Invasive Arterial BP Monitoring in Trauma and Critical Care*

Effect of Variable Transducer Level, Catheter Access, and Patient Position

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Objectives: (1) To determine the validity of current recommendations for direct arterial BP measurement that suggest that the transducer (zeroed to atmosphere) be placed level with the catheter access regardless of subject positioning; and (2) to investigate the effect of transducer level, catheter access site, and subject positioning on direct arterial BP measurement.

Design: Prospective, controlled laboratory study.

Setting: Large animal laboratory.

Subjects: Five Yorkshire pigs.

Interventions: Anesthetized animals had 16F catheters placed at three access sites: aortic root, femoral artery, and distal hind limb. Animals were placed in supine, reverse Trendelenburg 35°, and Trendelenburg 25° positions with a transducer placed level to each access site while in every position.

Measurements and main results: For each transducer level, five systolic and diastolic pressures were measured and used to calculate five corresponding mean arterial pressures (MAPs) at each access site. When transducers were at the aortic root, MAP corresponding to aortic root pressure was obtained in all positions regardless of catheter access site. When transducers were moved to the level of catheter access, as current recommendations suggest, significant errors in aortic MAP occurred in the reverse Trendelenburg position. The same trend for error was noted in the Trendelenburg position but did not reach statistical significance.

Conclusions: (1) Current recommendations that suggest placing the transducer at the level of catheter access regardless of patient position are invalid. Significant errors occur when subjects are in nonsupine positions. (2) Valid determination of direct arterial BP is dependent only on transducer placement at the level of the aortic root, and independent of catheter access site and patient position.

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Key words: arterial BP; catheter; critical care; invasive; monitoring; patient positioning; reverse Trendelenburg; supine; transducer level; trauma; Trendelenburg

Abbreviation: MAP = mean arterial pressure

Direct arterial BP monitoring is standard practice in a majority of trauma and critical-care patients and the most common invasive monitoring device used in the ICU.¹ This routine procedure may become problematic when patients are not in the supine position. In fact, increasingly aggressive positioning of these patients may introduce error into arterial pressures measured by this technique because of altered transducer and catheter locations. A surprising degree of controversy and confusion is evident in medical² and nursing journals³,⁴ and in critical-care texts⁵ regarding arterial BP measurement in nonstandard scenarios frequently encountered in trauma and critical care. Even among specialists, there is a persistent misunderstanding regarding the basics of how hydrostatic pressure influences measured pressures in a fluid-filled catheter system.⁶
Current standards of hemodynamic monitoring recommend zero reference point (a transducer zeroed to atmosphere) for all fluid-filled monitoring systems be placed level with the catheter tip to negate the effects of hydrostatic and atmospheric pressure. These guidelines further emphasize the relationship between transducer and catheter-tip location as the crucial factor in valid direct arterial BP measurement. We questioned the validity of this approach based on accepted physics principles and clinical experience with patients. We hypothesized instead that the transducer (zero-reference point) should always be placed level to the aortic root when measuring arterial BP, regardless of patient position or catheter-tip location, and that to do otherwise would introduce significant error. These experiments were conducted to test this hypothesis by studying the effect of three variables on direct arterial BP measurement: (1) transducer level (zero reference point), (2) catheter access site, and (3) patient position.

Materials and Methods

Yorkshire pigs (n = 5) weighing from 18 to 33 kg were preanesthetized with atropine, 0.05 mg/kg; acepromazine, 1.1 mg/kg; and ketamine, 22 mg/kg IM. Peripheral IV access was established, and sodium pentobarbital, 50 mg/mL, was administered to effect. Continuous anesthesia with sodium pentobarbital, 6 mg/kg/h, was delivered via an infusion pump (model 907; Harvard Apparatus; Holliston, MA), and pancuronium bromide was administered in a small bolus to maintain paralysis. Animals were then surgically prepared using a clean technique for hemodynamic and ventilatory monitoring. Surgical preparation included tracheal intubation via trachostomy, direct bladder catheterization, central venous cannulation of the internal jugular vein (7F triple lumen; Arrow International; Reading, PA) and 16F intra-arterial catheters (Cathlon; Johnson & Johnson; Arlington, TX) placed by cutdown in the right distal hind limb, left femoral artery, and the aortic root via the left carotid artery. Catheters were connected via identical lengths of tubing to three separate transducer/stopcock assemblies (Argon Model 049-992-000A; CB Sciences; Dover, TX) that were mounted on a movable platform (Cobe Cardiovascular; Arvada, CO) attached to an IV pole (Fig 1). Measurements were recorded on a recording and analysis system (PowerLab/16s; ADInstruments; Mountain View, CA) and computer (Dell Dimension XPS R400; Dell Computer; Round Rock, TX) [Fig 1]. Animals received ventilation (Amadeus FT; Hamilton Medical; Rháznins, Switzerland) at standard settings: tidal volume, 7 to 10 mL/kg, fraction of inspired oxygen, 0.50; and positive end-expiratory pressure, 5 mm Hg. Respiratory rate was titrated to keep minute volume near 4.0 L/min. Baseline arterial blood gases were measured (modelABL5; Radiometer; West Sussex, UK) to ensure normoxia at the beginning of each protocol.

Protocol

Prior to each experiment, the three transducers were separately zero-calibrated to the recording and analysis system using a standard mercury manometer (Baumanometer; W.A. Baum; Copiague, NY). Animals were placed in supine position on a positional operating table (model 25000115; Shor-line; Cow-bridge, UK) with the transducer platform leveled to the aortic root with a 24-inch carpenter’s level (Fig 2, left, A). The three catheter tips—aortic, femoral, and distal—were all within 2 to 3 cm of the same horizontal plane in this position. Each transducer was zeroed, and then arterial BP tracings for the three catheter locations were recorded simultaneously for 5 min. Animals were then placed in a 35° reverse Trendelenburg position (Fig 2, middle, B). Five minutes were allowed to elapse before any further measurements were taken. The transducer platform was then leveled with the aortic root, zeroed, and arterial BP tracings for the three catheter locations were again recorded simultaneously for 5 min. With the position of the animal unchanged, the transducer platform was moved down the IV pole and leveled with the femoral catheter. Again the transducers were zeroed and arterial tracings for the three catheter locations were simultaneously recorded. The transducer platform was then moved to the level of the distal (hind limb) catheter, zeroed, and arterial tracings recorded as before. Measurements were also taken of the vertical distance along the IV pole between aortic and femoral transducer levels, and between femoral and distal transducer levels so that these distances could be correlated with measured pressure differences. Animals were returned to the supine position for 5 min, and then the same protocol was repeated in a 25° Trendelenburg position (Fig 2, right, C). Following the experiment, animals were killed with an overdose of pentobarbital (90 mg/kg IV). The experiments described in this study were performed in compliance with standard practices of care for laboratory animals. The protocol was approved by the Committee for the Humane Use of Animals at the SUNY Health Science Center, Syracuse, NY.

Data Analysis

Seven data sets, each composed of three arterial tracings (aortic, femoral, and distal) were obtained as described above: one set from the supine position and three sets each from the Trendelenburg and reverse Trendelenburg positions. Each data set of tracings was converted into numeric systolic and diastolic means by the recording and analysis system by taking 20-s time...
intervals each minute during the 5-min tracing. Mean arterial pressure (MAP) was then calculated for all measurements using the standard formula,

\[
\text{MAP} = \frac{\text{diastolic} + (\text{pulse pressure}/3)}{	ext{Systolic} - \text{Diastolic}}
\]

Thus, each numeric data set consists of 45 measurements: 15 measurements for each catheter location (aortic, femoral, distal) made up of 5 systolic measurements, 5 diastolic measurements, and 5 MAP measurements. We generated seven numeric data sets for each of the five animals, accounting for 1,575 measurements. Only the MAPs were used to generate the final mean values for each catheter location. Statistical analysis was performed within positions and between transducer levels using Instat 2.0. All reported values are means \(\pm\) SD and were compared using analysis of variance. Differences were considered significant at a probability level of 95% (\(p < 0.05\)).

RESULTS

As demonstrated in Table 1, no significant differences in arterial pressures can be attributed to variable catheter site in the supine position. Animals placed in the reverse Trendelenburg position, with transducers at the aortic root, consistently showed a decrease in MAP due to orthostasis that was also independent of catheter site. However, as the transducer was lowered to the femoral and then distal catheter access sites, as current guidelines recommend, significant errors in measured arterial pressures occurred when compared to actual aortic root pressure being monitored almost simultaneously. The same trends were noted in the Trendelenburg position but did not reach statistical significance.

Measurements between each transducer level in centimeters showed that on average, every centimeter the transducer moved down resulted in a 0.63-mm Hg pressure decrease (Table 2). This corresponds closely with the known value of 0.73 mm Hg change for each 1 cm H\(_2\)O in either direction.

DISCUSSION

Invasive monitoring in trauma and critical care presents unique challenges due to the variable na-

| Table 1—Direct Arterial Pressures According to Three Variables* |
|-------------------------------|-----------------|-----------------|
| **Positions**                  | **Transducer Level** | **Catheter Access Site Measured, mm Hg** |
|                               | Aortic Root | Femoral | Distal |
| Supine                        | Aortic root | 100.1 ± 23.5 | 95.3 ± 21.5 | 92.8 ± 21.0 |
| Reverse Trendelenburg         | Aortic root | 48.1 ± 8.2\(\ddagger\) | 47.3 ± 10.1 | 46.2 ± 14.1 |
|                               | Femoral     | 63.8 ± 5.5   | 62.2 ± 11.2\(\ddagger\) | 60.3 ± 14.9 |
|                               | Distal      | 79.8 ± 12.2  | 76.3 ± 15.6 | 75.2 ± 19.41 |
| Trendelenburg                 | Aortic root | 93.9 ± 17.6\(\ddagger\) | 93.1 ± 16.9 | 91.1 ± 21.2 |
|                               | Femoral     | 88.6 ± 14.6  | 88.7 ± 14.6\(\ddagger\) | 86.4 ± 18.4 |
|                               | Distal      | 85.6 ± 16.9  | 85.4 ± 16.9 | 83.9 ± 18.8\(\ddagger\) |

*Data are MAP measurements (± SD) with varying position, transducer level, and catheter access site. Each value represents the mean of 25 measurements.
\(\ddagger p < 0.05\) vs all transducer levels in that position (analysis of variance).
\(\ddagger\)Values that would be obtained using current recommendations by placing transducer at the level of catheter access. Note the significant errors that occur when compared with the actual value measured at the aortic root. The same trend is present in the Trendelenburg position but does not reach statistical significance.
ture of injuries. It is often impossible to follow routine protocol with respect to patient positioning and monitoring devices such as catheters and transducers. Head injuries, congestive heart failure, respiratory insufficiency, and hemorrhagic shock are situations that may call for aggressive nonsupine positioning. Burn patients also present numerous problems for catheter access sites and positioning due to the location and percentage of total body surface area involved. Although these circumstances may be transient, many will be prolonged. Even so, each of these situations involves a decision on where to place the transducer for valid direct arterial BP measurements.

The purpose of these experiments was to test the effects and relationships of three variables—transducer level (zero reference point), catheter access site, and patient position—on direct arterial BP measurement. In doing so, we specifically sought to determine the validity of current guidelines that recommend that all fluid-filled monitoring systems be placed level with the catheter tip. While such recommendations are valid for patients in the supine position, they are prone to significant error in other circumstances. We found that in the reverse Trendelenburg position of 35°, errors in MAP of almost 30 mm Hg occurred in distal arteries when the transducer was placed at the level of the catheter tip. The same trend for error was noted in the Trendelenburg position but did not reach statistical significance.

The clinical implications of such errors are important to recognize, and a hypothetical example may be illustrative. At our institution, it is not uncommon to find a burn patient with only dorsalis pedis arteries available for arterial monitoring, who is in the reverse Trendelenburg position or sitting up in bed with a normal BP (120/80 mm Hg). On further inspection, one may note that the transducer is at the level of the catheter tip, down from the dorsalis pedis artery, from 20 to 30 cm below the correct level to transduce. When the transducer is moved to the aortic root, the patient has a clearly hypotensive pressure of 90/65 mm Hg. Thus, using current guidelines in this scenario represents a serious overestimation of tissue-perfusion pressure of the patient and a potential for further errors in clinical judgment.

The important findings to be emphasized from this study are: (1) that valid arterial BP measurements are obtained only when the transducer is placed at the level of the aortic root, and (2) that direct arterial BP measurement is independent of catheter access site and patient position if the transducer is at the proper level. In other words, a patient may be in any position, with a catheter in any artery, and the clinician will be able to obtain a valid arterial BP as long as the transducer is level with the aortic root. When this condition is met, it makes no difference where the catheter is inside the system, or what position the system happens to be in. Although these concepts may seem counterintuitive, they can be confirmed by simple manipulation of a fluid-filled catheter transducer system and graduated cylinder.

The principle behind these results, established by Courtois et al, is that the proper level for a transducer to negate the effects of hydrostatic pressure is always at the top of the fluid column in the system being analyzed (in this case, the aortic root). The reason the aortic root is the only reference position that will accurately reflect arterial BP is twofold. First, the central MAP and particularly the aortic mean is the key component in coronary and cerebral perfusion. This is the pressure that is sensed by baroreceptor mechanisms. Furthermore, this is the pressure that is indirectly measured using standard sphygmomanometer techniques. Second, clinicians are not interested and should not care what the pressure is in a distal peripheral artery. Not only is the value obtained inaccurate due to the effects of hydrostatic pressure, it is altogether the wrong pressure being obtained.

Although this study makes an important clarification regarding direct arterial BP measurement applicable to clinical practice, it raises other questions. For instance, where is the critical point, in degrees,
at which the reverse Trendelenburg position begins to cause statistically significant errors in arterial BP? Also, why did measurements in the Trendelenburg position not reach statistical significance? At what point, if any, would they reach significance? Although it may have been due to the fact that there was less inclination (25° in the Trendelenburg position compared to 35° in the reverse Trendelenburg position) making the distance from aortic root to catheter access site too short to provide an adequate fluid column, other factors may be influential. It may be a function of the differing capacitance in the arterial system above and below the aortic root. Obviously there are differences in hydrostatic gradients that exist from head to heart compared to foot to heart when in nonsupine positions. Yet another consideration is the effect lateral rotational therapy in the ICU may have on direct arterial pressure measurements. These will be topics of future study.

CONCLUSION

In conclusion, we demonstrated in a clinically relevant, large animal model the effect of position, catheter access site, and transducer level on arterial BP measurement. Although these concepts may be fairly well established in the minds of critical-care physicians, there is considerable confusion evident in others: particularly the practices and guidelines of ICU nurses. We found that current recommendations that suggest the transducer be placed level with the catheter tip are invalid in the nonsupine positions frequently encountered in trauma and critical care. Valid direct arterial BP measurements depend only on having the transducer level with the aortic root. We believe these findings are an important clarification deserving emphasis and application in the clinical care of trauma and critical-care patients.

REFERENCES

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