Multicenter Study of Noninvasive Monitoring Systems as Alternatives to Invasive Monitoring of Acutely Ill Emergency Patients*

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Background: Recent reports showed lack of effectiveness of pulmonary artery catheterization in critically ill medical patients and relatively late-stage surgical patients with organ failure. Since invasive monitoring requires critical care environments, the early hemodynamic patterns may have been missed. Ideally, early noninvasive hemodynamic monitoring systems, if reliable, could be used as the "front end" of invasive monitoring to supply more complete descriptions of circulatory pathophysiology.

Objectives: To evaluate the accuracy and reliability of noninvasive hemodynamic monitoring consisting of a new bioimpedance method for estimating cardiac output combined with arterial BP, pulse oximetry, and transcutaneous Po_2 and Pco_2; we compared this system of noninvasive monitoring with simultaneous invasive measurements to evaluate circulatory deficiencies in acutely ill patients shortly after hospital admission where invasive monitoring was not readily available. We also preliminarily explored early differences in temporal hemodynamic patterns of survivors and nonsurvivors.

Design and setting: Prospective comparison of simultaneous invasive and noninvasive measurements of circulatory function with retrospective analysis of data in university-run county hospitals, university hospitals and affiliated teaching hospitals, and a community private hospital.

Patients: We studied 680 patients, including 139 severely injured or hemorrhaging patients in the emergency department (ED), 129 medical (nontrauma) patients on admission to the ED, 274 high-risk surgical patients intraoperatively, and 138 patients recently admitted to the ICU.

Results: A new noninvasive impedance device provided cardiac output estimations under conditions in which invasive thermodilution measurements were not usually applied. There were 2,192 simultaneous bioimpedance and thermodilution cardiac index measurements; the correlation coefficient, $r = 0.85$, $r^2 = 0.73$, $p < 0.001$. The precision and bias was -0.124 ± 0.75 $L/min/m^2$. Both invasive and noninvasive monitoring systems provide similar information and identified episodes of hypotension, low cardiac index, arterial hemoglobin desaturation, low transcutaneous O_2, high transcutaneous CO_2, and low oxygen consumption before and during initial resuscitation. The limitations of noninvasive systems were described.

Conclusions: Noninvasive monitoring systems gave continuous displays of physiologic data that provided information allowing early recognition of low flow and poor tissue perfusion that were more pronounced in the nonsurvivors. Noninvasive systems may be acceptable alternatives where invasive monitoring is not available. *(CHEST 1998; 114:1643–1652)*

Key words: arterial blood pressure; estimation of cardiac output; hemodynamic monitoring; multicomponent noninvasive circulatory monitoring; oxygen consumption; oxygen delivery; pulse oximetry; thermodilution cardiac output measurement; thoracic bioimpedance; transcutaneous oximetry

Abbreviations: CI = cardiac index; Do_2 = oxygen delivery; dZ/dt = impedance waveform; ED = emergency department; HR = heart rate; MAP = mean arterial pressure; OR = operating room; PAC = pulmonary artery catheter; SaO_2 = arterial oxygen saturation; SAP = systolic arterial pressure; $tcPco_2$ = transcutaneous carbon dioxide tension; $tcPo_2$ = transcutaneous oxygen tension; Vo_2 = oxygen consumption; Zo = baseline impedance

The effectiveness of the thermodilution pulmonary artery catheter (PAC) in critically ill patients recently has been challenged by Connors et al,[1] who showed higher mortality in the initial care of a large series of critically ill medical patients with organ failure and 50% mortality. Similar results were reported in patients with myocardial infarction,[2–6] in recent randomized trials on surgical patients with

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organ failure on ICU admission[7,8] and in a recent PAC consensus conference.[9] However, randomized trials in surgical patients performed early showed improved outcome.[10–17] These outcome differences may be due to (1) definition of the term "early," (2) differences in the nature of circulatory problems in medical and surgical patients, and (3) use of well-defined treatment plans. Improved outcome should not be expected if therapy is not changed.

Noninvasive monitoring of circulatory dysfunction is an alternative approach that allows very early application throughout the hospital, including the emergency department (ED), operating room (OR), and hospital floors. The continuous on-line graphic displays of data allow prompt recognition of circulatory abnormalities and early therapeutic intervention in acutely ill emergency patients in whom time factors are crucial.[10,17,18] A new thoracic electrical bioimpedance device for continuous noninvasive cardiac output based on recently available hardware and software innovations was developed at Drexel University by Wang et al.[19–21] When combined with pulse oximetry and transcutaneous PO_2 and PCO_2, these noninvasive monitoring systems can be used for early warning of cardiac, pulmonary, and tissue perfusion functions.[22–35]

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The present study evaluates the accuracy and reliability of noninvasive methods compared with simultaneous invasive monitoring in acute emergency conditions. Acute circulatory patterns were also explored in survivors and nonsurvivors.

Materials and Methods

Clinical Series

We studied 680 selected high-risk patients with invasive and noninvasive circulatory monitoring shortly after their hospital admission; patients with significant risk of mortality or morbidity were selected. There were 268 studied in the ED, including 139 with multiple trauma and 129 with medical (nontrauma) emergencies; 274 patients were studied in the OR before, during, and after high-risk surgery; and 138 were studied shortly after admission to the ICU; each clinical subset was separately evaluated. There were 156 (23%) nonsurvivors and 524 (77%) survivors; 211 (31%) were female, 469 (69%) were male; the average age was 57 ± 15 years.

Of the 139 trauma patients, the mean Injury Severity Score score was 19 ± 4; the mean Revised Trauma Score was 6.9 ± 0.4. Trauma patients requiring immediate emergency surgery were transferred to the OR without delay, but if time allowed, they were monitored; no patient was delayed to obtain monitored data. Simultaneous bioimpedance and thermodilution measurements were obtained in the ED, intraoperatively, and in the immediate postoperative period in the ICU. The protocol was approved by Institution Review Boards of each institution; patients or their relatives signed informed consent for invasive monitoring.

Invasive Hemodynamic and Oxygen Transport Monitoring

Cardiac output was obtained by thermodilution PAC and recorded at frequent, but appropriate, intervals as determined by clinical need.[10–15] Intravascular pressures, heart rate (HR), and arterial and mixed venous blood gas samples were obtained anaerobically at the time of the cardiac output measurements and promptly analyzed.[9–12]

Noninvasive Cardiac Output Monitoring

A new thoracic bioelectric impedance device (Renaissance Technologies; Newtown PA) was applied shortly before or after a PAC had been inserted. Three ECG leads were placed across the precordium and left shoulder and four pairs of noninvasive disposable prewired hydrogen electrodes were positioned on the skin overlying the top and bottom of the lungs.[19–21] An electrical field was provided by a 100-kHz, 4-mA alternating current passed through two outer pairs of injecting electrodes, shaped like a strip; one pair was placed one on each side of the neck and the other pair at the base of the chest. One inner pair of sensing electrodes, shaped like a dot, was placed one on each side at the lateral aspect of the junction of the neck and chest; the second pair was placed one on each side of the lower chest at the level of the ziphisternal (ziphoid and sternum) junction. Each one of the electrode pairs was placed laterally 180° from the other. The inner sensing "dot" electrodes were placed at least 5 cm inside the outer injecting "strip" electrodes. The distance between the two pairs of inner sensing electrodes must be carefully measured with calipers to within ± 1 cm. The inner electrodes measure the

pulsatile change in impedance (resistance) throughout the cardiac cycle; as each cardiac contraction thrusts the stroke volume into the aorta, the increased blood and blood flow reduce the electrical impedance as the current preferentially travels by way of the aorta rather than through aerated alveoli. The electrical pulsatile impedance curve along with the ECG signal captured throughout the cardiac cycle were used to calculate the baseline impedance (Z_o) and the first derivative of the impedance waveform (dZ/dt).

The ECG and bioimpedance signals were filtered with an all-integer-coefficient filtering technology to decrease computations and signal processing time. This system used a fast Fourier analysis to represent the signal algebraically as integers and coefficients; this approach, in contrast to digitalization, eliminated multiple decimal places and thus reduced computational time. The digital signal processing also used time-frequency distributions to increase signal-to-noise ratios.[18]

Previous studies[22–24] demonstrated reasonable reliability in the absence of severe pulmonary edema, large pleural effusions, or marked expansion of the extracellular fluid from massive crystalloid infusions that occurred in about 8% of our patients. During the course of the present studies, we noted that when the Z_o was > 15 ohms and the height of dZ/dt was found to be > 0.3 ohms, there was better agreement, ie, r = 0.93, r^2 = 0.87, bias and precision -0.14 ± 0.54 L/min/m^2.

Pulse Oximetry

Routine pulse oximetry (Nellcor; Pleasanton, CA) was used to assess continuously arterial oxygen saturation (SaO_2). Values were observed and recorded at the time of the cardiac index (CI) measurements. Sudden changes in these values were noted and confirmed by the standard SaO_2 obtained by *in vitro* blood gas analysis.

Transcutaneous Oxygen and Carbon Dioxide Tensions

Standard transcutaneous oxygen tension ($tcPO_2$) measurements (Novametrix Medical Systems Inc; Wallingford, CT) were monitored continuously throughout the observation period. Values were noted and recorded at the exact times of the cardiac output measurements. This technology uses the same Clark polarographic oxygen electrode routinely used in standard blood gas analyses.[26–35] The oxygen tensions were determined in a representative area of the skin surface heated to 44°C to increase diffusivity of oxygen across the stratum corneum and to avoid vasoconstriction in the local area of the skin being measured.[26,28,30]

Previous studies demonstrated the capacity of $tcPO_2$ to reflect tissue oxygen tension.[26–33] $tcPO_2$ has been shown to reflect the delivery of oxygen to the local area of skin; it also parallels the mixed venous oxygen tension except under late or terminal conditions where peripheral shunting leads to high mixed venous hemoglobin saturation values.[26]

Transcutaneous CO_2 tension values ($tcPCO_2$) (Novametrix Medical Systems Inc), of the skin surface were monitored continuously by the standard Stowe-Severinghaus electrode[34,35] along with the transcutaneous O_2 sensor.

Experimental Design

Invasive and noninvasive measurements were begun shortly after ED admission in critically ill patients. Repeated measurements were made during periods when the patient was in a relatively steady state and there was no overt evidence of motion or anxiety. Serial sets of monitored data consisted of the following: (1) cardiac output measurements simultaneously measured by thermodilution and bioimpedance; comparisons were made of the average bioimpedance value taken from 10 beats at the exact time of each thermodilution curve; (2) SaO_2 values measured by pulse oximetry; (3) $tcPO_2$ and $tcPCO_2$; (4) when clinically and logistically possible, oxygen consumption (VO_2); (5) mean arterial blood pressure (MAP) by a noninvasive system (DynaMap; Critikon; Tampa FL); and (6) HR taken from the ECG.

We found that noninvasive monitoring could be applied in 2 to 5 min without interfering with the emergency patient's management. The invasive and noninvasive monitoring were undertaken when there was an appropriate interval before surgery; in some occasions, there was only time for the noninvasive systems and invasive monitoring was placed before or just after surgery. Although many patients had relatively normal values for prolonged periods, the objective of this study was to document episodes of hemodynamic deficiencies.

Finally the data of survivors and nonsurvivors were separately analyzed and evaluated. Table 1 lists indications for noninvasive monitoring used in this study.

Statistics

Data of variables collected sequentially over the time of initial evaluation and resuscitation were compared utilizing an analysis of variance and the Newman-Keuls test. Data sets obtained under comparable temporal conditions were evaluated using the two-tailed Student's *t* test. Differences were considered significant at probability values < 0.05.

RESULTS

Comparison of Bioimpedance and Thermodilution Cardiac Outputs

We compared 2,192 simultaneous measurements of cardiac output by thermodilution and the new

Table 1—*Indications Used for Monitoring*

1. Trauma team activation: SAP < 90 mm Hg; HR > 120 beats/min; respiratory rate < 10 or > 30 breaths/min; altered mental state or unresponsive to pain
2. Unstable appearance, but not meeting the above criteria
3. Blunt or penetrating truncal trauma with: overt blood loss > 500 mL; pelvic and femur fractures; multiple long bone or open fractures with blood loss; suspicion of future blood loss; potential for surgical operation
4. Patients requiring high-risk surgery with unstable vital signs, pallor, weak thready pulse, or suspicion of present or future blood loss
5. Head injury: Glasgow come score < 9; associated injuries with suspected or actual blood loss
6. Other trauma patients: burns, scalds, electrical injuries
7. Acute life-threatening nontrauma surgical patients with dehydration and fluid losses from diarrhea, GI fistulas, and vomiting
8. Acutely ill medical (nontrauma) patients with hypotension, oliguria, blood loss, anemia, tachycardia, fever, dehydration, etc, from acute myocardial infarction, sepsis or septic shock, acute exacerbation of chronic congestive failure, diabetic ketoacidosis, drug overdose with cardiac or respiratory depression, acute stroke, coma or neurologic failure, upper or lower GI bleeding, pneumonia, postcardiac arrest, cardiac or respiratory depression from drug overdose, and acute asthma with respiratory distress
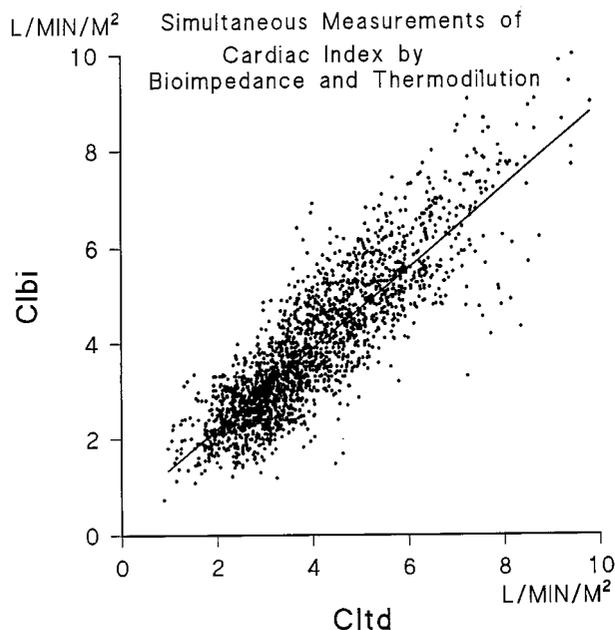9. Acutely ill ICU admissions unable to get an ICU bed

FIGURE 1. Regression analysis of bioimpedance cardiac index values (CIbi) plotted against their simultaneously measured thermodilution cardiac index (CItd) values. The regression equation was $y = 0.85x + 0.50$; $r = 0.84$; $r^2 = 0.71$; $p < 0.01$.

FIGURE 2. The differences in the two cardiac index values (CIbi-CItd) plotted against their average value ([CIbi + CItd]/2). The bias and precision analysis was $-0.124 + 0.85$ L/min/m^2.

bioimpedance methods; the regression formula was $y = 0.85x + 0.50$. The regression coefficient, r, was 0.85; r^2 was 0.73; and $p < 0.001$ (Fig 1). The bias and precision was -0.124 ± 0.75 L/min/m^2 (Fig 2); the confidence interval was -1.56 to $+1.32$/min/m^2. The average difference between the bioimpedance and thermodilution estimations was $16 \pm 14\%$ of their average value. These data were similar to previously reported studies comparing thermodilution and bio-impedance cardiac output values under more stable ICU conditions.[22-24] Data of patients observed in the ED, OR, and ICU were analyzed separately (Table 2). Compared with ICU patients, there was slightly better agreement in the OR patients and slightly less agreement in the ED patients, but these differences were not significant.

Comparison of In Vitro Hemoglobin Oxygen Saturation With Pulse Oximetry Values

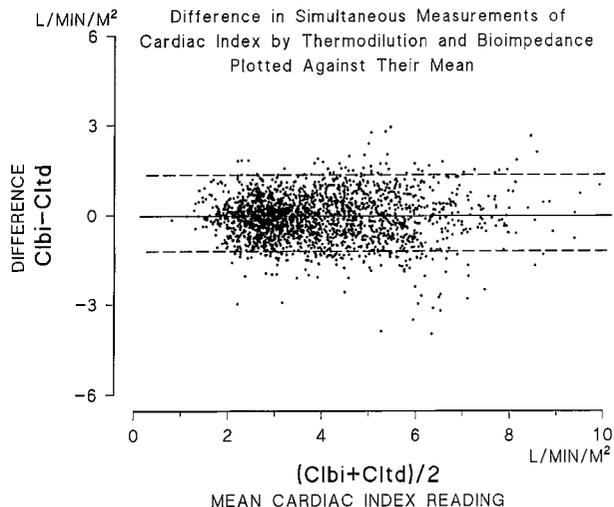Simultaneous measurements of arterial saturation by the standard *in vitro* blood gas analysis and pulse oximetry (SaO_2) were performed in 712 instances under conditions of this study. Figure 3, *top,* shows the scattergram of saturation measured by pulse oximetry plotted against measurements by blood gas analysis; the regression equation was $y = 0.83x + 16.6$; $r = 0.84$, $r^2 = 0.71$. Figure 3, bottom, shows the difference between each pair of measurements plotted against their average value; the bias and precision was $0.12 \pm 3.23\%$, which is consistent with prior studies.

Comparison of tcPo$_2$ and Vo$_2$

Vo$_2$ values were compared with simultaneous tcPo$_2$ at the initial baseline period, the nadir, and the postresuscitation period in 32 patients (Fig 4). Although the changes were significant ($p < 0.05$), they were frequently not synchronous; that is, the tcPo$_2$ nadir occurred first in 54%, they occurred together in 25%, and the Vo$_2$ occurred first in 15%. The tcPo$_2$ nadir occurred an average of 12.1 ± 7.7 (SD) min ($p < 0.05$) before the Vo$_2$ nadir.

Limitations of Noninvasive Methods

In all monitoring and imaging techniques, motion, anxiety, restlessness, shivering, hyperventilation, and

Table 2—*Correlations of Simultaneous Thermodilution and Bioimpedance Measurements in the ED, OR, and ICU*

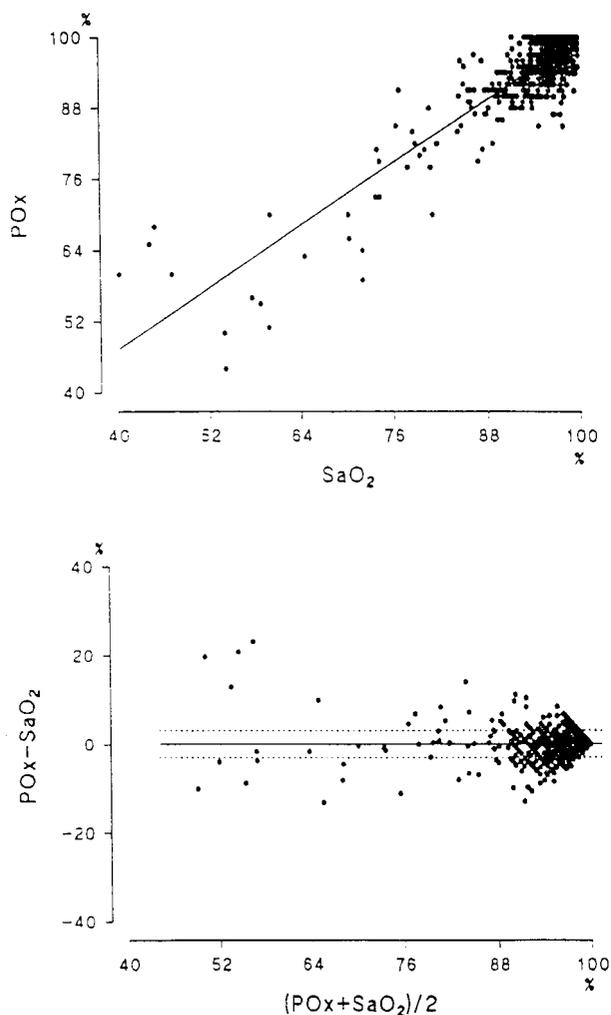| Site	Data Pairs	r	r^2	Formula	Bias and Precision, L/min/m^2
ED	990	0.83	0.68	Y = 0.81X + 0.63	-0.058 ± 0.78
OR	407	0.88	0.77	Y = 0.84X + 0.48	-0.027 ± 0.46
ICU	795	0.85	0.73	Y = 0.92X + 0.23	-0.17 ± 0.68
Total	2,192	0.85	0.73	Y = 0.85X + 0.50	-0.124 ± 0.75
Recent series*:	213	0.93	0.87	Y = 0.82X + 0.67	-0.14 ± 0.54

*Zo > 15, dZ/dt > 0.3 ohms.

FIGURE 3. *Top:* regression analysis of arterial hemoglobin oxygen saturation measured by pulse oximeter plotted against simultaneous values measured by *in vitro* blood gas analysis; $y = 0.83x + 16.6\%$, $r = 0.84$; $r^2 = 0.71$. Note the greater spread of values below 75%. *Bottom:* differences in arterial hemoglobin saturation measured by pulse oximeter and by *in vitro* blood gas analysis plotted against the average of these two measurements. The bias and precision analysis was $0.12 + 3.23\%$.

agitation may interfere with the measurements as well as increase some physiologic responses. When there is extensive pulmonary edema, pleural effusion, hemothorax, extensive chest wall edema from massive crystalloid infusions, or chest tubes parallel to the aorta, electrical signals travel through these electrolyte solutions and reduce the impedance signal to noise ratio. These conditions are identified by reductions in the control $Z_0 < 15$ ohms and in the height of the dZ/dt < 0.3 ohms; with values lower than these, impedance estimates were not considered reliable for clinical decisions, but were observed to track and trend thermodilution values. This is a major limitation of impedance methodology.

Using $Z_0 > 15$ ohms and dZ/dt values > 0.3 ohms

as criteria in 214 simultaneous pairs of thermodilution and impedance cardiac output measurements during the past 6 months, we found the r was 0.93, $r^2 = 0.87$; bias and precision were -0.14 ± 0.54 L/min/m^2, and the average difference was $9.8\% \pm 6.7\%$, which was similar to the difference between two consecutive thermodilution measurements ($9.6 \pm 7.7\%$).

Accuracy of pulse oximetry progressively decreased below 92% and became unreliable at values $< 85\%$. However, it is a standard of care for early warning of hypoxemia, since early recognition of respiratory problems is more important than SaO_2 accuracy at very low values.

$tcPO_2$ was used for several decades to track PaO_2 in neonates; however, it uses the Clark polarographic O_2 sensor to measure O_2 tension in a local segment of heated skin.[27] This is not necessarily the same in other peripheral tissues; because the skin is more sensitive to peripheral vasoconstriction from the adrenomedullary stress response, it provides an earlier warning than mixed venous hemoglobin saturation and VO_2.[25,26] Limitations of $tcPO_2$ are the electrode placement must be changed every 4 to 6 h to avoid first-degree skin burns, the thermal environment should be reasonably constant, and the membranes must be calibrated prior to each use and each change in skin site. The membrane must be changed when readings become unstable.

Abnormal Circulatory Values in Trauma Patients

Table 3 summarizes the observed variables, their normal values, criteria for each variable indicating circulatory deficiency, the number and percent of patients with abnormal values, the mean of each variable at its minimum (nadir) or maximum when abnormal, and preferred values defined by the survivors' patterns. Of 139 trauma patients, 52% had reduced CI that averaged 1.78 ± 0.11 (SEM) L/min/m^2 at its nadir; 55% had reduced $tcPO_2$ that averaged 19.2 ± 2.6 mm Hg; 45% had high $tcPCO_2$ values that averaged 70.5 ± 1.8 mm Hg; 41% had hypotension averaging 57.5 ± 1.8 mm Hg; and 18% had low arterial saturations averaging $84.8 \pm 1.4\%$. Fifty percent of the patients with VO_2 measurements had low values that averaged 91.6 ± 3.8 mL/min/m^2. Most patients had two or more abnormalities.

Patterns in Medical (Nontrauma) Patients

Patients with cardiac problems, including acute myocardial infarction, hypertensive crisis, and chronic congestive heart failure with acute exacerbation, neurologic failure, drug overdose, and hemorrhage initially had low CI that then decreased further along with tissue perfusion as reflected by $tcPO_2$; with resuscita-
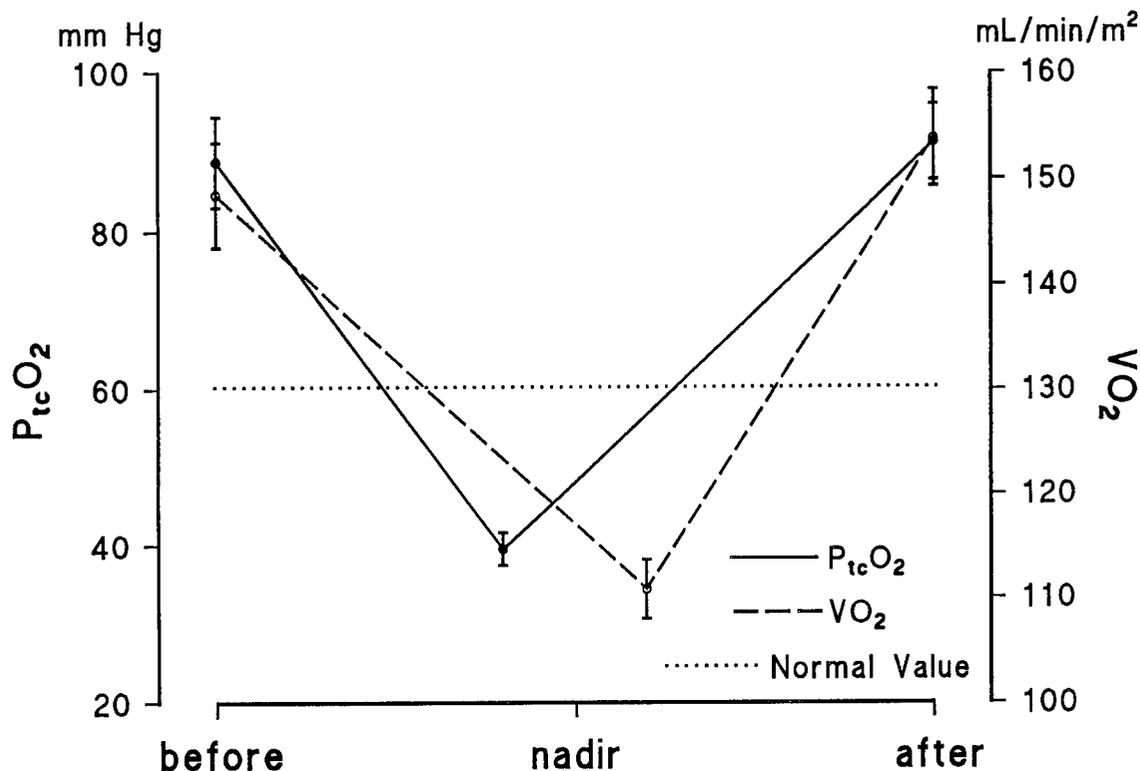
FIGURE 4. The pattern of changes in Vo_2 compared with the pattern of changes in $tcPo_2$. Mean values (dots) and SEM (vertical lines) for each variable are shown at the initial baseline period ("before"), at the nadir or lowest point, and after the initial resuscitation ("after"). The dotted horizontal line represents the mean normal value of each variable. Note the $tcPo_2$ nadir usually precedes the lowest Vo_2 value.

tion, the CI and $tcPo_2$ values of the survivors usually increased above normal values, but the responses of nonsurvivors were less pronounced. Patients with sepsis, septic shock, community-acquired pneumonia, and stress-related disorders started with higher than normal CI values, but these values deteriorated along with $tcPo_2$ as the shock syndrome progressed. With resuscitation, these values increased above their baseline control levels in survivors but not in nonsurvivors; this is consistent with previously reported values.[46]

Temporal Patterns Before and After CI Nadir

Although there were differences in the hemodynamic patterns of various etiologic groups, there were often similarities of these patterns that consisted of reduced CI and tissue perfusion. Reduced pulmonary function reflected by decreased pulse oximetry was seen in asthma, pneumonia, severe chest trauma, severe drug overdose, and in late stages of most shock syndromes. Figure 5 shows the

Table 3—*Variables, Units, Normal Values, Abnormal Values Indicating Circulatory Deficiency, Percentage of Patients with Abnormal Values, and Mean of Abnormal Values at their Nadirs*

Variables	Normal Values	Abnormal Values	Percent Abnormal	Mean ± SEM at Nadir
CI, L/min/m²	3.2 + 0.2	< 2.6	52	1.78 + 0.69
MAP, mm Hg	80–95	< 70	41	57.5 + 1.8
Sao_2, %	95–97	< 90	18	84.8 + 1.4
$tcPo_2$, mm Hg	50–80	< 45	55	19.2 + 2.6
$tcPco_2$, mm Hg	45–55	> 60	45	70.5 + 1.8
Vo_2, mL/min/m²	130 + 10	< 110	50	91.6 + 3.8

Table 4—*Incidence and Mean of Abnormal Values of Survivors and Nonsurvivors at Their Nadir or Maximum Change*

	Survivors		Nonsurvivors	
Variable	Incidence, %	Value ± SEM	Incidence, %	Value ± SEM
CI	48	1.93 ± 0.12	75	1.64 ± 0.27
MAP	43	58 ± 2	33	58 ± 4
Sao_2	16	85.2 ± 1.7	17	83 ± 0.7
$tcPo_2$	52	20.9 ± 2.8	50	9.5 ± 6
$tcPco_2$	46	69 ± 1.5	42	78 ± 7
Vo_2	63	93 ± 3.6	50	89 ± 9

common temporal pattern of all survivors' and non-survivors' values before and after their CI nadirs. The decreased CI measured by both methods was significantly greater in nonsurvivors than in survivors. There were slightly higher BPs and HRs and lower Sao_2 values in the nonsurvivors shortly before
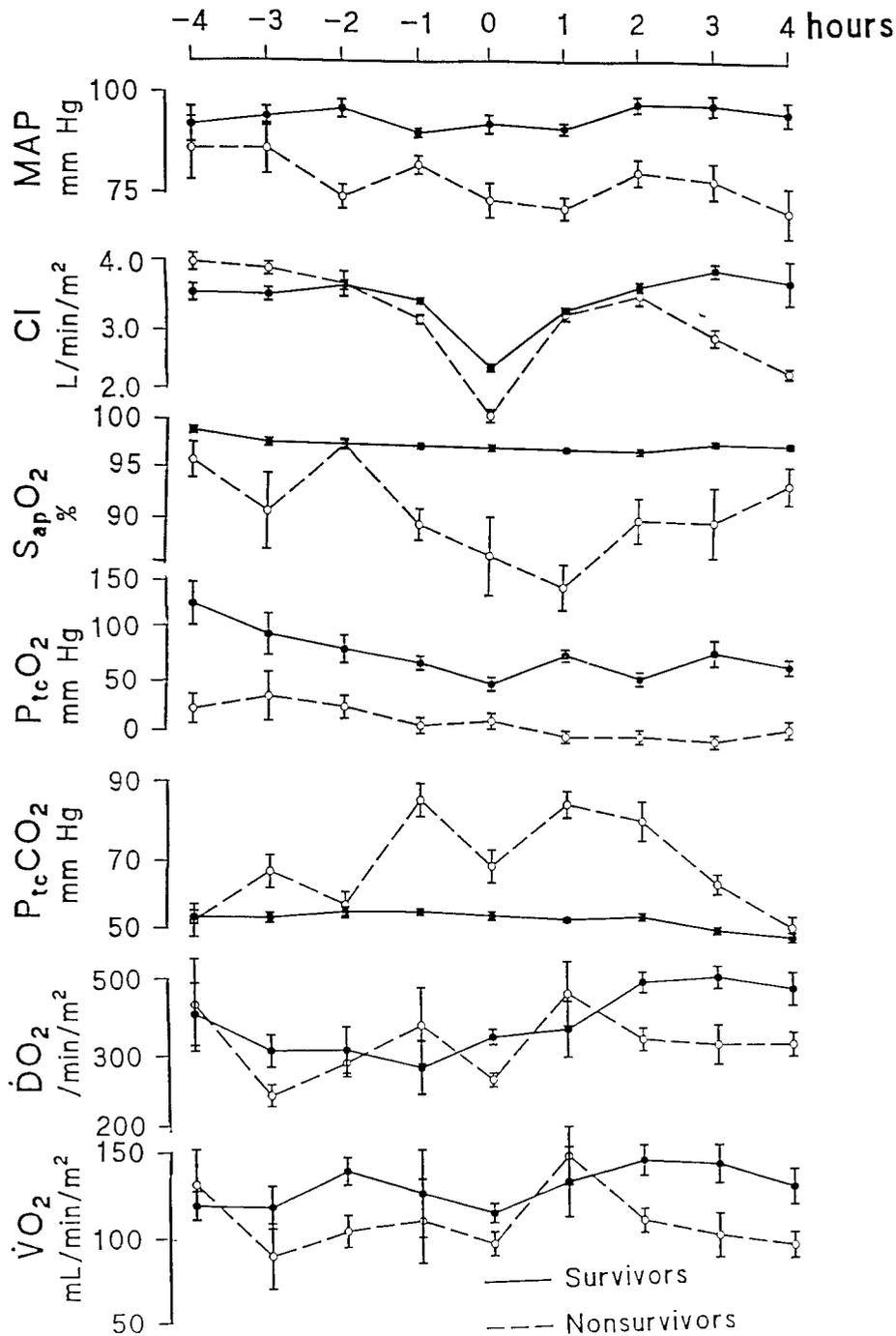

FIGURE 5. Survivors' (solid line) and nonsurvivors' (dashed line) temporal patterns for MAP, CI, pulse oximetry (Sao_2), $tcPo_2$, transcutaneous CO_2 tension ($tcPco_2$), oxygen delivery index (Do_2), and Vo_2 aligned before and after the time of the lowest (nadir) CI value. The time course is shown on the X axis measured in hours before and after the nadir, indicated by zero. Dots represent mean values, vertical bars SEM. Note the MAP, CI, Sao_2, $tcPo_2$, Do_2, and Vo_2 values of the survivors tended to be higher than those of the nonsurvivors, while $tcPco_2$ tended to be higher in nonsurvivors at comparable periods, suggesting greater circulatory function and greater responses of survivors. The transcutaneous O_2 and CO_2 changes tended to precede the CI nadir, and the Sao_2 of nonsurvivors followed the nadir.
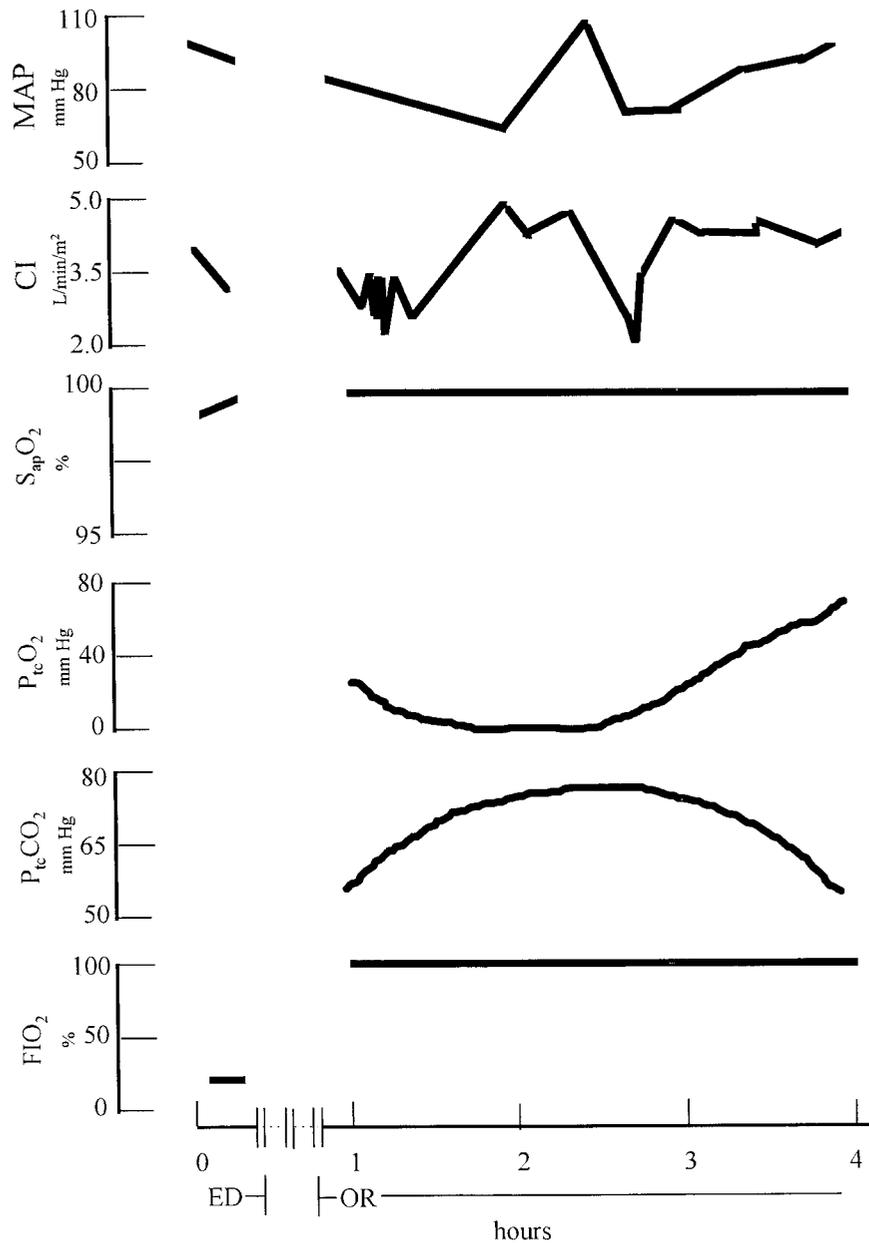
FIGURE 6. Data of a patient who sustained three gunshot wounds in his back that penetrated the liver and entered the right thorax. He arrived in the ED with MAP of 93 mm Hg, pulse oximetry of 98%, and CI of 3.75 L/min/m^2, after an 8-min ED stay, he was taken to the OR where laparotomy was performed. Anesthesia induction was uneventful, but shortly thereafter, his tcPo$_2$ rapidly fell from 58 to 29 to 3 mm Hg and tcPco$_2$ rose to 79 mm Hg, indicating poor tissue perfusion. After he was given fluids and 3 U of packed cells, the monitored values returned to acceptable levels; subsequently, approximately 1,500 mL of blood was found in the retroperitoneal space and right pleural cavity.

and after the CI nadirs. In the survivors, the CI and tcPo$_2$ values were initially higher, suggesting lesser blood volume deficits or better compensations. The transcutaneous O$_2$ and CO$_2$ changes tended to precede the CI nadir, and the SaO$_2$ changes of nonsurvivors followed the nadir.

DISCUSSION

The present study evaluated the accuracy and limitations of noninvasive monitoring in acutely ill emergency patients shortly after ED admission. When the Zo > 15 ohms and the dZ/dt > 0.3 ohms,

agreement of this bioimpedance method with thermodilution was satisfactory and sufficiently reliable to base decisions for treatment. More importantly, the impedance changes satisfactorily tracked and trended thermodilution values. The correlations of bioimpedance vs thermodilution cardiac output were equivalent to those of pulse oximetry compared with the standard blood gas analysis (Fig 3). We did not find any instance in which the impedance values would have led to incorrect or harmful therapy. Minor differences between thermodilution and impedance cardiac output estimations were offset by the continuous on-line display of data that allowed instant recognition of changes in the course of illness and the responses to therapy. Similarly, $tcPo_2$ gave a useful first approximation to tissue perfusion.[25–36]

As an example of noninvasive monitoring in "worst case" emergency conditions, Figure 6 shows the data of a patient who sustained three gunshot wounds to his right flank. Shortly after anesthesia induction, his $tcPo_2$ and CI rapidly fell and the $tcPco_2$ rose, despite maintenance of arterial pressures. With fluids and transfusions, these values returned to acceptable levels; 1,800 mL of blood was then found in the right pleural cavity and retroperitoneal space. His subsequent course was uneventful.

The ED is the primary entry point into medical care for many critically ill patients and this early period provides a crucial opportunity for early assessment and rapid therapeutic interventions that may affect outcome. A major dilemma is that shock is easily diagnosed in late stages when therapy is ineffective, but early diagnosis is difficult because shock is first recognized by imprecise signs and subjective symptoms. The present noninvasive systems provided early readily available screening methods for continuous assessment of circulatory parameters and titration of therapy to predetermined goals. They may be used as the "front end" of subsequent invasive monitoring to obtain early data before the patient's course becomes irreversible.

The importance of early monitoring and optimizing Do_2 and Vo_2 was shown by Boyd and Bennett[37] who reviewed seven prospective randomized series of patients who entered the ICU after organ failure or sepsis had occurred and had no outcome improvement with therapy; they compared these with seven other prospective randomized series that showed significant outcome improvement when early therapy was given to achieve physiologic goals in the first 8 to 12 h postoperatively,[10,12–17] or prophylactically.[12] Additional studies showed improved outcome when used intraoperatively,[38] in trauma,[39,40] in sepsis,[41–43] in acute myocardial infarction,[44,45] and in the elderly postoperative patient.[46] Boyd and Bennett[37] concluded that improved outcome is unlikely when ICU

admission for invasive monitoring is delayed until after organ failure occurs. Clearly time factors are of the essence. Noninvasive systems provide alternatives for early monitoring as they can be applied on ED admission, OR, hospital floors, or physicians' offices and used to follow the course of acute life-threatening illness.

It is less important in emergency conditions to have the same accuracy required in stable ICU conditions, since the patient's own baseline measurements are often unknown and optimal values for each patient may vary with comorbid conditions. In practice, a 10 to 20% difference between invasive and noninvasive cardiac output estimations in the ED would be acceptable when 30 to 50% changes from the normal range were present. However, thermodilution also has appreciable inaccuracies in both high and low cardiac output ranges and especially when the patient has hypothermia, dysrhythmias, Valsalva effects, motion artifacts, shivering, anxiety, and errors from calibration, injectate temperature, etc. Direct Fick Vo_2 measurements, the physiologists' gold standard, are precluded by the nonsteady states of emergency conditions.

Invasive hemodynamic monitoring in the ICU provide a series of snapshots at infrequent intervals. Noninvasive monitoring provides similar information for acutely ill patients as continuous, on-line, real-time displays anywhere in the hospital. Minor differences between impedance and thermodilution measurements were offset by the advantages of continuous graphic displays of data. We found noninvasive monitoring was easier, quicker, cheaper, and safer than invasive monitoring, but prospective clinical trials are needed to evaluate their cost-effectiveness.

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