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ORIGINAL ARTICLE

Agreement between non-invasive and invasive arterial blood pressure during surgery in the prone position: an error grid analysis

Takashi Juri[1] · **Koichi Suehiro**[1] · **Masayo Takai**[1] · **Daisuke Nakada**[1] · **Kanae Takahashi**[2] · **Yohei Fujimoto**[1] · **Takashi Mori**[1]

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Abstract

Purpose Prone position has recently gained renewed importance as a treatment for acute respiratory distress syndrome and spine and brain surgeries. Our study aimed to perform an error grid analysis to examine the clinical discrepancies between arterial blood pressure (ABP) and non-invasive blood pressure (NIBP) in the prone position and to investigate the risk factors influencing these differences.

Methods Error grid analysis was performed retrospectively on 1389 pairs of 100 consecutive prone positioning cases. This analysis classifies the difference between the two methods into five clinically relevant zones, from “no risk” to “dangerous risk”. Additionally, multivariable ordinal logistic regression analysis was conducted to evaluate the relationship between the risk zones of mean blood pressure (MBP), as classified by error grid analysis and the covariate of interest.

Results Error grid analysis showed that the proportions of measurement pairs in risk zones A–E for systolic blood pressure were 96.8%, 3.2%, 0.1%, 0%, and 0%, respectively. In contrast, the MBP proportions were 74.0%, 25.1%, 0.9%, 0.1%, and 0%. Multivariable ordinal logistic regression analysis revealed that the position of arms (next to the head) was a significant factor (adjusted odds ratio: 4.35, 95% CI: 2.38–8.33, $P < 0.001$).

Conclusion Error grid analysis revealed a clinically unacceptable discrepancy between ABP and NIBP for MBP during prone positioning surgery. The position of the arms next to the head was associated with increased clinical discrepancy between the two MBP measurement methods.

Keywords Blood pressure · Error grid analysis · Invasive arterial blood pressure · Noninvasive blood pressure · Prone position

Introduction

The importance of prone positioning has increased in recent years, not only for orthopedic and brain surgery in the operating room but also for the treatment of acute respiratory distress syndrome (ARDS) in the intensive care unit [1]. In the prone position, reductions in cardiac output and blood pressure have been reported, resulting from decreased venous return due to compression of the inferior vena cava and reduced compliance of the left ventricle due to increased intrathoracic pressure [2, 3]. In high-risk surgical and critically ill patients, invasive arterial blood pressure (ABP) measurement is the standard reference method for blood pressure monitoring. Another method is the intermittent non-invasive blood pressure (NIBP) measurement using oscillometric cuffs [4]. However, limited studies have examined the difference between ABP and NIBP in the prone position. Recognizing this difference is essential for hemodynamic management in perioperative and intensive care settings.

Previous comparative studies of blood pressure have generally used Bland–Altman analysis [5, 6]. This analysis provides the mean difference between the two measurement methods and 95% limits of agreement (LOA). This analysis helps quantify both the systematic error (bias) and the random variability (spread of the differences around the mean

✉ Koichi Suehiro
suehirokoichi@yahoo.co.jp

[1] Department of Anesthesiology, Osaka Metropolitan University Graduate School of Medicine, 1-5-7 Asahimachi, Abenoku, Osaka, Osaka 545-8586, Japan

[2] Department of Medical Statistics, Osaka Metropolitan University Graduate School of Medicine, Osaka, Japan

difference) between the test method and a reference method. However, the bias and LOA from Bland–Altman analysis do not provide much insight into clinical relevance. For instance, a measurement discrepancy of 10 mmHg assumes greater clinical importance when the patient's mean blood pressure (MBP) is 50 mm Hg as compared to a patient with an MBP of 100 mm Hg. To address this problem, Saugel et al. applied error grid analysis to validate blood pressure measurement methods [7]. This method plots the test method values against the reference values and divides the plot into zones that reflect the clinical risk associated with discrepancies in the measurements. Specifically, the difference between the two techniques was classified into five zones, ranging from "no risk" to "dangerous risk," based on the opinions of 25 experts, thereby making the differences clinically relevant. In our previous study, we used error grid analysis to compare ABP and NIBP in the supine position, revealing a clinically unacceptable difference in MBP, which was not evident in the Bland–Altman analysis [8].

Our study aimed to perform an error grid analysis to examine the clinical discrepancies between ABP and NIBP in the prone position and to investigate the risk factors affecting these differences.

Methods

Study preparation

This study was approved by the Ethics Committee of Osaka City University Graduate School of Medicine on February 14, 2019 (reference number: 4308). This study was conducted retrospectively, and the requirement for informed consent was waived by the Ethics Committee.

Participants

Patients who underwent general anesthesia in the prone position at our hospital between June 2018 and February 2019, during which ABP and NIBP were measured simultaneously, were included. The exclusion criteria were as follows: (1) patients aged < 20 years, (2) patients with preoperative arrhythmia, and (3) patients who underwent ABP and NIBP measurements on the ipsilateral side of the arm.

Blood pressure measurement and data collection

NIBP was monitored with an upper arm cuff (Comfort care, Adult cuff M1574A; Philips Electronics Japan Corp., Tokyo, Japan) connected to a digital monitor (IntelliVue MP70; Philips Electronics Japan Ltd., Minato City, Tokyo, Japan). A properly sized cuff was fitted to match each patient's arm circumference. Following our department's anesthesia protocol, NIBP measurements were taken every 15 min, even for patients who underwent ABP measurements. An arterial catheter (Terumo arterial catheter, 20 gauge; Terumo, Tokyo, Japan) was inserted into the radial artery after the induction of general anesthesia and connected to a disposable digital transducer (Tru Wave MP5100; Edwards Lifesciences, Irvine, CA, USA). After ensuring that the tubing system was free of air, the arterial transducer was calibrated to zero atmospheric pressure and placed at the level of the right atrium. Hemodynamic data, including ABP and NIBP, were automatically recorded every minute using an anesthesia management system (ORSYS; Philips Electronics, Tokyo, Japan). Before data analysis, blood pressure artifacts were removed using the following algorithm: (1) systolic blood pressure (SBP) greater than 300 mmHg or less than 20 mmHg; (2) diastolic blood pressure (DBP) greater than 225 mmHg or less than 5 mmHg; and (3) SBP less than DBP plus 5 mmHg [9].

Statistical analyses

Continuous data are expressed as median (interquartile range), while discrete data are expressed as percentages. *P* values < 0.05 were considered statistically significant.

Bland–Altman analysis with repeated measurements for each participant was used to calculate the mean difference between NIBP and ABP (mean bias) and the 95% limits of agreement [10]. To assess the precision and accuracy of the tested methods, we compared the results to the criteria established by the Association for the Advancement of Medical Instrumentation, which recommends an acceptable mean bias of less than 5 mmHg and a standard deviation of less than 8 mmHg [11].

Subsequently, we performed an error grid analysis to evaluate the clinical relevance of the discrepancies between NIBP and ABP. Error grid analysis classified each measurement pair into five risk levels, from zone A to E. Details of the risk zones are as follows:

A. No risk (i.e., no difference in clinical treatment between the tested and reference methods)
B. Low risk (i.e., values in the tested method deviate from those in the reference method, which may result in unnecessary treatments with mild non-life-threatening outcomes).
C. Moderate risk (i.e., values in the tested method deviate from those in the reference method, which may result in unnecessary treatments with moderate non-life-threatening outcomes).
D. Significant risk (i.e., values in the tested method deviate from those in the reference method, which may result in unnecessary treatments with severe non-life-threatening outcomes).

E. Dangerous risk (i.e., values in the test method deviate from those in the reference method, which may result in unnecessary treatments with life-threatening outcomes).

The error grid analysis was conducted using risk scores calculated based on the opinions of a panel of 25 specialists in anesthesiology and intensive care medicine. To perform this analysis, we employed a specific Excel spreadsheet provided by Saugel et al. [7]. The clinical difference between the two methods was considered acceptable if the percentage of zone A was at least 90%, the percentages of zones B, C, and D were 5%, 4%, and 2% or less, respectively, and that of zone E was 0%, as recommended in a previous study [7].

A proportional odds model of multivariable ordinal logistic regression analysis was used to evaluate the relationship between the MBP risk zones classified by the error grid analysis and the covariate of interest. This model summarizes the odds ratios calculated from the logistic regression model using incremental cutoff points to binarize the ordinal results. Proportional odds assume that the odds ratios obtained using any given cutoff point are the same for all cutoff points. Covariates of interest included age, sex, body mass index (BMI), arm position (placed in a neutral position beside the patient or next to the patient's head), continuous administration of vasopressors with reference to previous studies [12–14]. Additionally, a history of hypertension, coronary artery disease, cerebral infarction, smoking, and diabetes mellitus were included as covariates, considering these as risk factors for arteriosclerosis. In the multivariable ordinal logistic regression model, an estimator with the Huber–White robust standard errors was applied to control for correlations in repeated data obtained from the same cases. This Huber-White method used ordinary estimates of the regression coefficients and other parameters of the model using the R function "robcov" from the rms package.

In a previous report, Saugel et al. defined acceptability as when at least 90% of the measurements were classified as Zone A [7]. In our five preliminary tests (74 pairs), the proportion of Zone A was 81%. Using these data, we calculated that a sample size of 100 participants would be required to detect a difference with 80% power and an alpha of 0.05.

Data were analyzed using MedCalc version 20.014 (MedCalc Software Bvba, Ostend, Belgium) and R version 4.43.3 (R Foundation for Statistical Computing, Vienna, Austria).

Results

A total of 1389 pairs from 100 consecutive cases that met the criteria were analyzed. Patient characteristics are listed in Table 1. The median age of the patients was 71 years, and orthopedic surgery was the most common procedure (58%), followed by neurosurgery (42%).

Table 1 Patients characteristics and perioperative data

Variables	Median or %
Age (year)	71 [57, 76]
Female (%)	41 (41%)
BMI (kg/m^2)	23.7 [21.0, 26.4]
History of hypertension (%)	46 (46%)
History of coronary artery disease (%)	11 (11%)
History of diabetes mellitus (%)	22 (22%)
History of cerebral infarction (%)	6 (6%)
Smoker (%)	26 (26%)
Position of arms in neutral (%)	51 (51%)
Continuous administration of vasopressor (%)	30 (30%)
Type of surgery	
Orthopedic surgery (%)	58 (%)
Neurosurgery (%)	42 (%)

Data are expressed as median [interquartile range] and number (%)

BMI body mass index

The average of SBP from ABP and NIBP were 107.6 ± 16.0 mmHg and 99.0 ± 14.5 mmHg, respectively, while the MBP from ABP and NIBP were 73.6 ± 11.5 mmHg and 73.8 ± 12.3 mmHg, respectively.

The results from Bland–Altman analysis (Fig. 1) showed a mean bias of 9.7 ± 11.3 mmHg (LOA: −12.5 to 31.8 mmHg) for SBP and 0.7 ± 9.0 mmHg (LOA: −17.0 to 18.4 mmHg) for MBP, which indicated high accuracy for MBP compared to SBP; however, both were beyond the acceptable range for precision.

The error grid analysis showed that the proportions of measurement pairs in risk zones A–E for SBP were 96.8%, 3.2%, 0.1%, 0%, and 0%, respectively (Fig. 2A), indicating that most of the measurement pairs posed of no risk to patients. In contrast, the proportions of MBP were 74.0%, 25.1%, 0.9%, 0.1%, and 0% (Fig. 2B), indicating a clinically unacceptable difference between ABP and NIBP in MBP measurements, potentially leading to unnecessary treatment.

Multivariable ordinal logistic regression analysis, investigating potential confounding factors affecting the clinical risk of differences in MBP between ABP and NIBP, revealed the position of arms (next to the head) as a significant factor (adjusted odds ratio: 4.38, 95% confidence interval (CI): 2.38–8.04, $P < 0.001$) (Table 2).

Discussion

Our study employed error grid analysis to investigate discrepancies between ABP and NIBP measurements during surgery in the prone position. We found a clinically significant difference between ABP and NIBP for MBP, which was not evident in the conventional Bland–Altman analysis.

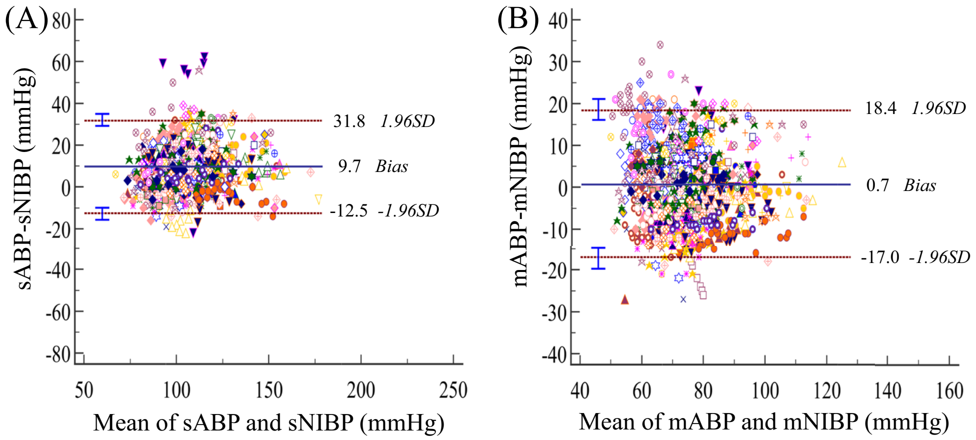

Fig. 1 Bland–Altman plot with repeated measurements for each subject for **A** systolic and **B** mean blood pressure. In each plot, the bias is indicated by a solid horizontal line, the 95% limit of the agreement by dashed horizontal lines, and 95% confidence interval of the 95% limit of the agreement by blue lines. Each symbol represents each case. *ABP* arterial blood pressure, *NIBP* non-invasive blood pressure

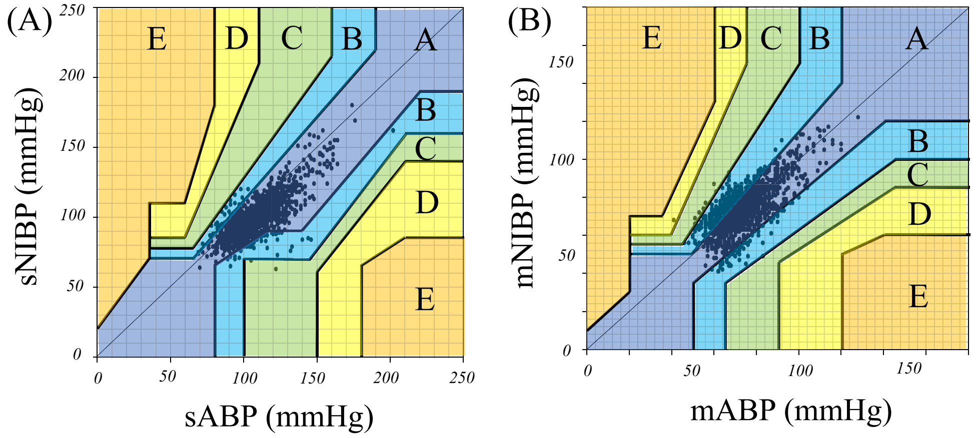

Fig. 2 Error grid analysis for **A** systolic and **B** mean blood pressure. In each figure, the grids are divided into 5 zones. Zones A-E represent no, low, moderate, significant and dangerous risk to the patient, respectively. *ABP* arterial blood pressure, *NIBP* non-invasive blood pressure

Table 2 Multivariable ordinal logistic regression analysis to evaluate potential confounding risk factors associated with increasing the clinical risk of the differences between invasive arterial blood pressure and non-invasive blood pressure

Variables	Adjusted odds ratio	95%CI	*P* value
Age	0.99	0.97 ~ 1.02	0.46
Female	0.59	0.29 ~ 1.19	0.14
BMI	0.97	0.89 ~ 1.05	0.46
History of hypertension	1.06	0.47 ~ 2.40	0.89
History of coronary artery disease	0.59	0.20 ~ 1.68	0.32
History of diabetes mellitus	1.20	0.62 ~ 2.33	0.59
History of cerebral infarction	1.59	0.70 ~ 3.63	0.27
Smoker	1.42	0.65 ~ 3.06	0.38
Position of arms next to the head	4.38	2.38 ~ 8.04	< 0.001*
Continuous administration of vasopressor	0.84	0.36 ~ 1.93	0.68

BMI body mass index

*statistically significant

Furthermore, the positioning of arms next to the patient's head was associated with a 4.4 times higher likelihood of falling into more dangerous zones classified by the error grid analysis for MBP compared to positioning them beside the patient's torso.

In recent years, prone positioning has garnered increased attention in spine surgeries and the treatment of ARDS caused by infectious diseases such as COVID-19 [1]. However, to our knowledge, no studies have investigated the discrepancies between invasive and non-invasive blood pressure measurements in this position. In healthy individuals, prone positioning induces physiological alterations in hemodynamics, such as a decline in preload caused by compression of the inferior vena cava. This decline reduces left

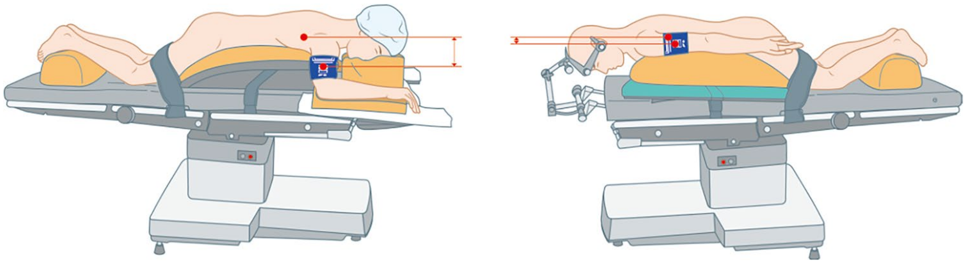

Fig. 3 Prone position in our hospital. In the position where the arm is placed next to the head, the difference in height between the center of the cuff and the level of the heart is greater compared to other positions

ventricular compliance, thereby decreasing cardiac output. To counterbalance this effect, peripheral vascular resistance is increased to maintain the blood pressure [2]. However, in patients with compromised cardiac function, this adjustment may exacerbate the reduction in cardiac output and lead to hypotension [15]. Given the documented association between intraoperative hypotension and increased postoperative complications in several observational studies, there is a particular need to consider the differences between ABP and NIBP, especially during prone positioning, where hypotension is more likely to occur [16–18].

In a previous study, we compared ABP and NIBP measurements in the supine position using error grid analysis [8], and the proportions of MBP in Zones A–E were reported to be 82.5%, 16.7%, 0.8%, 0%, and 0%, respectively. Comparing the results conducted in two different positions (supine and prone), while the proportions of Zones C, D, and E remained unchanged, the proportion in Zone A decreased during prone positioning. This may be because, in the supine position, the blood pressure cuff is positioned at nearly the same level as the heart. In contrast, in the prone position, with both arms of the patient positioned beside their head, the cuff is positioned lower than the heart, leading to higher readings of NIBP than the actual blood pressure.

Our findings highlight that positioning the patient's arms next to the head significantly worsens the discrepancy between ABP and NIBP measurements, potentially placing patients at a higher risk, as illustrated in Fig. 3. This discrepancy likely arises from the varying heights between the heart and the cuff resulting from the positioning of the arms next to the head, emphasizing the importance of considering the relationship between the cuff and the heart during prone positioning. Postoperative vision loss (POLV) is one of the complications associated with surgeries performed in the prone position, which, although rare, has the potential to cause devastating damage. The literature identifies several risk factors for POLV, with sustained hypotension playing a pivotal role. This condition can compromise blood flow to the optic nerve, ultimately leading to vision loss [19, 20]. Our findings suggest that arm positioning can introduce significant discrepancies in blood pressure readings, potentially leading to an underestimation of hypotension. Thus, enhancing the accuracy of blood pressure monitoring could directly contribute to preventing severe complications, including POLV.

Comparisons of ABP and NIBP in previous studies have identified factors such as age, obesity, and administration of vasoactive drugs that influence the differences between the two measurements [12–14]. However, in our study, age and BMI did not significantly affect the error in MBP, as assessed by error grid analysis. This could be attributed to the relatively homogeneous and older patient population in our study, which had fewer patients with obesity. Additionally, continuous administration of vasoactive drugs did not affect measurement errors, possibly indicating diminished effectiveness due to compensatory increases in peripheral vascular resistance during prone positioning-induced reductions in cardiac output.

The limitations of our study include its retrospective nature, which precludes the evaluation of preoperative differences in blood pressure between the arms. Therefore, some patients may have shown preoperative differences in blood pressure between the arms. Additionally, as a retrospective observational study, we cannot rule out the possibility of underdamping or overdamping phenomena affecting the accuracy of ABP measurements, particularly the systolic values, which may have been overestimated or underestimated. Since this was a single-center study, variations in cuff positioning during prone positioning across different facilities may yield different results.

In conclusion, using error grid analysis, our study revealed clinically unacceptable discrepancies between ABP and NIBP for MBP during surgery in the prone position. Furthermore, we identified intraoperative positioning as a significant factor influencing these differences. The relationship between cuff placement and heart position is crucial during surgeries in the prone position.

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Author contributions All authors contributed to the study's conception and design. Material preparation was performed by Nakada Daisuke. Data collection was performed by Masayo Takai and Yohei Fujimoto. Analysis was performed by Kanae Takahashi. The first draft of the manuscript was written by Takashi Juri and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data will be available upon reasonable request to corresponding author.

Declarations

Conflict of interest Koichi Suehiro has received speaker fees from Edwards Lifesciences and Otsuka Pharmaceutical Factory. Other authors have no conflict of interest.

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