Analysis of damping characteristics of arterial catheter blood pressure monitoring in a large intensive care unit

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Background. For many reasons, the invasive measurement of systolic and diastolic blood pressure should be accurate. Accuracy is determined, in part, by the damping characteristics of the arterial catheter blood pressure monitoring system.
Objectives. To ascertain the damping characteristics of arterial catheter blood pressure monitoring in a large tertiary intensive care unit (ICU) and to elicit any causes of under- or over-damping of the measurement systems.
Methods. A cross-sectional, observational study of arterial line measurements in a large general ICU. The coefficient of damping (CoD) was calculated from the waveform generated from a 'fast flush'.
Results. Thirty systems (19%) were adequately damped (CoD 0.4 - 0.8), 56 (37%) were overdamped, and 68 (44%) were underdamped. We did not find that poor damping characteristics were associated with the age of the arterial catheter or the type of catheter used.
Conclusion. Most systems observed in this study were inappropriately damped, which would result in the inaccurate display of the waveform and systolic and diastolic pressures.

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Haemodynamic instability is a feature of many admissions to the intensive care unit (ICU), and indeed theatres frequently require active management to ensure adequate and acceptable cardiac output and perfusion pressure, whilst preventing excessively high pressures. Thus, real-time, accurate measurement of arterial blood pressure (ABP) is vitally important for making clinical decisions. This becomes especially important where the clinical condition requires ABP to be tightly regulated around a target, such as in therapeutic hypotension in trauma,[1] or where decision-making is based on arterial waveform characteristics such as when using pulse-contour analysis.[2]

Real-time monitoring of ABP is commonly carried out invasively in theatres and ICUs using an arterial catheter placed within a peripheral artery, most commonly the radial artery, connected via fluid-filled tubing to a pressure transducer. Unfortunately, the method for monitoring ABP invasively is subject to distortions that can reduce the accuracy of the measurement, i.e. damping and resonance.[3-5] In this setting, damping refers to anything which absorbs energy within the oscillating system, resulting in an artificial reduction in the measured amplitude of the oscillating arterial pressure waveform, i.e. the pulse pressure. Conversely, resonance refers to an artificial amplification of the oscillating arterial pressure waveform when this waveform occurs at a similar frequency to the natural frequency of the measurement system, resulting in an exaggeration of the amplitude of the arterial pressure waveform. The extent to which a system is damped is described by the coefficient of damping (CoD), while the frequency of oscillation that the system resonates at, is known as the natural frequency (ω_n). Importantly, a certain amount of damping, where the CoD is ~0.7, is required for accurate blood pressure measurement; enough to damp artificial distortion inherent to the measurement system, but not so much that the true pressures and details of the arterial waveform are misrepresented.

In 1903, Frank[6] originally described the manner by which a system must respond to an oscillatory waveform to accurately measure ABP. This was later updated by Gardner,[4] who described the range of natural frequency and CoD that would give adequate response characteristics to accurately measure blood pressure; a ω_n of >10Hz is almost always required. The range of CoD that would give accurate ABP readings increases as ω_n increases, but 0.4 - 0.8 will give an accurate reading in the majority of cases.[4]

A number of factors are thought to contribute to suboptimal damping; air bubbles within the tubing system dramatically increase the CoD, as do blood clots – both resulting in overdamping, while excessive lengths of tubing reduce the CoD, resulting in underdamping.[4,7]

The aim of this prospective study was to carry out an evaluation of whether the arterial blood pressure monitoring systems used in a large tertiary hospital ICU had appropriate CoDs to accurately measure ABP and produce a reliable pulse contour. Secondary aims of the study were to examine the hypothesis that the time the arterial catheter had been in place, the site of the catheter, and the type of catheter used would affect the CoD.

Methods

Ethical approval was obtained from the University of Birmingham Research Ethics Committee to carry out this audit, with no requirement for individual patient consent. On randomly selected days, all patients in the Queen Elizabeth Hospital Birmingham Critical Care Unit, with an arterial line *in situ* were audited. Basic details were recorded: age, working diagnosis, site of arterial cannula, date and time of insertion, hours since insertion, type of cannula (manufacturer, gauge, length). The CoD was measured using the 'fast flush' method described by Jones and Pratt[8] and by McGhee and Bridges.[7] Briefly, the flush valve on the back of the BD DTX Plus Disposable Pressure Transducer (BD

Biosciences, UK) was opened to allow a fast flush of normal saline (0.9% NaCl), and then closed, to create a decaying waveform before the system returned to the normal monitoring of ABP. The flush was performed thrice. The resulting waveforms were displayed on the patient monitor, were anonymously photographed, and the resulting images analysed using ImageJ software (v1.44, NIH, USA) to measure the amplitude of the two initial oscillations in pixels (A_1 and A_2, Fig. 1). The CoD was then calculated according the formula described by Gilbert, as follows:[9]

$$\mathrm{CoD} = -\ln \frac{(A_2 / A_1)}{\sqrt{\pi^2 + [\ln(A_2 / A_1)]^2}}$$

Where no oscillations occur, it is known that the CoD is ≥1, and in these instances the CoD was recorded as 1.0.[9]

Statistical analysis was performed using Aabel version 3 statistical analysis software (Gigawiz Ltd., USA). Factorial ANOVA or linear regression analysis were used as appropriate and as detailed, with results considered statistically significant if $p<0.05$.

Results

A total of 154 patients with invasive blood pressure measurements were included in the study; 143 had BD Floswitch 20 g 4.5 cm arterial cannulae (BD Biosciences, UK), 10 had Vygon 20 g 8.0 cm arterial cannulae (Vygon UK Ltd., UK), and 1 had a 5Fr 20 cm femoral PiCCO line (Phillips Healthcare, UK). A total of 143 patients had catheters in the radial artery, 9 had brachial artery catheters, and 2 had femoral artery catheters.

Fifty-six (37%) damping assessments had a CoD ≥1, i.e. no oscillations occurred on the fast flush test. It was not possible to quantify the CoD in these patients, but they were classified as overdamped. Of the remaining 98 patients, the mean (standard deviation, SD) CoD was 0.35 (0.20). Of these, 30 (19%) had a CoD in the recommended range of 0.40 - 0.80 and 68 (44%) were underdamped (CoD <0.4) (Fig. 1). There were no damping measurements in the 0.8 - 1.0 range. There was no statistically significant relationship observed between the duration an arterial catheter had been *in situ* and its CoD, and there were no statistically significant differences between the CoDs recorded in the different arterial lines.

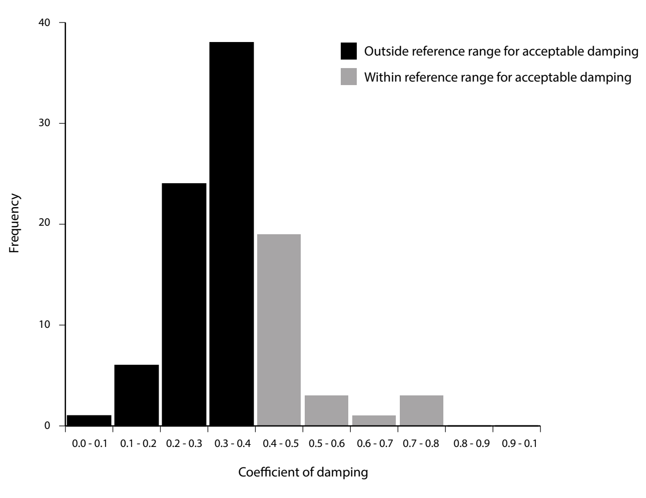

Fig. 1. Frequency histogram detailing CoD in the 98 patients in which it was possible to measure it.

Discussion

This study examined the CoD in a large sample of patients in the ICU setting (N=154). Importantly, we found that of the 154 damping measurements, only 30 (19%) had a CoD judged to be adequate for providing an accurate, reliable measure of ABP. This shows that a significant proportion of invasive blood pressure management does not conform to the standards required for accurate monitoring.

This is significant for at least three reasons. Firstly, although over- or underdamping affects mean arterial pressure (MAP) minimally, it leads to large inaccuracies in measurements of systolic and diastolic blood pressure,[7] both of which are key measured variables used to direct therapy, especially fluid resuscitation. Secondly, poor damping reduces the reliability of pulse pressure measurements, and thus removes another important clinical indicator. Finally, it makes the use of pulse contour analysis for the estimation of cardiac output impossible, as this relies on accurate, optimally-damped ABP measurements.

A number of papers have previously called for routine monitoring of arterial line damping.[4,7,9] This is underlined by the findings of Romagnoli *et al.*,[10] who found that systolic pressure (mean (SD)) was overestimated by 28 (15) mmHg in patients with underdamped ABP waveforms when compared with those with appropriately damped systems. Routine monitoring would ensure that inappropriately damped lines are recognised and, at the very least, taken account of, if not corrected or replaced. Further, our study indicates the need for national standards and guidelines to direct clinically acceptable standards of invasive ABP monitoring, which are thus far unavailable. Importantly, our new evidence makes it clear that further studies are required to assess the impact of poor damping characteristics on clinical care and outcomes.

Study limitations

Firstly, owing to the limited resolution of the patient monitoring screens, it was sometimes impossible to measure A2 in cases where the oscillations were very small. These would typically have represented CoDs between 0.9 and 1.0 and would therefore have fallen outside the required range for accurate measurement. Secondly, blood pressure was not recorded in this study, which necessitates further investigations to examine the clinical implications of our findings. Currently, invasive ABP measurement is considered the 'gold standard'.[11] It would be of interest to compare oscillometrically derived v. invasively derived ABP, and to examine over- or underdamped measurement systems lead to a disparity in the measured ABP Lastly, although the patients' broad diagnosis was recorded, no attempt was made to record specific blood pressure targets. The authors were therefore unable to detail for how many patients accurate blood pressure measurement was of critical importance, and for how many it was less important. However, it is important to note that all patients were critically unwell, by virtue of the fact that they were treated in the ICU.

Conclusion

This study showed that the majority of arterial catheter blood pressure monitoring systems in our ICU were either over- or underdamped, resulting in inaccurate systolic and diastolic pressure readings.

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