J Anesth (1994) 8:400–405

Journal of
Anesthesia

Simultaneous monitoring of noninvasive hemodynamic profile and capnography for tissue perfusion evaluation

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Abstract: To study the simultaneous variations of end-tidal CO_2 pressure ($PetCO_2$) and aortic blood flow (ABF) during modifications of tissue perfusion, continuous noninvasive hemodynamic monitoring and continuous recording of $PetCO_2$ were performed on 30 patients under general anesthesia and artificial mechanical ventilation. The 30 patients underwent orthopedic surgery on one of the lower limbs using a hemostatic tourniquet. Deflation of the pneumatic tourniquet resulted in a rise of ABF up to 39% ($P < 0.001$), a rise of $PetCO_2$ up to 17% ($P < 0.001$), and a drop of total vascular systemic resistance (TVSR) of 59% ($P < 0.001$). In all cases, the gradient of $Paco_2$-$PetCO_2$ showed mean variations of 1.2 ± 0.5 mmHg. According to these results, the observed variations can not be explained by an alteration of the Ventilation/Perfusion (V_o/Q) ratio alone. It may be suggested that tissue hypoperfusion produced by a tourniquet generates CO_2 and other metabolic products accumulation in tissues, which are removed during reperfusion. This would be expected to produce parallel increases in ABF and $PetCO_2$. If the results are confirmed with further studies, rapid variations of $PetCO_2$ during anesthesia may provide a noninvasive means of assessing the quality of global tissue perfusion.

Key words: End-tidal CO_2—Aortic blood flow—Hemostatic tourniquet—Tissue perfusion

Introduction

Capnography is widely used in anesthesiology to monitor the end-tidal CO_2 partial pressure ($PetCO_2$) [1,2]. It allows information to be obtained indirectly regarding the quality of alveolar ventilation and to assess the partial arterial pressure of CO_2 ($Paco_2$) [3].

$PetCO_2$ can also be a qualitative indicator of tissue perfusion, since variations in this parameter are used during cardiopulmonary resuscitation [4]. A rapid decrease in $PetCO_2$ during cardiac arrest is the result of a decrease in tissue perfusion. Increased $PetCO_2$ occurs when resuscitation is effective, indicating that cardiovascular activity restarts and that tissue perfusion recovers as well [5].

Similar changes might be seen when hemodynamic changes occur under general anesthesia, interfering with tissue perfusion. Confirmation of this fact could allow us to use such monitoring in anesthesiology because $PetCO_2$ depends on metabolic production of CO_2, alveolar perfusion and ventilation, and tissue perfusion [6].

Under general anesthesia with stable mechanical ventilation, it seems reasonable to assume that metabolism does not vary abruptly when the body temperature is stable. Therefore, even if the metabolic rate during general anesthesia slowly decreases [7], rapid variations of $PetCO_2$ in all likelihood depend on tissue and alveolar perfusion [8].

Changes in alveolar perfusion influence the ratio of ventilation/perfusion (V_o/Q); this is reflected by changes in the $Paco_2$—$PetCO_2$ gradient ($P(a\text{-}et)CO_2$). A stable $P(a\text{-}et)CO_2$ indicates that V_o/Q is also stable [9]. Thus, rapid variation of $PetCO_2$, parallel to variations of blood flow, appears to be mainly determined by changes in tissue perfusion [10].

To verify this hypothesis, variations in the hemodynamics and $PetCO_2$ were analyzed by restricting the blood flow in an anatomic region followed by reperfusion.

Methods

Following local ethics committee approval, we studied 30 ASA class 1 patients (mean age 36 ± 12 years) undergoing orthopedic surgery on an lower limb under

Address correspondence to: R. Muchada
Received for publication on November 15, 1993; accepted on February 12, 1994

general anesthesia after obtaining their informed consent.

All patients were under mechanical respiratory support with stable alveolar ventilation and a pneumatic tourniquet had been applied to prevent bleeding in the surgical field. This tourniquet (Inflatometer Regulator 3000, Zimmer, Warsaw-Indiana USA) was placed on the thigh and inflated to a pressure of 200 mmHg over patient systolic arterial blood pressure.

Noninvasive hemodynamic monitoring was achieved using a prototype modular unit built in the laboratory of Unit 281 of INSERM (National Institute of Health and Research in Medicine, Lyon, France). This unit allows continuous noninvasive monitoring of aortic blood flow (ABF) in the descending aorta with a special intra-esophageal echo-Doppler probe. ABF data were measured by continuously monitoring the aortic diameter using an echograph bidimensional scanner (10 mHz), and blood velocity data with a pulsed emission Doppler (5 mHz). Both parameters were simultaneously and continuously measured at the same anatomic level [11,12]. The hemodynamic profile was completed by measuring systolic, diastolic, and mean arterial blood pressure (SAP, DAP, MAP, respectively) using a digital plethysmograph (Finapres 2300, Ohmeda, Englewood, NJ, USA).

Electrocardiogram (ECG) and heart rate (HR) were obtained with an electrocardioscope (ITS 104, CGR, Paris, France). Systolic time intervals (STI), preejection period (PEPi) and left ventricular ejection time (LVETi), indexed to HR according to Weisler's formula [13], were automatically and continuously measured by integrating electrocardiogram signals and Doppler aortic blood velocity velocity signals using a computer program specifically designed for this purpose [14]. The PEP/LVET ratio was automatically calculated. Stroke volume (SV) and total systemic vascular resistances (TSVR) indexed on the ABF were also automatically calculated.

PetCO$_2$ was obtained with an infrared capnograph (Normocap 200, Datex, Helsinki, Finland) which was calibrated with the same gaseous mixture of CO_2 used to calibrate the blood gas (BG) analyzer. The suction outlet of the capnograph was always connected directly to the tracheal intubation tube near the patient's mouth. All data were stored on an IBM-compatible ATS computer. Results were presented in tables which were updated every 10 s. and recorded on a magnetic disk. An analog output connection gave a continuous record of PetCO$_2$ and ABF variations printed on paper. Arterial blood samples for BG analysis were processed with a blood gas analyzer, (ABL 240, Radiometer, Copenhagen, Denmark.). The maximum delay between sampling and determination was 8 min. General anesthesia included an oral premedication 2 h. before induction with alprazolam 0.5 mg and hydroxyzine 50 mg. Induction was achieved by intravenous (IV) injection of phenoperidine 0.014 mg·kg^{-1}, vecuronium bromide 0.08 mg·kg^{-1} and propofol 2 mg·kg^{-1}, and was maintained with 1% isoflurane, controlled with a gas monitor, (Servo 120, Siemens, Erlangen, Germany). Phenoperidine 0.007 mg·kg^{-1} was injected every 40 min and vecuronium bromide 0.03 mg·kg^{-1} when necessary. The lungs were ventilated with a ventilator (Servo 900 D, Siemens) with a stable tidal volume (TV) of 8 ml·kg^{-1}, and a respiratory rate of 12 cycles/min. An inspiratory gas mixture of 60% N_2O and 40% O_2 was used. Intravenous perfusion of lactated Ringer solution was limited to 4 ml·kg^{-1}·h^{-1}. Esophageal temperature was continuously monitored with a thermometer (YSI 43 DA module, YSI, Yellow Spring, Ohio USA).

Among the continuous sequence of measurements, four moments were recorded for retrospective chronologic analysis of events:

T1: 10 min after induction, when patients were stable under mechanical ventilation and after the tourniquet was inflated
T2: 2 min before removal of the tourniquet
T3: 3 min after decompression of the tourniquet
T4: 10 min after T3

Each time was identified on the continuous recording and arterial BG were measured simultaneously.
Results are presented as mean values (X) and standard deviation (± SD).

Statistical analysis was performed as follows: T1 values of each group were considered as references for each parameter. Student's t-test and analysis of variance were used to compare changes in the time course of each parameter and linear regression was used to correlate ABF and PetCO$_2$.

Results were considered significant when $P < 0.05$.

Results

The average time of tourniquet inflation was 57 ± 11 min. The variations of the different parameters are shown in Table 1. While T2, PEPi, and the PEP/LVET ratio increased, ABF, PetCO$_2$, and Paco$_2$ showed a slight, progressive decrease. These variations were statistically significant. At T3, ABF, SV, and HR significantly increased (39%, 20%, and 12%, respectively). PetCO$_2$ and Paco$_2$ siginificantly increased as well (17% and 15%), while MAP and TVSR decreased (18% and 59%), as did pH and base excess (0.8% and 2.11 mEq·l^{-1}). At T4, no other parameters, except for SV (which stayed high) and base excess (which remained low), showed a significant difference compared with the T1 values.

Table 1. Time changes of different parameters from T1 to T4 on 30 patients

Time	T1	T2	T3	T4
HR (b·min^{-1})	66 ± 11	68 ± 9	74 ± 10**	66 ± 7
MAP (mmHg)	78 ± 12	81 ± 13	69 ± 10**	78 ± 10
ABF (l·min^{-1})	3.29 ± 0.74	3.1 ± 0.82*	4.6 ± 1.09***	3.6 ± 0.8
TSVR (dyn·s·cm^{-5})	1994 ± 463	2128 ± 499	1135 ± 287***	1808 ± 411
SV (ml)	49 ± 12	49 ± 16	62 ± 16**	54 ± 13*
PEPi (ms)	141 ± 11	151 ± 12**	141 ± 11	146 ± 10
LVETi (ms)	419 ± 15	413 ± 20	429 ± 22**	417 ± 21
PEP/LVET	0.33 ± 0.03	0.36 ± 0.047*	0.32 ± 0.036	0.35 ± 0.06
PetCO$_2$ (mmHg)	35.1 ± 2.4	33.2 ± 3**	41 ± 5***	36 ± 3.7
PaCO$_2$ (mmHg)	38 ± 2.8	36 ± 3.29*	44 ± 4.9***	39 ± 3.7
P(a-et)CO$_2$ (mmHg)	3.34 ± 0.97	3.51 ± 0.6	3.2 ± 0.9	3.3 ± 0.8
pH	7.40	7.41	7.34***	7.379
Base excess	−0.08	−0.217	−2.53***	−1.8**

HR, heart rate; MAP, mean arterial pressure; ABF, aortic blood flow; TSVR, total systemic vascular resistance; SV, stroke volume; PEPi, preejection period; LVETi, left ventricular ejection time; PetCO$_2$, end-tidal CO$_2$ pressure; Paco$_2$, partial arterial pressure of CO$_2$; P(a-et)CO$_2$, Paco$_2$-PetCO$_2$ gradient. Values are expressed in means ± S.D. Significant differences versus T1: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

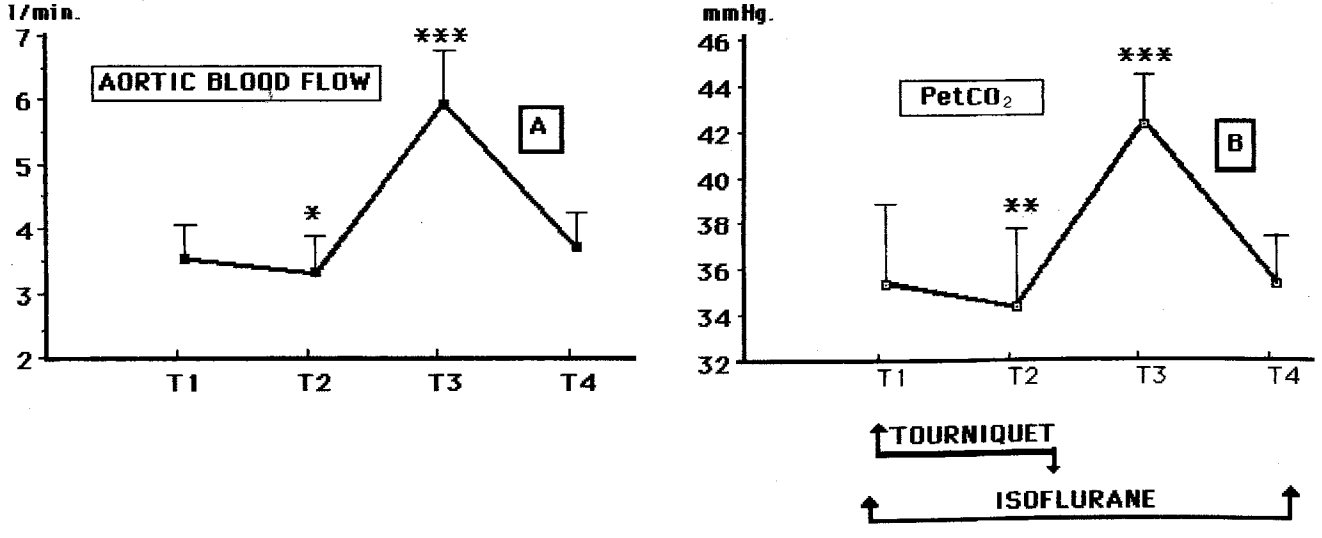

Fig. 1. A. Changes of aortic blood flow (ABF). Slight but significant decrease was noted between T1-T2. After tourniquet deflation, at T3, a rapid increase is shown. After 10 min (T4), ABF was not significantly different from T1 (*$P < 0.05$, ***$P < 0.001$). **B** Changes of end-tidal CO$_2$ pressure (PetCO$_2$). PetCO$_2$ decreased between T1-T2. After tourniquet deflation, at T3, PetCO$_2$ sharply and transiently increased appeared (**$P < 0.01$, ***$P < 0.001$)

ABF and PetCO$_2$ increased in all patients between T2 and T3. The changes in ABF and PetCO$_2$ are shown in Fig. 1 (A and B, respectively). A typical individual graph of continuous PetCO$_2$—ABF variations is shown in Fig. 2. The linear regression between PetCO$_2$ and ABF in 120 measurements (30 patients for each time) is shown in Fig. 3. There is a positive linear correlation between the two variables with significance (r: 0.509, r^2:

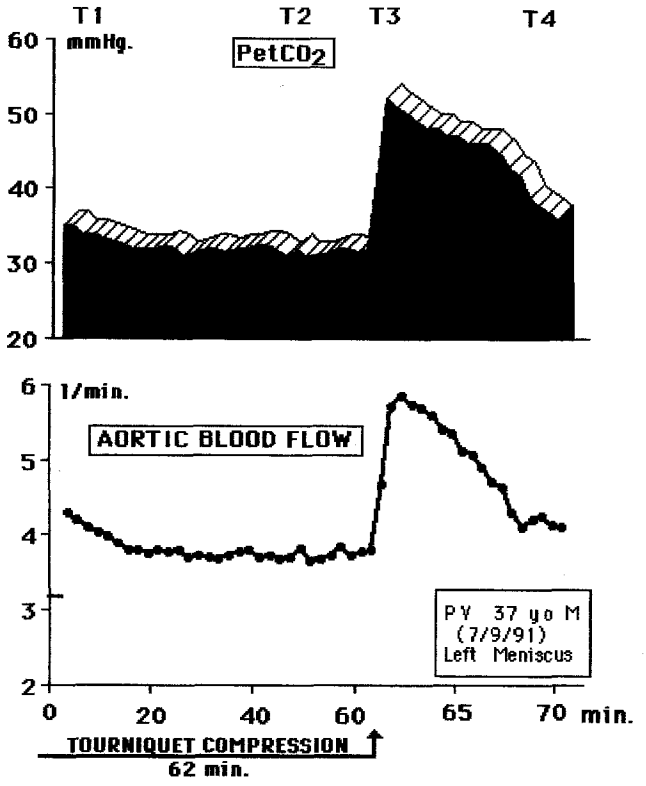

Fig. 2. Typical example of continous monitoring and parallel change of PetCO$_2$ and ABF in one patient during tourniquet deflation

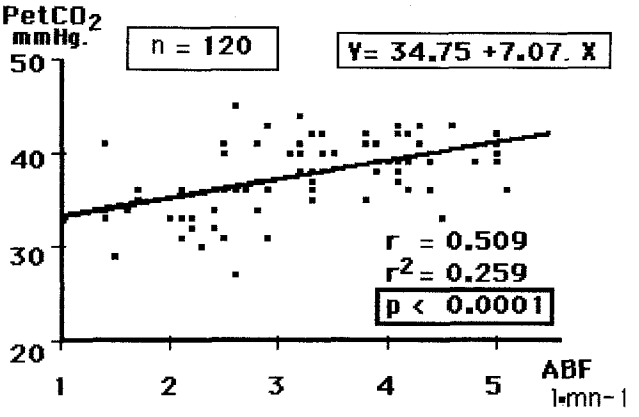

Fig. 3. Regression curve of PetCO$_2$/ABF for 120 comparative measurements. A highly significant relation was found between ABF and PetCO$_2$ values before and after tourniquet deflation, but looking at the correlation equation, it seems difficult to extrapolate one value from the other

0.259, $P < 0.0001$). During the study period, the patients' esophageal temperature was normal. Maximal variations did not exceed ± 0.35°C.

Discussion

The noninvasive hemodynamic system currently in use for patient monitoring is the latest version built by the INSERM laboratory. It has been used in our operating rooms since 1988 [12]. It has allowed the continuous monitoring of more than 1200 patients, and allows an almost real-time monitoring of changes in cardiovascular parameters over long periods of time.

Of course, this system does not permit a real cardiac output (CO) measurement since the ABF is obtained in the descending aorta. Nevertheless, experimental and clinical comparative studies with electromagnetic and thermodilution techniques show correlation coefficients of 0.94 and 0.97, respectively [11,12].

In contrast with other aortic blood flow measurement systems [15], this one takes the real value of aortic diameter into account. A narrow echographic ultrasound beam with an angular sensivity of ± 2° was used to position the pulsed-Doppler ultrasound beam; the latter is divergent, allowing to insonat 95% of the aortic transverse section. The high frequency ultrasound emissions used make it possible to obtain high quality ultrasound signals. The special characteristics of the ultrasonic probe [16] and the esophageal window allows us to easily obtain reliable and reproducible results [12].

Some studies have previously demonstrated the effects of tourniquet deflation on hemodynamics, oxygen consumption, CO_2, enzymatic changes, lactate production, and changes in cerebral blood flow [17–23]. In brief, they all stated that modifications did exist and that they were always transient, lasting between 7 and 40 min.

Our results agree with previous studies: the rise in PetCO$_2$ and fall in RSVT and pH were the general rule.

The only work found describing a decrease in cardiac output after tourniquet release was that of Edfeldt and Thomson [24]. This did not coincide with the results of the present work. The difference might be due to the use of droperidol during the anesthesia in patients older than in our series, and because droperidol may reduce CO, increase in the fall of TSVR, and block the baroreflex [25].

In our study, PetCO$_2$ and ABF significantly and slowly decreased during the beginning of the anesthetic period (T1-T2). This observation may reflect the normal fall in metabolic rate under general anesthesia [7], or cardiac depression under halogenated inhalational agents [26,1,28] if we take into count the increase of PEPi and PEP/LVET ratio. Then, when tourniquet was released and reperfusion occurred, ABF increased, and TSVR decreased, possibly induced by metabolic alterations produced in the ischemic area [18,19].

In a healthy myocardium, as seems to be the case with the ASA1class patients in this study, the new hemodynamic status with an afterload decreased, would have produced a recovery of contractility, reflected by the

lower PEPi and PEP/LEVT, and in the higher SV. The CO_2 accumulated in the distal part of the leg during the ischemic period was then transported by the circulation and eliminated by the pulmonary route with an acute increase in $PetCO_2$ as is shown in the example of Fig. 2. The time changes in $PetCO_2$ should confirm some observations [17,29,30] which suggest that intracellular production of CO_2 persists during hypoperfusion. It is also possible that the rise in $PetCO_2$ may be partially produced by changes in the Henderson-Hasselbalch equilibrium, after the release of H^+ radicals from the ischemic and hypercapnic region [22]. Even if this hypothesis is correct, the decrease in the blood pH after the tourniquet release and the increase in $PetCO_2$, should reflect improvement of perfusion in previously ischemic regions. These two kinds of acid production could explain the state of acidosis (metabolic and respiratory) which is responsible for the acute decrease of pH seen at T3. Washout of CO_2 is brief, ABF and $PetCO_2$ decrease in 10 min (T4), reaching values which are not significantly different from T1. During the study period, $P(a\text{-}et)CO_2$ did not show any significant variation, indicating that rapid changes of $PetCO_2$ observed, cannot be explained by variations of the V_o/Q ratio [31,32] but rather that they are the result of modification by tissue reperfusion. In conclusion, it appears that a relation does exist between $PetCO_2$ and tissue perfusion and that rapid variations of $PetCO_2$ may provide a noninvasive means of evaluating tissue perfusion. The concordant changes between $PetCO_2$ and ABF observed here and in previous reports [32], do not allow the extrapolation of one value from the other. The correlation between ABF and $PetCO_2$ shows a highly significant linear relation but not enough to permit such extrapolation. If these events are confirmed in future studies, diagnosis and therapeutics to improve tissue perfusion may be guided by continuous hemodynamic and $PetCO_2$ monitoring as described here in.

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