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ORIGINAL ARTICLE

Continuous noninvasive cardiac output in children: is this the next generation of operating room monitors? Initial experience in 402 pediatric patients

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Summary

Background: Electrical Cardiometry™ (EC) estimates cardiac parameters by measuring changes in thoracic electrical bioimpedance during the cardiac cycle. The ICON®, using four electrocardiogram electrodes (EKG), estimates the maximum rate of change of impedance to peak aortic blood acceleration (based on the premise that red blood cells change from random orientation during diastole (high impedance) to an aligned state during systole (low impedance)).
Objective: To determine whether continuous cardiac output (CO) data provide additional information to current anesthesia monitors that is useful to practitioners.
Methods: After IRB approval and verbal consent, 402 children were enrolled. Data were uploaded to our anesthesia record at one-minute intervals. Ten-second measurements (averaged over the previous 20 heart beats) were downloaded to separate files for later comparison with routine OR monitors.
Results: Data from 374 were in the final cohort (loss of signal or improper lead placement); 292 012 measurements during 58 049 min of anesthesia were made in these children (1 day to 19 years and 1 to 107 kg). Four events had a ≥25% reduction in cardiac index at least 1 min before a clinically important change in other monitored parameters; 18 events in 14 children confirmed manifestations of other hemodynamic measures; eight events may have represented artifacts because the observed measurements did not seem to fit the clinical parameters of the other monitors; three other events documented decreased stroke index with extreme tachycardia.
Conclusions: Electrical cardiometry provides real-time cardiovascular information regarding developing hemodynamic events and successfully tracked the rapid response to interventions in children of all sizes. Intervention decisions must be based on the combined data from all monitors and the clinical situation. Our experience suggests that this type of monitor may be an important addition to real-time hemodynamic monitoring.

Introduction

Anesthesiologists seek methods to advance patient safety and improve early recognition of evolving adverse events in a cost-effective minimally invasive manner (1,2). Continuous noninvasive measurement of cardiac output (CO) appears to be the next generation of monitors, but there are few data regarding this technology in children undergoing general anesthesia where rapid and oftentimes unpredictable changes in cardiac function occur. Our group felt that this device might provide a means for assessing real-time cardiovascular responses to anesthesia and surgical interventions. As experience with this device in the operating room has not been adequately assessed and this is unfamiliar technology, our study was observational only; the monitor was not intended to be used to make treatment decisions without input from standard monitors.

Materials and methods

After IRB approval and FDAAA trial registry (NCT01499615), 402 patients ranging from preterm neonates to teenagers were enrolled following verbal consent. The IRB determined that verbal consent was appropriate as there was no randomization and the device was noninvasive with minimal risk. As per manufacturer's instructions, in neonates and small infants, four EKG electrodes were placed on the left leg, left chest at the level of the sternal depression, left neck, and forehead or cheek. For older patients, two EKG electrodes were placed on the left chest and two on the left side of the neck (3). Patient gender, height, and weight were entered into the device which was set to estimate cardiovascular parameters at a 20-beat moving average recorded every 10 seconds. For patients who were cooperative, the EKG pads were placed prior to induction and for all others shortly after induction. The device's electrodes were placed by the same individual (JS) who remained in the operating room to assure consistent setup and data recording, and the occurrence and timing of observed events, that is, the type of induction (inhalation/IV), time and type of airway manipulations, placement of regional blocks, events during the case (turning lateral, prone, etc), and times for start and end of surgery, emergence, extubation, and any interesting perioperative events.

Data from the ICON® device (ICON®, Cardiotronic/Osypka Medical, Inc., La Jolla CA, USA) were uploaded to operating room monitors and integrated into our anesthesia information management system (AIMS; Metavison system iMDsoft®, Needham, MA, USA) at 1-min intervals. Detailed 10-s measurements recorded by the ICON® device were downloaded to Excel spread sheets for later analysis.

The device itself is small (~20 × 10 × 2.54 cm and weighs 1.36 kg) and was generally hung from an IV pole at the head of the operating room table. Every attempt was made to synchronize the time stamp on the anesthesia monitor and the ICON®, but times could have been different by up to 59 s due to the granularity of the AIMS system which only records data at 1-min intervals. The anesthesia care team was instructed that patient care decisions should be based on the usual clinically available parameters and that until further experience was gained, the data provided by the ICON® should only be used as supplemental information.

Data analysis

For each case, the AIMS record was printed at 1-min intervals (the greatest frequency allowed by the iMDsoft® system) and the data recorded (heart rate [HR] from EKG, HR from pulse oximeter), systolic blood pressures (SBP) and diastolic blood pressures, oxygen saturation, inspired and expired anesthetic concentrations compared with hemodynamic data estimated with the ICON® device). We looked for cases with marked changes in HR or SBP and then compared the estimated cardiac parameters of cardiac index (CI) and stroke index (SI) to standard monitors for confirmatory changes consistent with ongoing events. Changes in CI of ≥25% from a baseline value (average of prior 3 min ~ 18 assessments) were considered to be possibly clinically important. We also looked to see whether such changes preceded or were concordant with changes in HR and SBP. We performed *posthoc* analysis to determine whether such a change in CI could have provided an early warning of an evolving adverse hemodynamic event. Two members of the research team (CJC and TAA) had to agree that an event had occurred and that the event might have been recognized before clinically important changes occurred in SBP, HR, or oxygen saturation. Descriptive statistics only were used.

Results

Four hundred and two patients were enrolled of which 374 comprised the final population; in these 374 patients, 292 012 measurements were made during 58 049 min of anesthesia. Twenty-eight cases were excluded due to improper lead placement (e.g., right side rather than left due to the surgical procedure) or loss of signal (loose or lost EKG adhesion or inability to replace due to surgical procedure). Patients varied from preterm neonates to teenagers (ages 1 day to 19 years) and weighed from 1 to 107 kg (Tables 1 and 2). Two hundred and forty patients underwent inhalation induction and the remainder an intravenous induction; a baseline measurement prior to induction was made in 193. All ICON® data in Tables 3 and 4 and Tables S1 and S2 are 1-min averages of 1 to 6 determinations averaged over the previous 20 heart beats.

Table 1 Demographic information

	Mean ± SD	Range
Age (years)	6.47 ± 6.28	1 day to 19 years (Median 4)
Weight (kg)	27.47 ± 23.97	1–107 kg (Median 17)
Duration of Anesthesia (min)	107 ± 105	9–855 (Median 79)
Number of cardiac output determinations per child	522 ± 467	67–3655 (Median 394)

Table 2 American Society of Anesthesiologists (ASA) physical status, gender, ethnicity, and procedures

	Number
ASA physical status	
I	174
II	149
III	46
IV	5
Gender	
Male	246
Female	128
Ethnicity	
African American	21
Asian	25
Other	39
Hispanic	58
Caucasian	231
Type of surgery	
Plastic surgery	2
Neurosurgery	9
GI Endoscopy	31
Urology	54
Orthopedics	60
General surgery	218

During four events, a ≥25% reduction in CI was found 1 min or more before other clinically important changes in HR or SBP (Table 3). Three patients had evidence of decreased SI during extreme tachycardia (Table 4; Figure 1); in the two teenagers, significant concurrent increases in SBP occurred, and in the infant, there was no change in SBP. Figure 2 illustrates the effects of increased intraabdominal pressure on cardiac function during a laparoscopic procedure. Table S1 presents detailed information for 18 events in 14 children where the change in CI and other cardiac parameters were reflective of concurrent changes in vital signs. Table S2 presents eight examples of events that may have been artifacts because the data did not fit other clinical parameters.

Discussion

We performed this observational study with the ICON® monitor to determine whether electrical cardiometry could provide a useful adjunct to other operating room monitors by assessing in real-time cardiac parameters such as CO, CI, and SI. There was no intent to determine sensitivity or specificity. Our goal was to clarify whether the device tracked evolving cardiovascular events and whether the observations fit the clinical picture, to track interventions to correct adverse hemodynamic events and to ascertain whether there were events that might have been diagnosed before they became evident on standard monitors. Although not perfect, for the most part, the device tracked events as they evolved even in infants as small as 1 kg. One drug administration error was recorded, and a number of interesting events which were new to us were observed. The results suggest that there is much we still have to learn regarding the stress of anesthesia on patients particularly during induction. Although one could question the value of a 1-min warning regarding an evolving adverse hemodynamic event, the clinical value would be assessed by the severity of such an event, for example, anaphylaxis or adverse responses to surgical manipulations or anesthetic medications. Our study was not powered to detect rare events although one drug error was recorded.

Electrical Cardiometry™ (ICON, Cardiotronic/Osypka Medical, Inc., La Jolla CA, USA) is a noninvasive method of continuous CO monitoring that takes advantage of changes of electrical impedance with the change in orientation of the red blood cells in the aorta (random chaotic orientation during diastole [high-impedance state]) to an aligned or parallel orientation during systole (low-impedance state), causing a change in electrical conductivity (3,4). This device estimates CO, CI, stroke volume (SV), SI, and a variety of other cardiac parameters using a complex mathematical algorithm (electrical velocimetry relates the maximum rate of change of impedance to peak aortic blood acceleration during the cardiac cycle) with the simple application of four EKG electrodes (4). The accuracy of this monitor has been validated and compared with other measures of CO such as the Fick equation (5), thermodilution (3,6), and echocardiography (7) in diverse pediatric populations including patients with congenital heart disease (8) and critical illness (9–12), neonates (7), and obese adolescents (13). One study of patients who had recovered from critical illness demonstrated a bias toward underestimation of CI (12) and another found it to be useful in patients who had undergone cardiac surgery (8). A study of 115 paired measurements with an echocardiogram in neonates found similar estimates of

Table 3 Examples of cases where the device may have provided an advanced warning before significant changes in other hemodynamic responses and the response to interventions

Time	Event	Intervention	HR	SBP	CI	SI
1) Adverse hemodynamic response to increased intraabdominal pressure						
9 : 46			99		3.600	35.85
9 : 47			98		3.655	36.47
9 : 48	Increased intraabdominal pressure with insufflation		95	108	3.283	33.58
9 : 49			95		3.180	33.16
9 : 50			89		2.858	32.07
9 : 51			73	90	1.945	27.05
9 : 52			62		1.606	25.42
9 : 53			65		1.493	23.52
9 : 54		Ephedrine 10 mg	68	72	M*	M*
9 : 55		Reduced intraabdominal pressure	65		1.585	23.47
9 : 56			73	84	1.728	23.95
9 : 57			75		M*	M*
9 : 58			77		2.025	26.69
9 : 59			79		2.180	27.58
10 : 00			80	99	2.247	28.08

This was a 17-year-old female undergoing laparoscopic cholecystectomy. Three minutes after insufflation to 14 mmHg, the heart rate slowed modestly to 73 $b{\cdot}min^{-1}$ and systolic blood pressures (SBP) decreased to 90 mmHg. At this point, there was a ~47% reduction in cardiac index (CI) from preinsufflation values. The heart rate (HR) continued to decline and 2 min before ephedrine was administered the CI had ↓ ~56%. Ephedrine was then administered at a point where the CI had further ↓ ~59% ~ 1 min prior to the ephedrine. The monitor detected a significant decrease in CI at a point where there was only a modest decrease in SBP, but ephedrine was not administered until the HR had further decreased to 65–68 $b{\cdot}min^{-1}$ and SBP decreased to 72 mmHg. Thus, the monitor tracked the effects of increased intraabdominal pressure and could have provided an earlier indication (perhaps as long as 3 min) that ephedrine and reduction in intraabdominal pressure might be indicated to restore CI and SBP. Even after administration of ephedrine, the SBP was restored, but the CI remained somewhat diminished compared with preinsufflation values possibly due to the intraabdominal pressure needed for the procedure (Figure 2)

Time	Event	Intervention	HR	SBP	CI	SI
2) Drug error						
15 : 18			143		1.905	13.37
15 : 19			145	56	1.848	13.06
15 : 20			141		1.870	13.20
15 : 21	Caudal injection		144		1.993	13.84
15 : 22			146	60	2.560	17.58
15 : 23			145		2.482	17.14
15 : 24			146		2.380	16.42
15 : 25			149	65	M*	M*
15 : 26			151		3.440	23.06
15 : 27			148		3.523	23.67
15 : 28			151	48	3.552	23.55
15 : 29			152		3.510	22.96
15 : 31			152	54	3.537	23.24
15 : 34			155	61	3.723	24.06
15 : 37			165	63	4.197	25.01
15 : 40			175	81	4.447	25.61
15 : 43			159	82	4.227	26.49

This was a 2-month-old 4-kg female undergoing bilateral inguinal hernia repair. 1 $ml{\cdot}kg^{-1}$ of 1 : 10 000 epinephrine was administered rather than 1 $ml{\cdot}kg^{-1}$ of 0.125% bupivacaine with epinephrine 1 : 200 000. CI ↑~37% within 1 min of administration and ↑CI ~87% 4 min after injection with minimal early changes in other vital signs. Similar changes in other cardiac parameters were noted. This case will be reported in greater detail elsewhere. The error was recognized ~ 5 min later, but in retrospect, the monitor indicated a change several minutes before the error was realized.

Table 3 Continued

Time	Event	Intervention	HR	SBP	CI	SI
3) Adverse response to turning prone						
11 : 36	Before induction		85	115	4.270	46.54
11 : 37	Propofol		93		3.803	39.31
11 : 38	Fentanyl		118	104	3.350	
11 : 41	Intubation		58		2.760	32.24
11 : 42			65	85	2.618	36.92
11 : 45	Turned prone		60	82	M*	M*
11 : 46			63		M*	M*
11 : 47			61		1.810	30.52
11 : 48			57	74	1.902	32.60
11 : 49			56		1.720	30.67
11 : 50			56		1.627	29.12
11 : 51			57	69	1.622	28.63
11 : 52			55		1.674	28.85
11 : 53			52		1.660	29.31
11 : 54			52	61	1.434	27.17
11 : 55		Ephedrine 10 mg	51		1.17	22.70
11 : 56		Ephedrine 5 mg	52		1.115	21.57
11 : 57			53	51	1.118	21.42
11 : 58		Atropine 0.4 mg	53		1.307	24.73
11 : 59			99		1.970	28.28
12 : 00			87	86	2.388	26.41

This was a 17-year-old 65-kg male undergoing pilonidal cyst resection in the prone position. Following induction and intubation, his heart rate slowed to an expected value for his age with a modest decrease in SBP. After turning prone, there was a further minor decrease in heart rate and his CI↓ ~31%. One minute later, his SBP was noted to be 74 mmHg. Over the following 6 min, the HR was relatively stable in the low 50s, but SBP decreased further to 61 mmHg and CI was now ↓~45%. Over the next 2 min, the CI further decreased ~56%. Three doses of ephedrine were administered, but the next SPB 1 min later was 51 mmHg with CI still ↓ ~57% of preturning baseline. At this point, atropine was administered, and 2 min later, the HR increased to 87, SBP to 86 and CI↑ to ~91% of baseline. In this case, the monitor tracked a more severe reduction in CI than manifest by SBP and it tracked the lack of response to multiple doses of ephedrine, but a positive response to the combined effects of ephedrine and atropine.

Time	Event	Intervention	HR	SBP	CI	SI
4) Adverse response during and shortly following anesthetic induction						
13 : 21			80		4.228	54.20
13 : 22	Fentanyl 100 μg		84		4.242	52.08
13 : 23	Propofol 100 mg		84		4.400	51.55
13 : 24			73	106	4.102	49.89
13 : 25	Propofol 50		67	81	3.187	47.35
13 : 26	Intubation		62		3.097	45.43
13 : 27			66	100	3.202	44.03
13 : 28			66		2.888	42.90
13 : 29			66		2.903	40.75
13 : 30			59		1.980	33.10
13 : 31			58	74	1.907	32.34
13 : 32			56		1.858	32.36
13 : 33			58	71	1.877	32.40
13 : 34			54		1.828	32.95
13 : 35			51		1.773	33.72
13 : 36		Atropine	51	69	1.667	33.15
13 : 37			62		2.128	33.17
13 : 38			88		3.005	34.10
13 : 39			92	92	3.263	35.59

This was a 16-year-old 50-kg female undergoing Port-A-Cath insertion. Approximately 4 min after intubation, her heart rate slowed to the upper 50s and her SBP was reduced to 74 mmHg. At this point, her CI↓~40%. Three minutes later, her SBP decreased slightly to 71 mmHg and the CI had ↓~41%. Three minutes later, the HR ↓ to 51 b·min^{-1} with SBP 69 mmHg and her CI↓~48%. At this point, she was administered atropine which rapidly restored her HR and CI. The monitor tracked the developing event and indicated a greater decrease in CI than was evident from other clinical parameters.

*Missing data usually due to patient movement, loss of EKG adherence or electrocautery.

Table 4 Apparent adverse affects of tachycardia on cardiac index and stroke index during induction or emergence

Time	Event	Intervention	HR	SBP	CI	SI
1) Extreme tachycardia during sevoflurane induction in a 11 year old						
16 : 43			78		3.598	39.04
16 : 44	Start sevoflurane induction 6%		97		3.807	38.21
16 : 46			180	122	3.073	15.88
16 : 47			189		3.040	16.27
16 : 48	Sevoflurane 5%		165		3.430	24.06
16 : 49	Sevoflurane 4%	Fentanyl 30 μg then intubation	140	140	5.072	35.86
16 : 50			123		4.598	38.24
16 : 51	Sevoflurane 2%		112		4.957	43.56
16 : 52			107	102	4.512	42.92
16 : 55			89	94	3.673	40.57
16 : 58			121	93	4.350	35.70
17 : 01			111	91	4.318	38.68
This was a 11-year-old 31-kg male undergoing mask induction for a laparoscopic cholecystectomy. The change in cardiac index (CI) coincided with changes in other vital signs, but it is of interest that there was no painful stimulus occurring and the child had undergone what appeared to be a smooth induction. It is also of interest that his SI decreased ~58% when the heart rate (HR) was >165 b·min^{-1}. It appears that the rapid heart rate reduced cardiac filling time and therefore reduced SI. He also developed hypertension which would also have increased afterload and also could have decreased SI. All parameters rapidly normalized over the next several minutes.						
2) Extreme tachycardia during emergence in a 4-month-old infant						
16 : 12	Sevoflurane 1.6%	End surgery apply dressings	161	62	3.610	23.83
16 : 13			176		3.444	21.34
16 : 14			161		3.756	22.12
16 : 15			174	63	3.645	22.72
16 : 16			173		3.860	22.54
16 : 17			167		3.900	22.71
16 : 18	Sevoflurane 1.6%		153		3.800	23.39
16 : 19			147	49	3.430	22.63
16 : 20			145		3.483	23.80
16 : 21	Sevoflurane 1.6%		144		3.270	22.61
16 : 22	Sevofluraneoff		146	50	3.325	22.92
16 : 23			150		3.453	23.35
16 : 24			150		3.642	24.25
16 : 25			186	67	3.490	22.77
16 : 26		Extubation	194		3.422	17.74
16 : 27			184		3.297	17.09
16 : 28			192		3.160	15.61
16 : 29			176	116	M*	M*
16 : 30			192	110	M*	M*
This was a 4-month-old 6-kg male for ventriculoperitoneal shunt revision. During emergence, his HR increased from ~150 to 194 b·min^{-1}. His systolic blood pressures (SBP) and CI were maintained, but his SI was reduced ~36% when his HR was >150 b·min^{-1}. It appears that the apparent decrease in SI was secondary to reduced cardiac filling time.						
3) Extreme tachycardia during sevoflurane induction in a 10 year old						
8 : 00	Baseline		83		3.725	45.36
8 : 01			77	117	M*	M*
8 : 02			79		3.350	42.42
8 : 03	Sevoflurane 6%		105	99	3.390	39.88
8 : 05			162	160	5.023	31.56
8 : 07			117	160	5.620	47.11

Table 4 Continued

Time	Event	Intervention	HR	SBP	CI	SI
8 : 09	Sevoflurane 3.5%		101	118	4.935	48.43
8 : 11			92	115	3.728	39.49
8 : 12	Sevoflurane 2%		84		3.492	40.53
8 : 13			84	112	3.765	42.69
8 : 15			92	103	3.755	41.03

This was a 10-year-old 51-kg male for Port-A-Cath removal. He was calm at baseline, but did not want his port accessed and preferred an inhalation induction. During induction, his HR ↑ 77 to 162 b·min^{-1} and his SBP ↑ 117 to 160 mmHg. During this phase, his CI ↑ ~58%. These changes in CI were consistent with the observed changes in other vital signs, but the SI was noted to decrease during the tachycardia likely due to decreased cardiac filling time.

*Missing data usually due to patient movement, loss of EKG adherence or electrocautery.

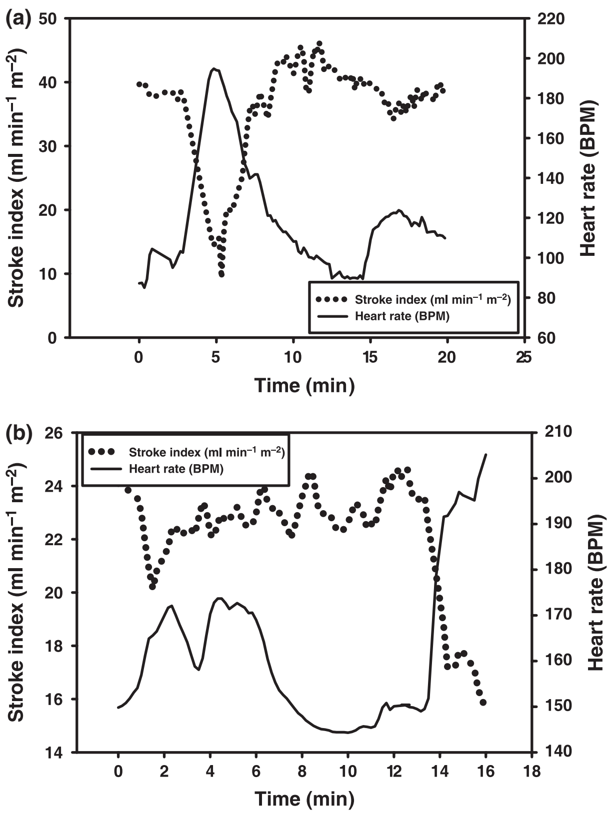

Figure 1 These figures illustrate apparent decreased SV and SI in response to extreme increases in heart rate (HR) resulting in decreased ventricular filling time. (a) A 11-year-old 31-kg male developed tachycardia and hypertension during mask induction. Cardiac index (CI) ↑ from 3.5 to 5.0 l·min^{-1}·m^{-2} and HR ↑ from 122 to 180 b·min^{-1}; systolic blood pressures (SBP) ↑ 122 to 140 mmHg. His SI and SV decreased ~58% when the HR was >165 b·min^{-1}. It appears that the rapid heart rate reduced filling time and therefore reduced SI and SV (Time plotted from 16 : 43 to 17 : 01). (b) This is a 4-month-old 6-kg male who underwent a ventriculoperitoneal shunt revision. During emergence, the HR increased from ~150 to 194 b·min^{-1}. Both SI and SV had started to increase during emergence, but rapidly declined when the HR was greater than 170 b·min^{-1}. Despite this high HR and the decrease in SI and SV, the systolic blood pressure was well maintained (Time plotted from 16 : 12 to 16:28).

left ventricular output with the ICON® (534 ± 105 ml·min^{-1}) and an ECHO estimation (538 ± 105 ml·min^{-1}) with precision estimated at ~30% with both devices (7). No studies have examined this device in a large series of anesthetized patients.

Anxiety, surgical- and anesthesia-induced stresses, reflexes, state of hydration, blood loss, and many other factors influence cardiovascular responses during anesthesia. Although anesthesiologists are aware of

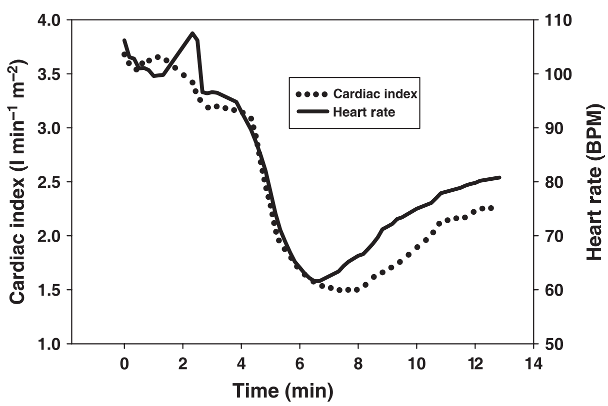

Figure 2 This was a 17-year-old female undergoing laparoscopic cholecystectomy. Insufflation took place at minute 2. Three minutes after insufflation to 14 mmHg, the heart rate slowed modestly to 73 b·min^{-1} and systolic blood pressures (SBP) decreased to 90 mmHg. At this point, there was an ~47% reduction in cardiac index (CI) from preinsufflation values. The heart rate (HR) continued to decline, and 2 min before ephedrine was administered, the CI had ↓ ~56%. Ephedrine was then administered (minute 7) at a point where the CI had further ↓ ~59%. The monitor detected a significant decrease in CI at a point where there was only a modest decrease in SBP, but ephedrine was not administered until the HR had further decreased to 65–68 b·min^{-1} and SBP decreased to 72 mmHg. Thus, the monitor tracked the effects of increased intraabdominal pressure on venous return and could have provided an earlier indication (perhaps as long as 3 min) that ephedrine might be indicated to restore CI and SBP. Even after administration of ephedrine, the SBP was restored, but the CI remained somewhat diminished compared with preinsufflation values (Time plotted from 09 : 46 to 10 : 00).

these factors, we are unable to appreciate heart beat to heart beat changes in cardiac function. We instead rely upon surrogate markers such as softening of heart tones, changing HR, and increasing or decreasing SBP. Our large case series has shown that continuous cardiovascular parameter assessment is feasible during anesthesia for patients of all sizes and that in some cases, such monitoring may provide useful information regarding evolving adverse hemodynamic changes and the response to interventions. Patients who experienced bradycardia and/or hypotension following induction and prior to airway instrumentation, or a vagal reflex had decreased cardiac parameters followed by the expected increases after airway instrumentation or surgical incision. Most commonly, the ICON® tracked hemodynamic events that were also tracked by standard monitors such as increased or decreased HR and SBP in response to surgical stimuli. Most children demonstrated a change in estimated cardiac parameters consistent with changes in HR (the most common observation regardless of age). Teenagers with a slow HR responded with improved cardiovascular parameters following administration of vagolytic medications. In several cases (Table 3), the use of the ICON® information may have allowed earlier recognition of an evolving event, whereas in most cases (Tables S1 and S2), the observed changes reflected other concurrent monitored parameters such as HR and SBP.

We also observed hemodynamic responses that we had previously no means of quantitating in anxious teenagers (sweaty palms, slightly increased blood pressure and HR prior to induction) who sustained a 50–80% reduction in CI within several minutes following induction. These changes in CI were not generally appreciated by standard clinical measures. Three patients developed extreme tachycardia during induction or emergence from anesthesia that demonstrated maintenance of CO, but decreased SV and SI (Figure 1; Table 4).

Several patients demonstrated either sudden increases or decreases in estimated cardiovascular parameters without concordant changes in HR or SBP; others demonstrated marked reduction in CI upon turning prone without obvious changes in other monitored parameters. Further studies are needed to determine whether these were artifacts caused by changes in cardiac and great vessel position within the thorax as they relate to the electrodes or whether these are true physiologic changes.

Other devices can assess continuous CO, but most are invasive, for example, an arterial line to assess the wave contour (14–17), pulse dye densitometry, continuous measure of central venous oxygen Fick estimation of CO (18), Fick estimate of CO using expired carbon dioxide (necessitating tracheal intubation) (19–21). Another device using similar technology in comparison with MRI and Fick determinations of CO found poor accuracy with the Physioflow (Neumedx, Philadelphia, PA, USA) (22,23). A study examining endotracheally sourced impedance cardiography (ECOM; ConMed Corp, Irvine, CA, USA) found wide limits of agreement in adults with thermodilution and TEE measurements (24). A meta analysis of bias and precision statistics regarding comparisons of continuous CO measurement techniques suggested that the limits of agreement should be ±30% and that trend analysis requires a new method of data analysis (25,26). It would be very difficult to apply this rigorous analysis to the operating room where so many variables are constantly changing. A recent study designed to develop reference values using the ICON® compared their findings with published normal values for the Fick method, thermodilution, echocardiography, and cardiac MRI found all of these methods to report higher values (0–19.6%) than those obtained by the ICON® in patients 2 weeks to 21 years of age. Thus the ICON® seems to slightly underestimate CO.

The main advantage of the ICON® is that it is noninvasive and easy to set up. However, drawbacks include the inability to place the electrodes prior to induction in toddlers, inability to use when surgery involves the left chest or neck, electrocautery-induced loss of data, occasional poor adhesion of the EKG electrodes resulting in loss of signal, rare development of minor hematoma on sensitive neck vessels upon removal of the EKG electrode, and possible artifacts related to changes in patient position and patient movement.

The 'holy grail' of monitoring is a device that provides a warning of an impending or developing adverse event before it becomes clinically important (1,2,27). Capnography and pulse oximetry provide a timely warning of adverse airway and ventilation-related events and malignant hyperthermia (28–31). Pulse oximetry provides immediate information regarding evolving desaturation prior to recognition by the anesthesia team and facilitates intervention before serious hypoxemia ensues. The Cardiotronic ICON® may represent the next generation of monitors that provides real-time information regarding evolving adverse cardiovascular events and immediate feedback that the interventions were successful earlier than by remeasuring NIBP even in infants as small as 1 kg.

Our assessment is that this monitor provides a new dimension to our ability to track physiologic responses to anesthesia and surgical-related events. However, the anesthesia team must filter this additional information with the global picture of all other physiologic parameters. This study revealed real-time information regarding wide fluctuations in cardiovascular parameters related to preoperative anxiety, stress, or pharmacodynamic responses to inhalation induction with sevoflurane, and transient although important decreases in SI related to rapid increases in HR. This is information that previously would only be available with the help of an ECHO or TEE which are impractical for routine cases.

If other investigators confirm our observations, such real-time data may provide an improved perspective regarding the conduct of anesthesia. Should we be more willing to provide a premedication to anxious teenagers who tell us they are not nervous when it is clear from their cold hands that they are? Does sevoflurane cause a pharmacodynamic response independent of stress that induces extreme tachycardia in some patients? Should we be more generous with the use of atropine or glycopyrrolate to treat even modest bradycardia in athletic teenagers? Should we administer a vasopressor rather than a vasoconstrictor when hypotension is encountered in teenagers? Each of these questions is fodder for further investigation.

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Disclosure

Charles J. Coté is a Section Editor of Pediatric Anesthesia.

Conflict of interest

The authors declare no conflict of interest.

Supporting information

Additional Supporting Information may be found in the online version of this article:

Table S1. Examples of cases where the monitor provided simultaneous confirmation of changes manifest by other hemodynamic measures and responses to interventions.

Table S2. Interesting observations and possible artifacts.

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