IMPROVED ACCURACY OF CARDIAC OUTPUT ESTIMATION BY THE PARTIAL CO₂ REBREATHING METHOD
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ABSTRACT. Objective. This study investigated the accuracy of the NICO monitor equipped with the newer software. Additionally, the effects of the increased dead space produced by the NICO monitor on ventilatory settings were investigated. Methods. Forty-two patients undergoing elective aortic reconstruction participated in this prospective, observational study at a university hospital. Cardiac output was continuously monitored using both the NICO monitor and continuous cardiac output (CCO) measured by a pulmonary artery catheter. A NICO monitor equipped with ver. 4.2 software was used for the first 21 patients while a NICO monitor equipped with ver. 5.0 software was used for the rest of the patients. Cardiac output measured by bolus thermodilution (BCO) at 30 min intervals was used as a reference. Results. The bias ± precision of the NICO monitor was 0.18 ± 0.88 l/min with ver. 4.2 software (n = 182) and 0.18 ± 0.83 l/min with 5.0 software (n = 194). The accuracy of the NICO monitor is comparable to CCO, whose bias ± precision against BCO is 0.19 ± 0.81 l/min (n = 376). At the same level of CO₂ production and minute ventilation, PaCO₂ was lower in the patients monitored by NICO with ver. 5.0 software than patients with ver. 4.2 software. Conclusions. This study demonstrated the improved performance of the NICO monitor with updated software. The performance of the NICO monitor with ver. 4.2 or later software is similar to CCO. However, the cardiac output measurement did not fulfill the criteria of interchangeability to the cardiac output measurement by bolus thermodilution. Updates to ver. 5.0 attenuated the effects of rebreathing introduced by the NICO monitor without compromising the accuracy of the cardiac output measurement.

KEY WORDS. cardiac output, monitor, partial CO₂ rebreathing, NICO, pulmonary artery catheter, aortic reconstruction.

INTRODUCTION

The non-invasive cardiac output (NICO; Respironics-Novametrics, Wallingford, CT) monitor is one of the less-invasive cardiac output monitors and employs the indirect Fick partial CO₂ rebreathing method while also measuring pulmonary capillary blood flow (PCBF) [1, 2]. This device is characterized as minimally invasive for intubated, mechanically ventilated patients and is easy to setup with operator-independent performance. Although the basic principles are scientifically justified, this monitor uses a relatively complex algorithm and several assumptions. Previous reports, including ours, have demonstrated...
the larger bias of the NICO monitor compared to the thermodilution method [3–14]. Furthermore, a simulation study has revealed that the NICO method is relatively accurate when PCBF is between 3 and 6 l/min but that PCBF and cardiac output (CO) are overestimated below this range and underestimated above this range [15]. The manufacturer has been constantly updating the device software, but the accuracy of this device has not been extensively reviewed after these updates [16]. Application of the NICO monitor inevitably increases dead space and results in CO₂ accumulation. To alleviate CO₂ retention, the rebreathing cycle was reduced from 50 to 35 s with ver. 4.5 or later software. However, the impact of this possible improvement has not been reported.

The purpose of this prospective, observational study was to re-evaluate the accuracy of the NICO monitor equipped with next generation software in comparison with conventional bolus thermodilution in patients undergoing elective aortic reconstruction. Additionally, the effects of the shorter rebreathing time accompanied by the newer software on ventilatory settings were investigated.

**METHODS AND MATERIALS**

Following institutional review board approval, 42 patients undergoing elective aortic reconstruction for infrarenal abdominal aortic aneurysm were enrolled in this study after obtaining their informed consent. The study protocol is based on our previous report [9]. Anesthetic management was standardized in all patients as follows; after epidural catheterization at the Th 10/11 or 11/12 interspace, general anesthesia was induced with intravenous fentanyl and propofol and maintained with sevoflurane inhalation with or without nitrous oxide. Patients were paralyzed with vecuronium and mechanically ventilated with either the AS/3 ADU (Datex-Ohmeda, Helsinki, Finland) or KION (Siemens, Solna, Sweden) anesthesia machine. Tidal volume and respiratory rate were initially set at 10 ml/kg and 10 bpm, respectively, and were adjusted to maintain PaCO₂ between 35 and 45 mmHg. Fluid administration, blood transfusion, epidural injection of local anesthetics, administration of inotropic and vasodilatory drugs, and other anesthetic management procedures were at the discretion of the attending anesthesiologist. An 8F pulmonary artery catheter (746HF8, Edwards Lifesciences, Irvine, CA) was inserted via the right internal jugular vein. Continuous cardiac output (CCO) and mixed venous oxygen saturation was continuously monitored with the Vigilance monitor (Edwards Lifesciences, Irvine, CA). These data were downloaded to a computer every 30 s for subsequent analysis.

These patients were divided into two groups according to the time of enrollment. Second generation software (software ver. 4.2) was used for the first 21 patients. In the other 21 patients, cardiac output was monitored with the same device updated with the newer software (software ver. 5.0). The NICO sensor was placed between the endotracheal tube and the heat and moisture exchanger (Hygrobac S, DAR-Mallinckrodt, Mirandola, Italy). Meticulous attention was paid to maintain adequate rebreathing circuit volume during monitoring. Data including average-mode cardiac output (CO-a), fast-mode cardiac output (CO-f), PCBF, CO₂ production (VCO₂), minute ventilation (MV) and end-tidal PCO₂ (PetCO₂) were downloaded to a computer every 3 min. CO-a was used for the evaluation of CO.

Bolus thermodilution cardiac output (BCO) measurements were made every 30 s after stable CCO and NICO measurements were obtained. Blood gas data were input to the NICO monitor prior to each BCO measurement to allow for the precise estimations of shunt fraction and NICO values. The injection of ice-cold saline was repeated four times within 7 min, and averaged data were used for analysis. The BCO measurements were included in the analysis only if the stability of hemodynamic status was achieved. Hemodynamic stability was arbitrarily defined as there being no fluid challenge or change in pharmacological intervention at least for 5 min. Non-shunted pulmonary blood flow was calculated with the following formula; non-shunted pulmonary blood flow = BCO × (1–shunt fraction). Shunt fraction (Qs/Qt) was calculated from the following formula: Qs/Qt = CcO₂–CaO₂/CcO₂–CvO₂ (CcO₂: end-pulmonary capillary oxygen content, CaO₂: arterial oxygen content, CvO₂: mixed venous oxygen content) [17]. CvO₂ was calculated using SvO₂ data obtained from PAC.

Data are expressed as mean ± SD and were statistically analyzed using the Prism software (ver. 4, Graphpad, San Diego, CA). Correlations and linear regression between either CCO or NICO against BCO were determined. A Bland–Altman analysis was used to compare the bias (the mean of the differences) and precision (standard deviation of bias) of NICO and CCO against BCO. Since multiple measurements were employed in each subject, modifications were used in calculating precision and the limits of agreement [18, 19]. The interchangeability between either CCO or NICO against BCO was defined as percentage error at the mean value of CO within 28% or relative error less than ±20% in more than 75% of measurement pairs [20]. Percentage error (expressed in %) was defined as 100 × 2 SD of the difference/mean value of