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RESEARCH

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Prediction of the ideal length of insertion to monitor left atrial pressures in pediatric open-heart surgery: a retrospective cohort study

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Abstract

Background Monitoring the left atrial pressures (LAP) is an important perioperative management tool for maintaining adequate cardiac output. However, incorrect placement of the LAP-monitoring catheter tip often leads to inherent risk. This study aimed to evaluate the length of the LAP catheter in pediatric open-heart surgery and devise a simple formula to predict the ideal length of insertion based on correlated demographic and clinical characteristics.

Methods We conducted a retrospective clinical cohort study involving 79 infant patients aged ≤ 1 year who underwent open-heart surgery and right internal jugular vein (RIJV) catheterization to monitor the LAP. Pearson correlation coefficient and multiple regression analysis were employed to determine the association between the optimal depth and patient characteristics. In the variable selection stage, Least Absolute Shrinkage and Selection Operator (LASSO) regression was utilized to select the most valuable variables as candidates for subsequent multiple regression analysis. Then a simple formula was derived to predict the ideal depth for the LAP measurement.

Results The participants consisted of 50 (63.3%) males and 29 (36.7%) females. Among them, 10 patients (12.7%) were preterm. The average age was 4.4 months; the average weight was 5.5 kg, and the average height was 60.5 cm. Height, body surface area (BSA), weight, age, and head circumference were strongly associated with the ideal length of the catheter. In the LASSO regression analysis, height and weight had the highest correlation coefficients. In the multiple regression model, only height showed a significant effect ($P < 0.001$). Consequently, we developed a new height-based formula: L (cm) = 5 + 0.1 × height (cm). The proportion of optimal depth determined by the new simplified formula was 88.6%.

Conclusions Height was identified as the most significant individual predictor of ideal length in this study. The newly developed formula, L = 5.0 + 0.1 × height (cm), is feasible and can be utilized to determine the optimal depth of the catheter to monitor the LAP via RIJV during pediatric open-heart surgery.

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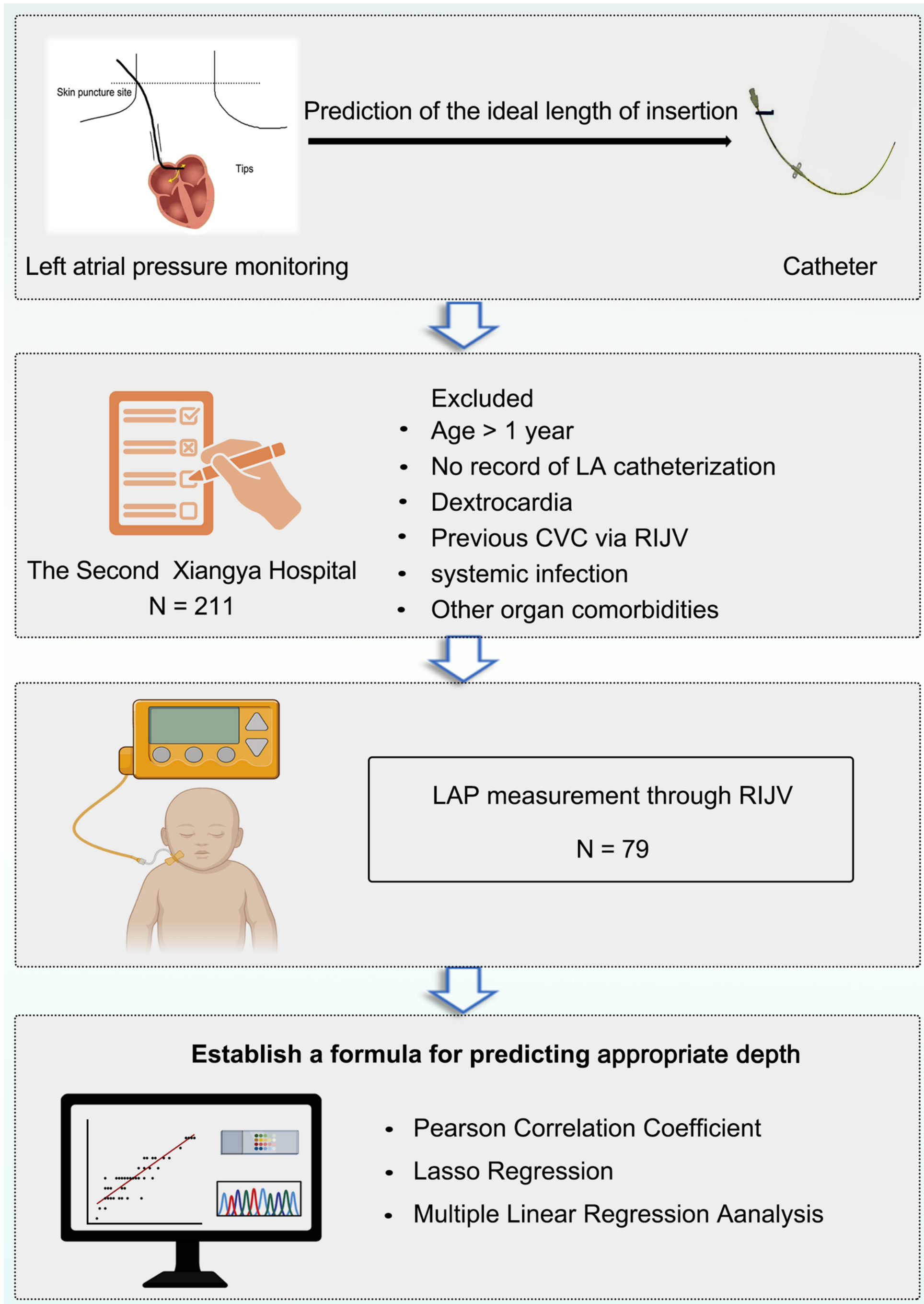
Graphical abstract



Keywords Pediatrics, Left atrial pressure, Right internal jugular vein, Ideal length, Formula, Height

Background

The primary goal of perioperative care in patients undergoing open-heart surgery is to maintain an optimal cardiac output. The output of the left side of the heart is related to the left atrial pressure (LAP), which reflects left ventricular filling [1]. Thus, monitoring the LAP during the intraoperative period following separation from cardiopulmonary bypass and postoperative phase is beneficial for congenital cardiac surgery and critical care management [2]. Recent research has shown that a new method for monitoring the LAP, in which the catheter is placed in the internal jugular vein, passed into the superior vena cava and right atrium (RA), and then placed in the left atrium (LA) by the surgeon, can potentially eliminate the risk of cardiac tamponade and displacement compared to transthoracic catheters [3]. However, the appropriateness of the catheter location cannot be determined until the heart is opened, and incorrect placement of the LAP-monitoring catheter tip often poses an inherent risk. Therefore, predicting and calculating the ideal length of insertion for LAP monitoring via internal jugular vein catheterization prior to the procedure is crucial from a clinical perspective. This ensures that the catheter is placed in one step, thereby reducing the need for time-consuming repositioning procedures and preventing of serious complications due to improper placement of the catheter tip, especially in infants. Furthermore, it provides suitable depth references in patients who need LAP monitoring via the internal jugular vein but do not require sternotomy [4].

The optimal catheter insertion length for central venous catheters via the right internal jugular vein (RIJV) in children has been previously identified [5–7]. However, no studies have investigated the association between the demographic and clinical characteristics and the length of insertion for assessing the LAP along the same route.

Therefore, this study aimed to examine the relationship between the demographic and clinical characteristics including age, sex, height, weight, body mass index (BMI), body surface area (BSA), head circumference, anterior fontanelle size, gestational age at birth, caesarean delivery, multiple pregnancies and RA diameter, and the ideal length for catheterization. The parameter most strongly associated was selected to develop a novel formula for predicting and determining the depth of insertion through the RIJV in infants. Another goal of this study was to validate the accuracy of the new formula to make it more suitable for clinical applications.

Methods

Ethical approval

The study was approved by the Research Ethics Committee of the Second Xiangya Hospital, Central South University, Changsha, China (LYF2023108). All parents of the patients participating in this study voluntarily signed the informed consent.

Patients and data sources

Graphical Abstract shows the flowchart of the workflow used in this study. This study enrolled pediatric patients aged ≤ 1 year, who underwent open-heart surgery and LAP measurement via RIJV catheterization at the Second Xiangya Hospital of Central South University from May 2022 to November 2023. The open-heart surgery included complete repair of Tetralogy of Fallot, ventricular septal defect, right ventricular double outlet, aortic correction, arterial catheter ligation and other procedures. The exclusion criteria were as follows: (1) age > 1 year; (2) no record of LA catheterization; (3) dextrocardia; (4) previous central venous catheterization via the RIJV; and (5) systemic infection or other organ comorbidities.

Patients were inclined to the left while concurrently lowering their head down, with a rolled towel place transversely under the shoulder and rotated to facilitate the exposure of the puncture site. The insertion point was selected as the midpoint between the tip of the mastoid and the clavicular insertion of the sternocleidomastoid [8]. After marking the puncture spot, povidone iodine was applied three times for skin preparation. In addition, sterile barriers, including masks and caps, and sterile gowns, and gloves were donned. The length of the single lumen LA catheters of approximate diameter 0.91 mm (ARROWgard Blue, Arrow International, Reading, PA) was 13 cm and fixed to the skin with a purse-string suture [9]. After the catheterization was completed, the surface of the catheter was covered with a sterile dressing. We specified the tool utilized for measuring the catheter length: a standard measuring tape accurately calibrated in millimeters. Additionally, we ensured that the measuring instrument remained straight and free from twists during the measurement process. To avoid cross-infection, a line was inserted into the RIJV for LAP monitoring and a catheter into the femoral vein for central venous pressure monitoring and inotrope administration. All catheterizations were performed by two experienced anesthesiologists under the guidance of a portable sonography machine (GE Logiq E, Milwaukee, WI) with a 5–10-MHz linear-array transducer and a sterile sleeve was draped over ultrasound probe after the induction of general anesthesia to enhance the procedure's efficacy and reduce the risk of complications [10]. All patients underwent visual confirmation of LA pressure curves immediately after the catheters reached the calculated insertion depth and postoperative X - radiography upon their arrival at the intensive care unit (ICU).

Through a retrospective review of each child's medical records, we retrieved information on the age, sex, height, weight, BMI, BSA, head circumference, anterior fontanelle size, gestational age at birth, cesarean delivery, multiple pregnancies, and RA diameter. The parents or guardians of the patients provided written informed consent prior to the procedure.

Calculation of the ideal length of insertion

In our standard practice, the actual length of the LAP-monitoring catheter inserted is recorded in the medical charts. The anesthesiologist then records the measured length of insertion as the surgeon cut the catheter shorter to allow leave approximately 1 cm of the catheter tip in LA during the transatrial surgical procedure after repairing the primary defect. And the surgeons sutured the interatrial septum around the line purse string approach so that no residual atrial septal defect (ASD) would be remain after the line was removed. The distance between the length of the original catheter and the cut length was determined as the ideal length of insertion. Specifically, it is the depth at which the catheter can effectively perform monitoring without causing issues like tissue damage. The acceptable difference between the actual depth of insertion and expected calculated by formula was established as less than or equal to 0.5 cm for the optimal depth [11].

Statistical analysis

Pearson correlation analysis was employed to explore the relationships between the ideal length and the age, sex, height, weight, BMI, BSA, head circumference, anterior fontanelle size, gestational age at birth, caesarean delivery, multiple pregnancies and RA diameter. The correlation was quantified by the R-value. Specifically, an R - value less than 0.4 indicated a weak correlation; an R - value between 0.4 (inclusive) and 0.7 signified a moderate correlation; and an R - value of 0.7 or greater denoted a strong correlation. To avoid collinearity issues between clinical characteristics and insertion depth, we utilized LASSO regression with ten-fold cross-validation to perform variable shrinkage and selection among the 13 variables. The number of variables included in the final model was determined based on the corresponding position of lambda.1SE. Then we generated three-dimensional scatter plots to visualize the optimal depth versus the significant variables, and the best relevant parameter was derived by Multiple linear regression. Thereafter, a new formula was established.

The Bland–Altman analysis was used to validate the consistency between the results of predicted and true length by calculating the mean difference and 95% limits of agreement (LOA) [12, 13]. Bias was evaluated by calculating the mean absolute percentage error (MAPE) and mean absolute error (MAE) for the new formula. The root mean square error (RMSE) was calculated to evaluate the precision of the new formula. The smaller the MAPE, MAE, and RMSE values, the more accurate the prediction of the intubation length. All statistical analyses were conducted using Statistical Package for the Social Sciences (SPSS Windows version 11.0; SPSS Inc., Chicago, IL) and LASSO regression for variable shrinkage and selection was conducted using R 4.0.5 [14]. The visualization of the data was accomplished by Python (version 3.11.5), R 4.0.5 and GraphPad Prism (version 8.0.2). P-values < 0.05 were regarded as statistically significant.

Table 1 Demographic and clinical characteristics

Characteristics	Total
Number of enrolled patients	79
Age (month)	4.4 ± 3.9 (3.5–5.3)
Male (%)	50 (63.3%)
Height (cm)	60.5 ± 9.3 (58.4–62.6)
Weight (kg)	5.5 ± 2.2(5.0-5.9)
BMI (kg/m^2)	14.4 ± 2.1 (14.0-14.9)
BSA (m^2)	0.3 ± 0.1 (0.2–0.3)
Prematurity (%)	10 (12.7%)
Caesarean delivery	35 (44.3%)
RA diameter (mm)	18.5 ± 3.8 (17.6–19.3)
Gestational age at birth	$38^{+3}(33^{+3}-40^{+5})$
Anterior fontanelle size (cm^2)	2.1 ± 2.0 (1.6–2.5)
Multiple pregnancies	5 (6.33%)
Head circumference	38.1 ± 4.3 (37.1–39.0)
Length of catheterization	11.0 ± 1.0 (10.0–12.0)
Diseases	
Tetralogy of Fallot	17 (21.5%)
Ventricular septal defect	15 (19.0%)
Double-outlet right ventricle	14 (17.7%)
Aortic disease	12 (15.2%)
Pulmonary atresia	9 (11.4%)
Anomalous pulmonary venous drainage	5 (6.3%)
Patent ductus arteriosus	3 (3.8%)
Others	4 (5.1%)

Data are presented as mean ± standard deviation or (range) or numbers

Results

Demographic and clinical characteristics of patients

This study enrolled 79 patients, consisting of 50 males (63.3%) and 29 females (36.7%). The patients' ages ranged from 3 days to 1 year. Among them, 69 (87.3%) were full - term, while 10 (12.7%) were preterm. The mean weight was 5.5 kg (range: 2.5–10.5 kg), and the mean height was 60.5 cm (range: 47–82 cm). Table 1 presents the demographics and clinical characteristics of all the patients.

Correlation analysis of the ideal length of insertion and clinical parameters

Pearson correlation analysis was conducted to identify the variable with the strongest correlation that could predict the length of catheterization via the right internal jugular vein (RIJV) in infants. Height ($R = 0.931$, $P < 0.001$), body surface area (BSA) ($R = 0.928$, $P < 0.001$), weight ($R = 0.897$, $P < 0.001$), age ($R = 0.860$, $P < 0.001$), and head circumference ($R = 0.762$, $P < 0.001$) exhibited a strong correlation with the length. Right atrium (RA) diameter ($R = 0.576$, $P < 0.001$), anterior fontanelle size ($R = -0.548$, $P < 0.001$), and body mass index (BMI) ($R = 0.471$, $P = 0.001$) were moderately correlated with the depth. In contrast, sex ($R = 0.122$, $P = 0.538$), gestational age at birth ($R = -0.088$, $P = 0.224$), multiple pregnancies

($R = -0.103$, $P = 0.205$), and cesarean delivery ($R = -0.175$, $P = 0.178$) were not significantly correlated (Fig. 1; Table 2).

Clinical variables selection and model construction

After conducting LASSO regression with ten-fold cross-validation, the variables height and age were selected for inclusion based on the criteria of lambda.1SE. The pathways of variable shrinkage and cross-validation are indicated in Fig. 2A and B, respectively. The coefficients and three-dimensional spatial scattering distribution of height and weight are shown in Fig. 2C and D, respectively.

Subsequently, a multiple regression analysis was performed for the strongly correlated clinical parameters (height and weight) and ideal length of the catheter, as shown in detail Supplementary Table 1. Based on the regression analysis results, the height variable was chosen as the major parameter because it a greater difference compared to the other clinical parameters. Thus, the following height-based formula was established to predict the length of insertion (Fig. 3):

$$\text{Length (L)} = 5.102 + 0.0984 \times \text{height (cm)} \ (R^2 = 0.870, P < 0.001).$$

A simplified formula was developed after rounding off the intercepts and slopes as follows:

$$\text{(Newsimpleformula) L (cm)} = 5 + 0.1 \times \text{height (cm)}.$$

Validation of the prediction accuracy of the new formula

To validate the prediction accuracy of the new formula, we first used the Bland–Altman analysis to ensure that the results generated by the new formula were consistent with the ideal length. According to our data, the mean difference in the optimal depth values derived from the new formula was 0.008 cm (95% LOA, −0.856 to 0.703 cm). The absolute value of the difference was small when using the new formula. Furthermore, the new simple formula demonstrated low RMSE (0.294), MAPE (0.128), and MAE (0.157) values, as well as a high proportion of the acceptable depth of insertion of the retrospective cohort (88.6%), indicating that the optimal depth estimated by the new formula was accurate (Table 3). Based on these findings, we formulated simple and practical suggestions (Table 4). When our formula was applied to the current data, the ideal length of insertion through the RIJV was within this range in 76 patients (96.2%).

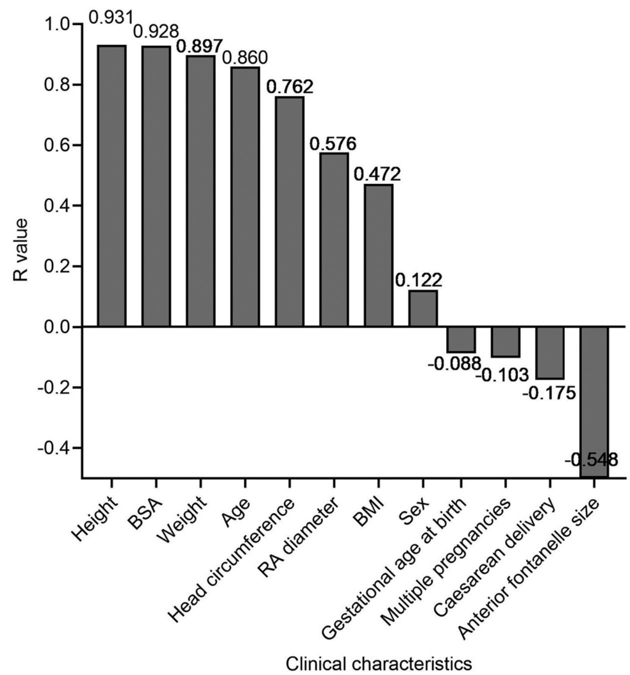


Fig. 1 Pearson correlation coefficient analysis of ideal length of catheter with growth parameters. Height had the highest corrected determination coefficient ($R = 0.932$), followed by BSA($R = 0.928$), weight ($R = 0.897$) and age ($R = 0.860$). BSA, body surface area; BMI, body mass index; RA, right atrium

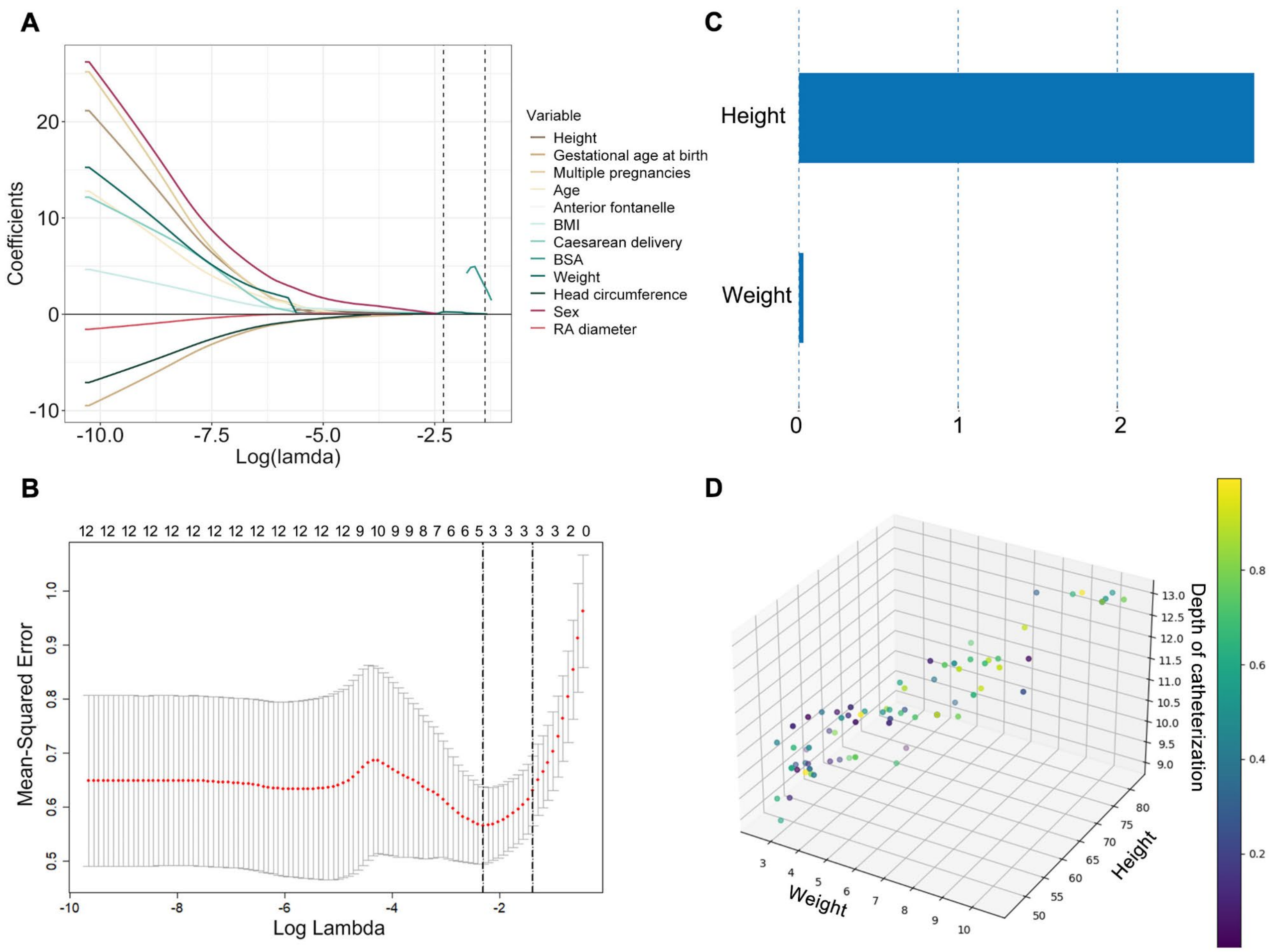
Table 2 Pearson correlation analysis

Factors	OD	
	R	P
Age	0.86	**< 0.001**
Sex	0.122	0.538
Height	0.931	**< 0.001**
Weight	0.897	**< 0.001**
BMI	0.471	**0.001**
BSA	0.928	**< 0.001**
Prematurity	-0.088	0.496
Caesarean delivery	-0.175	0.178
RA diameter	0.576	**< 0.001**
Head circumference	0.762	**< 0.001**
Anterior fontanelle size	-0.548	**< 0.001**
Birthweight	0.039	0.198
Multiple pregnancies	-0.103	0.205

OD: Optimal depth; Weak Correlation: $R < 0.4$;Moderate Correlation: $0.4 \leq R < 0.7 \leq$Strong Correlation: $R \geq 0.7$

Discussion

This is the first study to predict the ideal length of the catheter to monitor LAP via the RIJV in pediatric open-heart surgery based on significantly associated demographic and clinical characteristics. A series of analyses revealed that height was the best predictor of optimal depth, followed by weight. A new formula based on height was developed using linear regression analysis to predict the length of insertion in infants. When validating the prediction accuracy of the new formula, a simplified version of the new formula, L (cm) = 5 + 0.1 × height (cm), provided a more appropriate position for the catheter.



2.

Fig. 2 Variable shrinkage and selection using LASSO regression. (**A**) As the value of Log Lambda increases, the prediction error of the model increases simultaneously, while the number of independent variables decreases accordingly; (**B** Cross-validation LASSO (cv.LASSO) with ten folds for variables selection. Height and weight were selected for the optimal parameter using lambda.1SE for variable selection; (**C**-**D**) The predicted coefficients (**C**) and three-dimensional spatial scattering distribution of height and weight (**D**). LASSO: Least Absolute Shrinkage and Selection Operator; BSA, body surface area; BMI, body mass index; RA, right atrium

LAP has been recognized as one of the most critical parameters influencing the quality of life and potential deterioration or improvement of LA unloading [15]. If the LAP is too low, the anesthesiologist can administer fluids. Conversely, if the LAP is excessively high, regardless of whether the central venous pressure is high or low, the anesthesiologist should use a positive inotropic agent rather than increasing the fluid volume [16]. Multiple studies have demonstrated that real - time LAP hemodynamic data can be employed to reflect the variability of left ventricular filling pressures in patients undergoing procedures such as arterial switch surgery, common atrioventricular canal repair, and heart transplantation [17–20]. According to the available clinical research, monitoring LAP aids in the management of hemodynamic stability during the perioperative period of cardiac surgery, especially in pediatric patients. In our study, we also utilized effective LAP to assess fluid status and left heart function throughout the intraoperative period following separation from cardiopulmonary bypass and postoperative stages, allowing us to provide more specialized treatment to infants with double-outlet right ventricle or congenital aortic arch anomalies. Furthermore, continuous LA pressure monitoring is helpful in precisely adjusting the use of vasoactive medications, optimizing the dosage and titration of these medications to maintain hemodynamic stability.

In clinical practice, multiple approaches for LAP monitoring are utilized, with the invasive method of cardiac catheterization serving as the gold standard [21]. The typical approach of inserting a catheter into the RA via the RIJV has been employed to monitor the LAP. This method entails an inherent risk that can be mitigated using real-time ultrasonography guidance [22]. However,

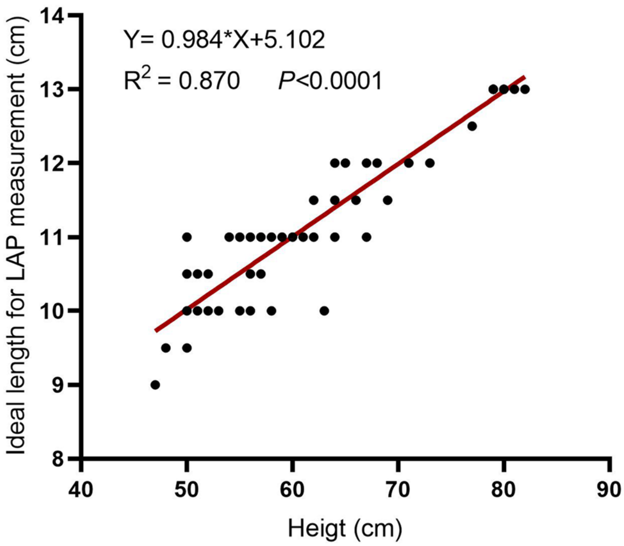


Fig. 3 Linear regression line between ideal catheter length and height. The line of regression showed: $R^2 = 0.870$, $Y = 0.098*X + 5.102$, $P < 0.001$. LAP: left atrial pressure

Table 3 The prediction accuracy of new formula

	New formula
MD (cm) (95% CI)	0.008
95% LOA (cm)	-0.856 to 0.702
RMSE	0.294
MAPE	0.128
MAE	0.157
Appropriate depth, n (%)	70 (88.6%)

MD: mean difference; LOA: limits of agreement; RMSE: root mean square error; MAPE: mean absolute percentage error; MAE: mean absolute error

Table 4 Suggested depth for LAP measurement through RIJV

Height (cm)	Depth of RIJV Catheterization (cm)
40–50	9–10
50–60	10–11
60–70	11–12
70–80	12–13

other issues must be considered, such as those related to the depth of catheter insertion, arrhythmias, clot formation, air embolism and cardiac tamponade [23, 24]. Arrhythmias were frequently present during catheterization procedures. Therefore, to avoid complications caused by inappropriate placement of the LAP-monitoring catheter tip, its location and depth should be correct both before and after the procedure. In infants requiring LAP monitoring via the RIJV but not sternotomy, the primary imaging methods used to verify the catheter position are chest radiography and echocardiography, which means that the tip misplacement may not be detected immediately, thus increasing the risk of adverse effects [25]. Furthermore, if the imaging reveals that the tip is misplaced, the catheter must be repositioned, and another inspection is required to confirm its position, thereby increasing the risk of infections or unnecessary radiation exposure for the patient.

Efforts have been made to create a formula to calculate the length of insertion of the central venous catheter via the RIJV, and numerous formulae, methods, and parameters, such as weight, height, age, sex, BMI, BSA, prematurity status and so on, have been investigated in the pediatric population [5, 8, 9]. In this study, considering that cardiac disease could influence the size of the left atrium (LA) and right atrium (RA), and thus the ideal length, the parameter of the RA diameter was incorporated. Additionally, Caesarean delivery and multiple pregnancy were also included in the analysis because they were potential factors reflecting the growth and development of fetuses. Specifically, in cases of multiple pregnancies, the intrauterine environment is shared among multiple fetuses. This situation can lead to differences in growth patterns, body proportions, and cardiovascular development when compared to singleton pregnancies. Ding and colleagues reported that the catheter length in the LA should not be too long, and its length is typically ranging from 1.5 to 2.0 cm; however, there is currently no available data regarding the length or appropriate location and its exact influencing factors are available [16]. Our findings clearly showed that height, and weight were significantly correlated with the depth of insertion. Height was chosen as the key parameter because its correlation was greater than that of the other demographic and clinical characteristics. For the convenience of calculation, the intercepts and slopes were rounded off to obtain a new simplified formula based on the height. Following further analysis, the simplified formula, $L (cm) = 5 + 0.1 \times height (cm)$, was found to be accurate in calculating the ideal length of catheter. Moreover, for LAP monitoring via the RIJV, we formulated simple and practical guidelines to determine the appropriate insertion position.

The reliable formula for predicting the length of insertion developed in this study may have clinical significance. Firstly, the predictive formula can serve as a preoperative planning tool. This allows the surgical team to prepare the necessary catheters of suitable lengths in advance, reducing the time spent during the operation on selecting the right catheter. Secondly, the formula can act as a supplementary reference during the intraoperative phase. Even though direct visualization is available, the formula can offer an additional layer of assurance. In complex cases where visual assessment might be challenging due to anatomical variations or other factors, the predicted catheter length can guide the surgeons. Moreover, in the long term, the predictive formula can contribute to the standardization of catheter length selection across different surgical teams within our institution.

By having a consistent method for predicting catheter length, we aim to reduce inter - operator variability and improve the overall quality and reproducibility of the surgical procedures. Finally, we also plan to explore the potential application of the predictive formula in training new surgeons. It can be used as an educational tool to teach trainees how different patient factors influence catheter length selection, helping them develop a better understanding of the underlying principles and improve their surgical skills more efficiently [4].

This study has several limitations. First, pediatric patients aged > 1 year were not enrolled; consequently, the new formula may be inadequate for this age group. Second, the new formula is restricted to the Asian ethnic groups, and we should also take into account individual patient variability despite the strong correlation shown by the formula. Additionally, the formula is designed to serve as a useful starting point or a supplementary tool for anesthesiologists and surgeons during the preoperative planning phase. It should not substitute for a thorough clinical assessment, which includes a detailed review of the patient's medical history, physical examination, and imaging studies. Finally, further evaluation of this algorithm in a broader population is required to support the current findings and to formulate more comprehensive and age - specific formula for predicting the ideal catheter length. Looking ahead, we plan to recruit a more diverse population encompassing varying levels of care (such as primary, secondary, and tertiary care facilities) to improve the generalizability of our research.

Conclusions

Our newly developed formula, $L\ (cm) = 5 + 0.1 \times height\ (cm)$, provides a rapid and straightforward method to calculate the appropriate depth for LAP monitoring via RIJV catheterization in pediatric patients.

Abbreviations

RIJV	Right internal jugular vein
LAP	Left atrial pressure
LASSO	Least Absolute Shrinkage and Selection Operator
RA	Right atrium
LA	Left atrium
ASD	Atrial septal defect
BMI	Body mass index
BSA	Body surface area
LOA	Limits of agreement
MAPE	Mean absolute percentage error
MAE	Mean absolute error
RMSE	Root mean square error

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12872-025-04616-9.

Supplementary Material 1

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Author contributions

YZ and XC had the idea for the article, ZW and HL performed the literature search and drafted the work, RD and SZ critically revised the work. All authors reviewed the manuscript. All author read and approved the final manuscript.

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Data availability

The datasets used and/or analyzed during the current study available from thecorresponding author on reasonable request. The raw SPSS fle of this studybefore analysis is available upon your request.

Declarations

Ethics approval and consent to participate

The study was approved by the Research Ethics Committee of the Second Xiangya Hospital, Central South University, Changsha, China (LYF2023108). All parents of the patients participating in this study voluntarily signed the informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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