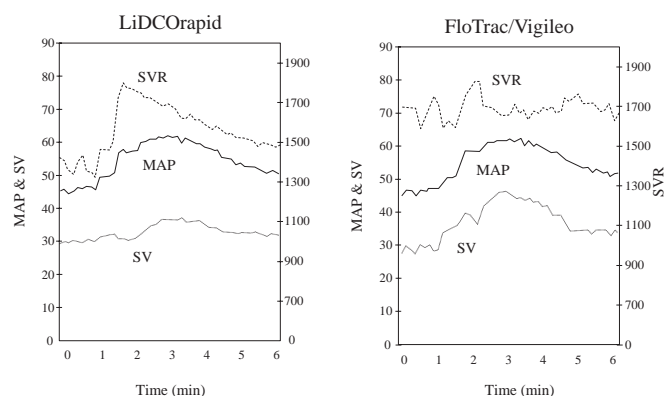CO: cardiac output

Figure 4.

Comparison of the responsiveness of MAP, SV and SVR measured by the LiDCOrapid and FloTrac/Vigileo systems to administration of a 0.1-mg bolus of phenylephrine.
Case 4: 65-year-old female (height: 162 cm, weight: 62 kg); Case 5: 73-year-old female (height: 151 cm, weight: 40 kg); Case 6: 57-year-old male (height: 166 cm, weight: 66 kg).
MAP: mean arterial pressure, SV: stroke volume, SVR: systemic vascular resistance

Discussion

In our study, the precision of both the LiDCOrapid and the FloTrac/Vigileo systems was nearly identical to that of thermodilution. Our results indicate that the LiDCOrapid sensor reflected the pharmacological activity of phenylephrine as a selective a 1-adrenergic receptor agonist more accurately than the FloTrac/Vigileo system did.

It was previously reported that the FloTrac/Vigileo system, which is commonly used in Japan, is less sensitive to rapid changes in SVR compared with those induced by fluid loading. Monnet et al.[2] reported that even the updated third-generation FloTrac/Vigileo system did not accurately detect changes in SVR and, compared with CO changes detected using fluid loading, CO changes induced by norepinephrine administration

were not accurately detected by this system. These data indicate that the system is unsuitable for patients receiving catecholamines.

The newly released LiDCOrapid system uses an algorithm that is independent of blood pressure waveforms and calculates CO by converting arterial pressure waveforms to blood volume waveforms. Therefore, it is believed to offer accurate evaluation, even when there are rapid changes in vascular resistance, such as those occurring in a hyperdynamic state and after the administration of vasoactive agents. The present study verified the precision of the FloTrac/Vigileo and LiDCOrapid systems by comparing their measurements with thermodilution measurements. In addition, it also compared their drug responsiveness.

A complete comparison of the FloTrac and LiDCOrapid arterial pressure sensors is impossible, because even when the same patient or blood vessel is examined, the time points for FloTrac and LiDCOrapid measurements differ.

In this study, we constructed a device that connected the FloTrac and LiDCOrapid sensors, facilitating simultaneous analysis of the same arterial pressure signals from the same blood vessel, allowing us to perform beat-to-beat comparison. Moreover, before performing these measurements, we clarified that the characteristics of the monitoring circuit were identical to those of the FloTrac sensor. Arterial pressure measurements in the LiDCOrapid system were unaffected by line damping (frequency response) and large changes in resistance. This independence from the circuit suggests another method for comparing the two systems. The output of the arterial pressure measurements obtained using the FloTrac sensor could be directed into the LiDCOrapid sensor, thereby gathering data from both sensors. Although this method is theoretically plausible, its precision remains unexplored.

When the FloTrac/Vigileo and LiDCOrapid systems were compared with thermodilution, Bland–Altman analysis yielded PEs of 29.82% and 31.58%, respectively. Critchley et $al.$ reported that a PE of $\pm 30\%$ indicates an accuracy identical to that for thermodilution.[6] Therefore, both systems in our study demonstrated a precision that was nearly identical to that of thermodilution.

Our results also indicated that the responsiveness to phenylephrine administration differed between the two systems. By analogy with Ohm's law:

Blood pressure = Blood flow × Vascular resistance (R).

Therefore, PP ∝ SV × R

and SV ∝ PP × 1/R.

As CO = pulse wave number (PR) × SV,

CO ∝ PR × PP × 1/R

Because the FloTrac/Vigileo system estimates and calculates SV from the SD of PP and vascular resistance from blood pressure waveforms, arterial pressure waveforms are extremely important, and blood pressure waveforms greatly affect CO values. After phenylephrine administration, increases in PP and AUC lead to a higher SD, which may explain why blood pressure increases were mistakenly interpreted as SV increases.

With the LiDCOrapid system, the individual case features are determined according to equation 1, and then arterial pressure waveforms are converted to blood-volume waveforms and SV can be calculated using pulse power, independently of blood pressure waveforms. Following phenylephrine administration, vascular volume can be determined from changes in arterial pressure using the curve produced by equation 1, regardless of changes in blood pressure waveforms. In summary, SV and CO are calculated, following which SVR can be calculated on the basis of these calculations. While the FloTrac/Vigileo system measures vascular resistance from pressure waveforms and uses this to calculate CO, the LiDCOrapid system measures CO and uses this to calculate vascular resistance. Therefore, the latter algorithm is barely affected by pressure waveforms.

For this reason, we selected a pressure line for the FloTrac/Vigileo system, but not for the LiDCOrapid system. Dyer et $al.$[7] reported differences in the responses of circulation parameters, including CO, to ephedrine and phenylephrine administration during Caesarean section surgery under spinal anaesthesia. CO decreased while SVR increased after phenylephrine administration, whereas CO quickly increased after ephedrine administration. Their report focused on the differences between the pharmacological response to phenylephrine and ephedrine. However, these authors used the LiDCOplus system, the predecessor of the LiDCOrapid system, and might have achieved different results using the FloTrac/Vigileo system. Although we only investigated the responsiveness to phenylephrine in this study, we found that the LiDCOrapid sensor was quicker in detecting increases in SVR compared with the FloTrac/Vigileo system, whereas the FloTrac/Vigileo system reported higher CO increases than the LiDCOrapid system did. We did not observe a decrease in CO, as reported by Dyer et $al.$[7], but we confirmed that the LiDCOrapid sensor offers greater accuracy in detecting responses to phenylephrine. Although the FloTrac/Vigileo system is widely used in Japan, our study demonstrated that it may occasionally be inaccurate, particularly in detecting rapid changes in SVR. Therefore, measurements obtained using this system should be carefully assessed.

Limitations

In this study, we analysed only three patients. We could not completely assess the accuracy of the FloTrac/Vigileo and LiDCOrapid systems by comparing their measurements with thermodilution measurements, or from the responses in circulatory parameters after phenylephrine administration. More studies are required to more precisely evaluate these two measurement systems.

Conclusions

Minimally invasive monitoring that accurately reflects haemodynamics is important in goal-directed therapy. In this report, we analysed the algorithms used by the FloTrac/Vigileo and LiDCOrapid monitoring systems to calculate CO and compared the accuracy and precision of their measurements with those of thermodilution. We also investigated differences in their responsiveness to phenylephrine administration. When compared against thermodilution, the LiDCOrapid system appears to demonstrate acceptable accuracy and precision for clinical use and accurately reflected changes in blood pressure, vascular resistance and CO following phenylephrine administration. In contrast, measurements obtained using the FloTrac/Vigileo system should be carefully interpreted. We conclude that the LiDCOrapid system represents a useful clinical tool and an accurate aid to perioperative fluid and circulation management.

Conflict of interest

Dr. Nishida has received grants and endowments from Edwards Lifesciences and Nihon Kohden Corporation. The other authors declare that they have no competing interests.

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sample and data collections.

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