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Accuracy of Noninvasive Blood Pressure Monitoring in Critically Ill Adults

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Abstract

Background: Blood pressure (BP) is routinely invasively monitored by an arterial catheter in the intensive care unit (ICU). However, the available data comparing the accuracy of noninvasive methods to arterial catheters for measuring BP in the ICU are limited by small numbers and diverse methodologies. **Purpose:** To determine agreement between invasive arterial blood pressure monitoring (IABP) and noninvasive blood pressure (NIBP) in critically ill patients. **Methods:** This was a single center, observational study of critical ill adults in a tertiary care facility evaluating agreement (≤10% difference) between simultaneously measured IABP and NIBP. We measured clinical features at time of BP measurement inclusive of patient demographics, laboratory data, severity of illness, specific interventions (mechanical ventilation and dialysis), and vasopressor dose to identify particular clinical scenarios in which measurement agreement is more or less likely. **Results:** Of the 1852 critically ill adults with simultaneous IABP and NIBP readings, there was a median difference of 6 mm Hg in mean arterial pressure (MAP), interquartile range (1-12), $P < .01$. A logistic regression analysis identified 5 independent predictors of measurement discrepancy: increasing doses of norepinephrine (adjusted odds ratio [aOR] 1.10 [95% confidence interval, CI 1.08-1.12] $P = .03$ for every change in 5 µg/min), lower MAP value (aOR 0.98 [0.98-0.99] $P < .01$ for every change in 1 mm Hg), higher body mass index (aOR 1.04 [1.01-1.09] $P = .01$ for an increase in 1), increased patient age (aOR 1.31 [1.30-1.37] $P < .01$ for every 10 years), and radial arterial line location (aOR 1.74 [1.16-2.47] $P = .04$). **Conclusions:** There was broad agreement between IABP and NIBP in critically ill patients over a range of BPs and severity of illness. Several variables are associated with measurement discrepancy; however, their predictive capacity is modest. This may guide future study into which patients may specifically benefit from an arterial catheter.

Keywords
vascular access devices, hemodynamic monitoring, blood pressure, shock

Introduction

Sepsis is the leading cause of death in hospitalized patients in the United States,[1] and causes approximately one-fifth of all deaths worldwide.[2] Hypotension is the defining feature of septic shock and initial therapeutic efforts are targeted towards normalizing blood pressure (BP) to improve organ perfusion and prevent tissue ischemia. In the last 20 years, successful efforts to manage sepsis-induced hypotension have focused on interventions in the early phases of severe illness, in particular timely diagnosis,[3,4] prompt administration of antibiotics,[5] and appropriate intravenous fluid administration.[6] Over that same time period, there has been a progressive deemphasis on invasive physiological monitoring, such as basing therapeutic decisions on central venous pressure[7] or central venous oxygen saturation.[8] However, clinicians still routinely invasively monitor BP with arterial lines instead of utilizing less invasive methods such as sphygmomanometers with a BP cuff.[9] Currently, the Surviving Sepsis guidelines recommend invasive arterial blood pressure monitoring (IABP) over noninvasive blood pressure monitoring (NIBP) in adults with septic shock—however, this is a weak recommendation based on very low-quality evidence.[6]

The available data comparing the accuracy of noninvasive methods compared to arterial catheters for measuring BP in the intensive care unit (ICU) are limited by small numbers and diverse methodologies.[10–14] The largest analysis comparing IABP and NIBP in critically ill patients included 736 patients

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and found a mean difference of 1.0 mm Hg (±10.2), which was not statistically significant—however, there was only one measurement done per patient.[12] Others have had fewer than 300 patients,[10,11,14] similarly only one or a few spot measurements, and different definitions of measurement agreement.[13–15]

Studies examining clinical outcomes have not identified an advantage to invasive BP monitoring. For example, Hsu et al found no mortality difference among propensity matched pairs with and without arterial catheters; however, all of these patients were hemodynamically stable and were being managed for respiratory failure.[16] There has not been a formal prospective comparison managing hypotensive critically ill patients without arterial lines.

Indwelling arterial lines have multiple disadvantages and in fact may cause harm and delay care. First, they require specialized training for placement and monitoring that is not universally available, especially in resource poor settings. They are painful for the patient potentially requiring systemic sedation to place and maintain, limit movement and participation in physical therapy, and risk digital ischemia. Additionally, the generally accepted belief that brisk arterial blood flow protects arterial lines from causing bloodstream infections has been challenged. In fact, an analysis of 2095 patients with arterial and/or central venous catheters in which the lines were cultured found no significant difference in rates of bacterial colonization or catheter-related infection ($P = .80$).[17]

Therefore, our goal is to identify the agreement between NIBP measurements in comparison to IABP in critically ill patients over the duration of their course. We additionally attempt to identify patient-level factors that predict agreement or lack thereof to identify those who may specifically benefit from arterial line placement.

Methods

This is a retrospective observational study involving patients in the medical ICU (MICU) at MedStar Georgetown University Hospital, an inner-city tertiary care facility. Approximately 50% of the patients are either directly admitted from the emergency room or are internal upgrades, while the remaining 50% come from external facilities as transfers. Their medical conditions skew toward cancer, strokes, and pre- / post- visceral organ transplant with a smaller proportion of cardiac patients, reflecting services provided by the hospital. All patients are staffed by pulmonary critical care trained intensivists.

The Institutional Review Board of Georgetown University Medical Center (approval number STUDY00004907, title: “Noninvasive blood pressure monitoring vs invasive arterial pressure monitoring in intensive care patients” on August 15, 2022) approved the protocol. All procedures followed were in accordance with the Helsinki Declaration of 1975. Informed consent was waived. The study involved minimal risk to subjects because it was a retrospective review of de-identified data for adult subjects that were already collected.

The study population included all consecutive patients admitted to the MICU from April 2019 to July 1, 2021, if an arterial catheter was placed and at least one BP measurement was taken from the arterial line along with a simultaneous measurement made noninvasively. All instances of simultaneous BP measurements for a patient during their hospitalization were recorded as pairs. ICU patients with arterial lines have BP measurements taken every hour, and in many cases the cuff is left in place with BP measurements also recorded hourly. We elected to only include simultaneous measurements as pairs (as opposed to allowing for any time lapse) given the dynamic and rapidly changing nature of BP in ICU patients. The primary outcome is the agreement of the mean arterial pressure (MAP) between the 2 methods.

We defined measurement agreement as a difference of ≤10% in simultaneously recorded IABP and NIBP pairs. While prior studies have defined 10 mm Hg as a clinically important difference in BP,[11,18] for critically ill patients, smaller differences in BP may be considered clinically important. For example, if the IABP MAP is 60 mm Hg and the NIBP recording is 67 mm Hg, using an absolute value cutoff of 10 mm Hg would classify those measurements as concordant. However, in clinical practice, the 60 mm Hg versus 67 mm Hg might result in titration of vasopressors.[6] Similarly, at higher BP values, a reading of 120 mm Hg versus 131 mm Hg would trigger an absolute value cutoff, even though in most clinical situations that difference would not impact management. Therefore, we believe the 10% difference more accurately reflects clinically important differences in this population.

In order to determine if there were patient features that predicted discrepancy, we recorded variables *at the time of BP measurement* potentially related to measurement difference based on biologic plausibility and prior data.[10–14] These include patient demographics, whether or not the patient was mechanically ventilated or on continuous renal replacement therapy, patient severity of illness as measured by the Sequential Organ Failure Assessment (SOFA) score,[19] specific laboratory data (WBC, lactate, creatinine), the dose of norepinephrine (NE), site (femoral vs radial) of the arterial line, and its age (in days). The SOFA score was recorded the day of the BP measurements in all patients. The most proximate WBC and creatinine were recorded if available within 12 h (and lactate within 4 h) of the measurement.

Data were obtained directly from the health system’s clinical data warehouse. Summary statistics describe the frequency of each categorical variable and either mean (for normally distributed) or median (for non-normally distributed) of continuous variables. In a comparison between patient features at the time of a concordant versus discrepant measurement, continuous data were compared via the Student *t* test and Wilcoxon rank sum test for normally and non-normally distributed data, respectively. Categorical data were analyzed with a χ^2 test. For the purposes of predictive modeling, we considered the measurement pair (rather than patient) to be the level of interest in regression modeling using a 10% difference in BP as the outcome variable.

Candidate predictor variables had statistically significant univariate associations. To account for within-patient associations due to the multiple observations for each patient, associations between BP deviation and patient variables were examined on at the measurement level for each patient using generalized estimation equations for panel data (xtgee in Stata; family: binomial; link function: logit, exchangeable correlation structure) that allowed robust standard errors.

Data extraction, cleaning, and preprocessing were performed in R, and analysis using Python v3.9.

Results

Patient Characteristics

Over the study period (April 2019-July 2021) there were 1852 critically ill patients with simultaneous IABP and NIBP measurements. Demographic features and diagnoses are described in Table 1. The group was 43% female, 46% Black; the majority had at least one comorbidity including diabetes (37%) and obesity (34%). Per *ICD-10* coding, respiratory failure (34%), sepsis (23%), and primary CNS disease (eg, stroke) [18%] were the 3 most common admission diagnoses.

The arterial lines were predominantly radial (Table 1) and remained in place for a median of 2.5 (0.9-6.8) days. There were 53,286 simultaneous IABP and NIBP measurements among the 1852 patients—however, we only considered measurements within 30 mm Hg of each other, given the high likelihood of an erroneous measurement at this BP difference or greater. This left 52,717 pairs for a median of 13 (5-30) per patient. 42,184 of the comparisons were made between a radial line and a cuff, 6768 with a femoral line and 3765 with a brachial, axillary, or dorsalis pedis line.

Table 1. Patient Characteristics.[a]

	Total (n = 1852)
Age, median (IQR)	63 (53-72)
Female, n (%)	802 (43)
Measurements, median (IQR)	
Height, cm	170 (163-179)
Weight, kg	79 (65-96)
BMI	27 (23-32)
Morbidly obese (BMI > 40), n (%)	145 (8)
Race, n (%)	
Black or African American	855 (46)
White	718 (39)
Other	177 (10)
Unknown	102 (6)
Comorbidities, n (%)	
Hypertension	1130 (61)
Diabetes mellitus	704 (38)
Chronic kidney disease	407 (22)
Coronary artery disease	241 (13)
Cancer	537 (29)
Cirrhosis	278 (15)
Organ transplant	74 (4)
HIV	20 (2)
Location of line, n (%)	
Radial	1498 (81)
Femoral	198 (11)
Other	156 (8)

Abbreviations: BMI, body mass index; IQR, interquartile range.
[a]Other lines include brachial, axillary, and dorsalis pedis.

Table 2 describes the clinical features of the patients at the time of a simultaneous IABP / NIBP measurement. Fifty-four percent were mechanically ventilated, 19% on continuous renal replacement therapy, 36% of patients were on NE, and the median admitting SOFA score was 8, interquartile range (5-13).

Measurement Agreement

The median IABP MAP value was 77 (68-90) and NIBP 84 (76-95) for a difference of 6 (1-12) mmHg ($P < .01$). Systolic and diastolic BP concordance are shown in Table 2. Using a 10% difference in MAP as a cutoff, 67% of the measurements were in agreement. Figure 1 visually demonstrates the agreement in MAP values as a Bland-Altman plot; 7.2% of the measurement pairs were identical, 36.8% are within 5%, roughly one-quarter of the patients (23.2%) had no discrepant measurements. For those with at least 10 measurement pairs, 79% had at least one discrepant comparison. The measurement discrepancy between IABP and NIBP MAP for radial lines alone (representing 81% of lines and 85% of the measurements) was 7 mm Hg (1-13).

Relevant clinical characteristics of the patients at the time of the measurement comparison are shown in Table 2. Notably, measurement discrepancy was associated with parameters that would suggest a slightly greater severity of illness: the median NE dose was higher (9 [3-11] vs 6 [3-8]) and a greater proportion of individuals were mechanically ventilated (61% vs 56%) and on continuous renal replacement therapy (22% vs 15%)—though these differences are small.

In order to further explore these observations, we generated a logistic regression model using a 10% difference in IABP and NIBP MAP values as the dependent variable inclusive of all covariates in Table 2 as candidate predictors. *ICD-10* diagnoses were excluded due to their inherent inaccuracy.[20,21] After this multivariate adjustment, 5 variables remained independent predictors of measurement discrepancy: increasing doses of NE (adjusted odds ratio [aOR] 1.10 [95% confidence interval 1.08-1.12] $P = .03$ for every change in 5 µg/min), lower MAP value (aOR 0.98 [0.98-0.99] $P < .01$ for every change in 1 mm Hg), higher body mass index (BMI) (aOR 1.04 [1.01-1.09] $P = .01$ for an increase in 1), increased patient age (aOR 1.31 [1.30-1.37] $P < .01$ for every 10 years), and radial arterial line location (aOR 1.74 [1.16-2.47] $P = .04$) (Figure 2). At MAP cutoffs of 55 mm Hg or less, 65 to 75 mm Hg, and >75 mm Hg, 62%, 67% and 71% of measurements are concordant, respectively.

Notably, if we instead defined agreement using an absolute value cutoff of 10 mm Hg, 73% of the measurements would be in agreement with the same 5 variables predicting discrepancy (not shown). In a univariate analysis, there is an association between initial measurement disagreement and future

Table 2. Clinical Features That Predict Discrepancy.[a]

	Total (n = 52,717)	Concordant (n = 33,739)	Discrepant (n = 18,978)
BP mm Hg, (Systolic / Diastolic, MAP), mean			
IABP	122 / 60, 80	126 / 64, 86	117 / 55, 74
NIBP	121 / 65, 86	119 / 66, 86	121 / 64. 86
Age, median (IQR)	63 (53-71)	62 (52-70)	65 (55-73)
Female, n (%)	21,357 (41)	43%	38%
BMI	27 (23-32)	26 (22-32)	28 (23-33)
Race, n (%)			
Black or African American	26890 (51)	49%	53%
White	18487 (35)	36%	34%
Other	6427 (12)	13%	11%
Unknown	913 (2)	2%	2%
Mechanical ventilation, n (%)	30812 (58)	56%	61%
Dialysis, n (%)	9787 (19)	15%	22%
Laboratory data, median (SD)			
WBC (10^3/μL)	11.9 (8.3-17)	11.7 (8.1-16.6)	12.1 (8.5-17.6)
Lactate (mmol/L)	1.2 (0.7-1.9)	1.1 (0.7-1.8)	1.3 (0.8-2.0)
Creatinine (mg/dL)	1.1 (0.7-2.3)	1.0 (0.7-2.0)	1.2 (0.8-2.5)
Norepinephrine μg/min, median (IQR)	7 (2-9)	6 (1-8)	9 (3-11)
SOFA, median (IQR)	8 (5-12)	8 (4-11)	9 (6-13)
Arterial line location, n (%)			
Radial	45075 (85)	82%	88%
Femoral	5641 (11)	14%	8%
Other	2001 (4)	4%	4%
Arterial line age hours, median (IQR)	4 (1.2-8)	4 (1-8)	4 (1.5-8)

Abbreviations: IABP, invasive arterial blood pressure monitoring; NIBP, noninvasive blood pressure; MAP, mean arterial pressure; BMI, body mass index; SOFA, Sequential Organ Failure Assessment; IQR, interquartile range.
[a]Presented here are mean BPs, noted as mean SBP / mean DBP, mean MAP. Clinical features most proximate to a simultaneous IABP and NIBP measurement were then analyzed—including SOFA score for that day, WBC/Creatinine level within 12 h, lactate within 4 h, and present Norepinephrine dose. All comparisons between Concordant and Discrepant measurements are statistically significant ($P < .01$).

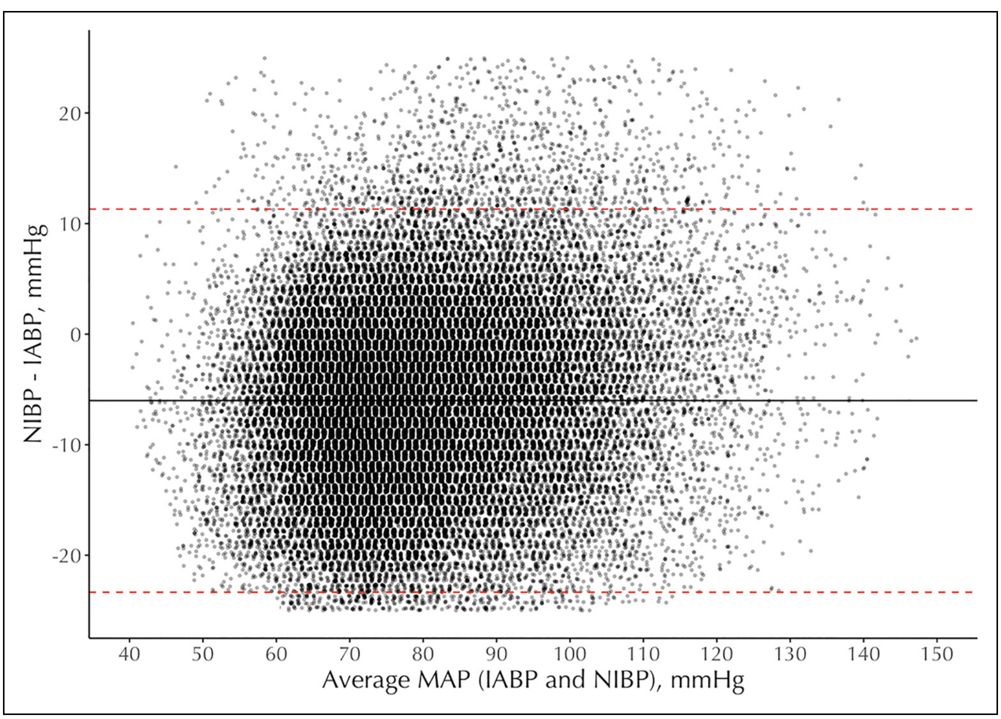

Figure 1. Bland-Altman plot of invasive arterial blood pressure monitoring (IABP) and noninvasive blood pressure (NIBP) agreement in measurement of mean arterial pressure (MAP). This demonstrates a bias of −6 mm Hg (IABP vs NIBP, MAP) and 95% limits of agreement of −23 to 11 mm Hg.

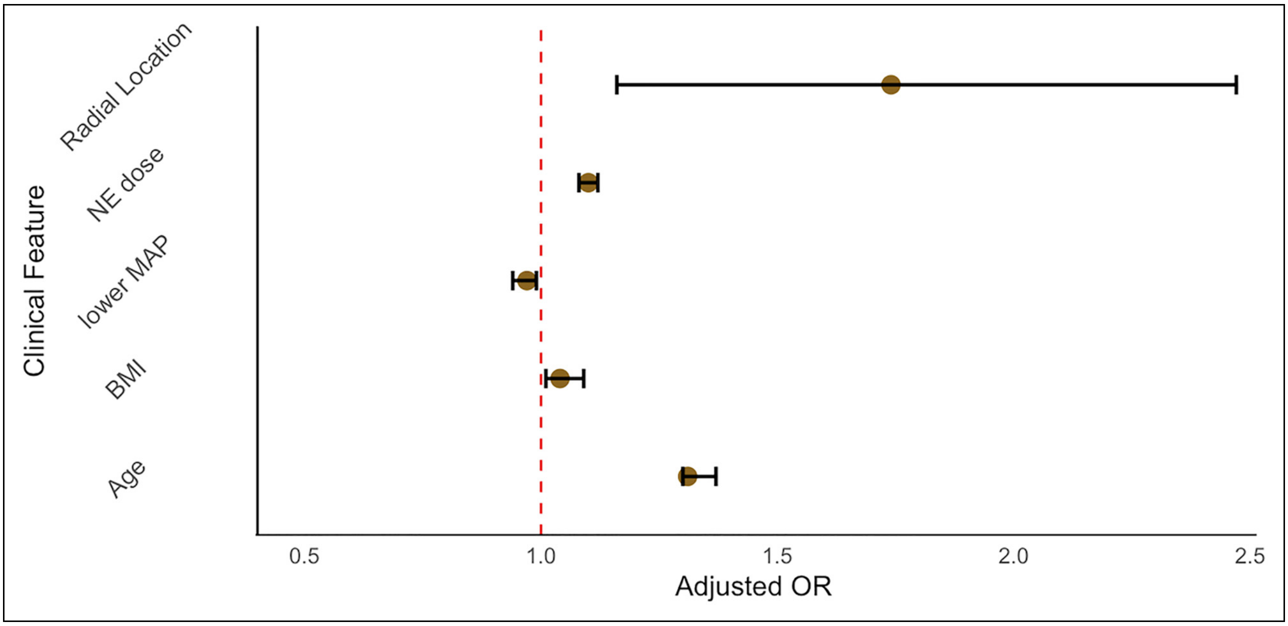

Figure 2. A logistic regression model using a 10% difference in invasive arterial blood pressure monitoring (IABP) and noninvasive blood pressure (NIBP) mean arterial pressure (MAP) values as the dependent variable identifies 5 independent predictors of measurement discrepancy, with adjusted odds ratio (aOR) shown above.

disagreement: 70% future agreement if the first measurement agrees versus 61% if it doesn't ($P = .01$). However, after multivariate adjustment inclusive of the covariates considered above performed on subsequent measurements (ie, excluding the initial one), it is not an independent predictor of measurement disagreement.

Discussion

In this extensive real-world observational examination of a medically and demographically diverse critically ill cohort, we found agreement in the majority of simultaneous noninvasive (cuff, NIBP) and arterial line (IABP) BP measurements across a range of BP and severity of illness. While patients with multiple simultaneous measurements often had at least one discrepant measurement, roughly one-quarter had none at all. The median difference of 6 mm Hg in MAP we identified is similar to other published papers which have generally also shown small differences in BP measurements between the 2 approaches.[11,12] The difference is driven by a lower arterial line diastolic BP—a finding previously described,[22] but of unclear overall significance particularly in regard to tissue perfusion.[14]

We identified 5 variables independently predictive of IABP and NIBP disagreement: higher doses of NE, lower MAP value, higher BMI, increased patient age, and radial arterial line location (Figure 2). These trends align with typical clinical expectations as they are scenarios believed to compromise the accuracy of cuff BP measurements.[14,23] The radial artery and catheter are narrower in diameter than their femoral counterparts which may in part explain more divergent measurements; however, it is worth nothing the majority of measurements were made with radial catheters. Importantly, while these variables are statistically significant predictors in a regression model, the adjusted odds ratios are low indicating only modest ability of these factors to predict measurement disagreement. The statistical significance is driven in part by the large sample size.

Notably, the SOFA score (an integrative metric of patient severity of illness) was *not* predictive of measurement disagreement; specifically, there was similar IABP and NIBP agreement across a wide range of SOFA scores (ranging 1-24 in this cohort). This may be counterintuitive for clinicians who might generally expect invasive BP readings to be more accurate in patients who are more ill. Potentially, this provides preliminary rationale for further investigation into protocols that limit the use of arterial lines. For patients in whom readings are more likely to be concordant, NIBP alone may be sufficient. This is particularly important since arterial lines are associated with pain, digital ischemia, infection, limited mobility, and can potentially increase the total sedation required.

To our knowledge, this is the largest evaluation of agreement between NIBP and IABP in critically ill patients to date, inclusive of over 50,000 BP measurements spanning over 1800 patients. An oft cited recent study includes a total of 736 BP measurements (one per patient), whereas our analysis includes a median of 13 measurements per patient.[12] Furthermore, this represents the most comprehensive investigation of clinical scenarios where disparities between NIBP and IABP measurements could arise. In pursuit of this, we focused on clinical factors (such as laboratory results, vasopressor dosages, and SOFA scores among others) concurrent with the BP reading, rather than initial patient characteristics acknowledging the swiftly changing and dynamic course of critically ill patients. Additionally, unlike prior studies which omitted patients who were mechanically ventilated or on vasopressors we included patients reflective of a typical ICU population (with a high prevalence of vasopressor use, mechanical ventilation, and renal replacement therapy) in who arterial lines are considered.

There are several limitations. First, this is single center and retrospective. However, the studied population is derived from a tertiary academic center, spans over 2 years, is racially diverse and is inclusive of a wide range of presenting illnesses (albeit, with limited numbers of cardiac patients). Secondly, the decision to obtain a simultaneous measurement of NIBP and IABP was based on clinician or nursing preference and not protocolized. That is, with a functional arterial line, there is no requirement to continue to regularly check NIBP. This is a potential confounder, as it is possible that patients with more discrepant readings had NIBP checked more frequently. Additionally, the arterial lines were placed for different reasons and provide additional clinical utility beyond BP monitoring (eg, arterial blood gases, the need for frequent blood tests, continuous BP monitoring during procedures, or rapid changes in clinical status) since patients had a variety of presenting illnesses and we did not restrict the population to just those in shock. However, irrespective of the reason for placement arterial lines are ultimately used to monitor BP and we elected to include all patients to have as many measurements as possible. Fourth, while some patients were on multiple vasopressors, we elected to only evaluate the dose of NE. However, NE is by far the most commonly used vasopressor. Finally, measurement discrepancy is an intermediate outcome.

Conclusions

In the MICU, there is broad agreement between invasive and NIBP measurements across a wide range of BP values and patient severity of illness. This provides preliminary rationale for further research into protocols limiting the use of arterial lines for the purposes of BP monitoring.

Declaration of Conflicting Interests

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