Invasive v. non-invasive blood pressure measurements — the influence of the pressure contour

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Summary

A reasonable correlation exists between invasive and non-invasive methods of measuring systemic blood pressure. However, there are frequent individual differences between these methods and these variations have often caused the validity of the non-invasive measurement to be questioned. The hypothesis that certain invasive systolic blood pressures may represent a pressure impulse rather than a flow-generating pressure was used to classify the invasive pulse pressure contour into various types, and the invasive pressure measurement was then correlated with the non-invasive. There was a significantly greater difference between these two methods of measuring systolic blood pressure in patients exhibiting prominent inotropic pressure pulse phenomena compared with patients without such phenomena. Since non-invasive monitors measure blood pressure by volume displacement or flow detection and invasive ones measure pressure impulses rather than flow, it was concluded that the pressure measured by the non-invasive monitor more accurately reflects the propulsive pressure-causing flow when inotropic pressure pulse phenomena are present.

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The relationship between invasive and non-invasive measurements has been the subject of a number of investigations, most of which have shown extremely good correlations.[1-4] The correlations are, however, between group averages and individual measurements may show gross discrepancies casting doubt on the validity of the non-invasive measurement.

It was noted that patients with peripheral invasive arterial pulse wave contours exhibiting a so-called double dichrotic notch with an inotropic pressure pulse (Fig. 1) seemed to have a larger discrepancy between the invasive systolic blood pressure and the non-invasive systolic blood pressure. The hypothesis that large differences between the invasive and non-invasive measurements could be predicted by an analysis of the invasive peripheral pulse pressure contour was therefore examined.

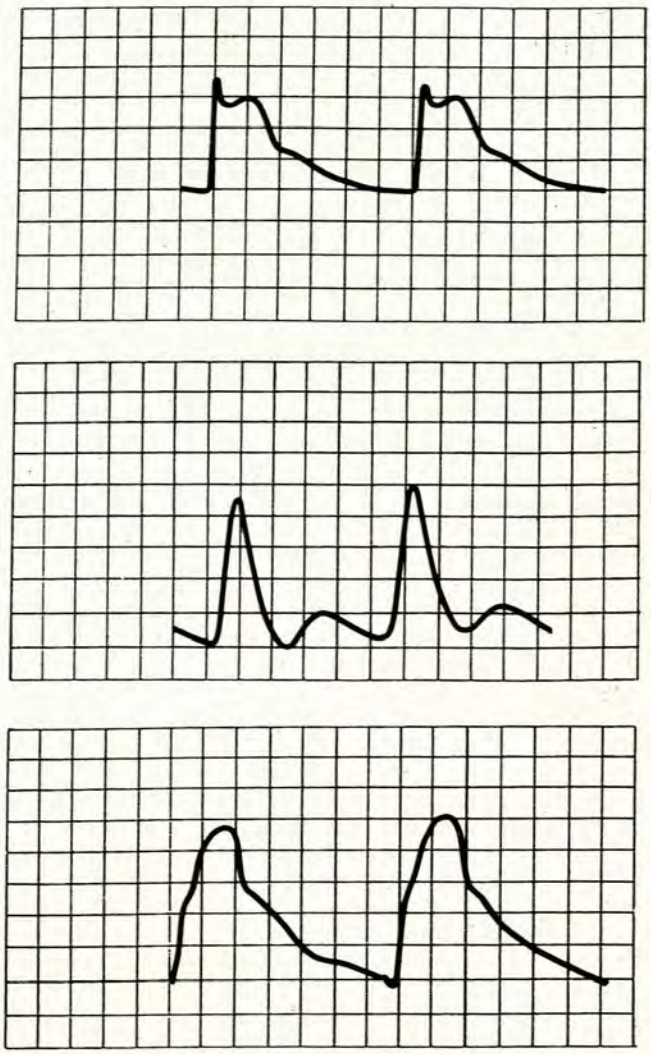

Fig. 1. Pulse pressure contour. Type A shows a steep peaked systolic pulse (above) **or a separate inotropic peak** (middle). **Type B shows a rounded waveform** (below) **with the dichrotic notch visible.**

Patients and methods

Twenty-one patients in the Intensive Care Unit, King Edward VIII Hospital, Durban, with invasive arterial pressure monitoring were investigated. The peripheral pulse pressure contour was examined on the oscilloscope display and divided into one of two types according to the presence or absence of an inotropic pressure pulse (Fig. 2). Pressure contours that did not clearly fit into one of the categories, or which were obviously damped, were excluded from the investigation. The study only started after identification of the pressure contour type and allocation of each patient to the appropriate group.

The invasive arterial monitoring system consisted of a 20 g polyvinyl chloride cannula (Medican; Medical Specialities, Randburg) placed in the radial, femoral or brachial artery and connected via a 120 cm length of pressure tubing (LMF 120; Bentley Laboratories Europe, Uden, The Netherlands) to a disposable pressure transducer system (Deltran II; Utah Medical Products Inc., Midvale, Utah, USA) incorporating a continuous flush device. The transducer was connected to a patient monitor (90303 Alpha PC; Spacelabs Inc., Redmond,

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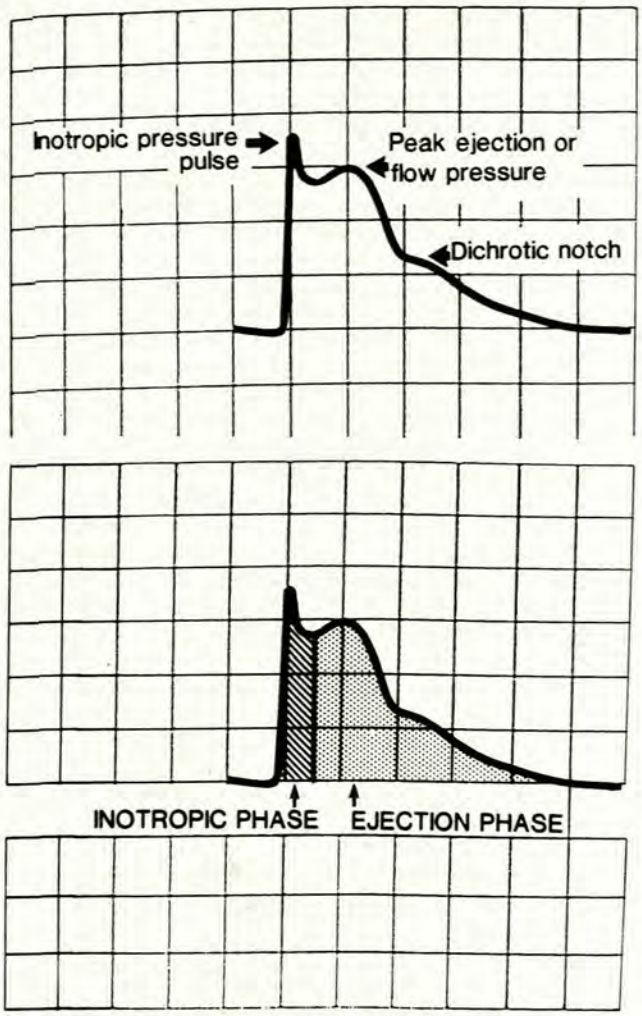

Fig. 2. Terminology of the pressure pulse. The top figure shows the terminology of the peaks, i.e. inotropic pressure pulse (in contrast to the concept of pulse pressure), and the classic dichrotic notch. The lower figure shows the two phases of the arterial pulse: the initial inotropic phase, which is usually of shorter duration than the later volume ejection phase.

Washington, USA) and the resultant pressure trace and digital systolic, mean and diastolic pressures as well as the pulse rate were displayed.

The non-invasive monitoring system consisted of the reusable standard adult arm cuff (bladder width 12 cm), 3,6 m pressure tubing and a Dinamap 1846 pressure monitor (Critikon, Tampa, Florida, USA) with printer. Patients with arm circumferences outside the prescribed limits for the standard arm cuff were excluded.

Both systems were calibrated before use against a static pressure from a mercury manometer to ensure comparable readings. Each patient had 5 consecutive non-invasive measurements at 2-minute intervals. The digital values displayed on the invasive blood pressure monitoring system were recorded at the start of cuff inflation. Respiratory fluctuations of the invasive blood pressure measurements were monitored over the 10-minute period of the investigations. Fluctuations exceeding 5 mmHg were noted.

The average pressures were calculated using all 5 sets of measurements for each patient. The average of 5 values was designed to negate any effect of respiratory fluctuations. The maximum difference between the invasive and the non-invasive methods of determining blood pressure was also selected and is reported for each patient. Correlations between invasive and non-invasive blood pressure measurements were determined by calculating least squares regression. Student's *t*-test was used for determining differences between the average values. A median test and Fisher's exact probability test were used to test the distribution of the maximum differences between the invasive and non-invasive measurements. A P value $< 0,05$ (two-tailed) was considered significant.

Results

Twenty-one patients were investigated of which 13 had type A pressure patterns, and 8 type B. The average age ($\pm$ SEM) of patients in group A was 39,0 $\pm$ 5,82 years and in group B 41,2 $\pm$ 4,63 years. This difference is not statistically significant and there was no significant difference between groups in the following areas: male:female ratio; position of arterial cannula; drugs used (inotropic agents), controlled v. spontaneous ventilation; and disease. There were 7 patients in group A with radial artery lines, 4 with femoral and 1 each with brachial and axillary arterial lines. Five patients in group B had femoral lines and 3 radial arterial lines.

The group correlations between the slopes of the invasive and non-invasive measurements were not statistically significantly different from unity in both group A and group B for all measurements (Table I) and were therefore also not significantly different from one another. The scatter within group A for systolic blood pressures was much larger than in group B (Fig. 3). This was also reflected in the correlation coefficients (Table I), which were all below 75% for blood pressure measurements in group A and all above 90% in group B.

TABLE I. CORRELATIONS BETWEEN INVASIVE AND NON-INVASIVE BLOOD PRESSURE MEASUREMENTS

		95% CI					
Group A (N=65)	Slope	Min.	Max.	r^2	Intercept	t	P
Systolic	**0,7851**	**0,558**	**1,012**	**73,1**	**16,3**	**2,16**	**0,04**
Mean	**0,978**	**0,646**	**1,309**	**52,8**	**3,4**	**0,34**	**0,7**
Diastolic	**1,008**	**0,647**	**1,369**	**47,4**	**2,4**	**0,27**	**0,8**
Pulse rate	**0,973**	**0,730**	**1,216**	**92,2**	**1,5**	**0,65**	**0,5**
Group B (N=40)							
Systolic	**0,839**	**0,552**	**1,126**	**93,1**	**21,2**	**4,25**	**< 0,001**
Mean	**0,858**	**0,566**	**1,151**	**90,6**	**13,8**	**3,04**	**< 0,001**
Diastolic	**1,043**	**0,708**	**1,378**	**94,6**	**−1,97**	**0,6**	**0,5**
Pulse rate	**0,957**	**0,645**	**1,270**	**92,7**	**3,7**	**0,8**	**0,4**

Slope and intercept were determined by least squares linear regression; 95% confidence intervals (CI) (minimum and maximum) are given for the slopes; r^2 = square of the correlation coefficient expressed as a percentage, i.e. the percentage of explained variation for the slope; t = Student's t-test for the appropriate degrees of freedom for the intercept; P = probability of the intercept not being different from zero.

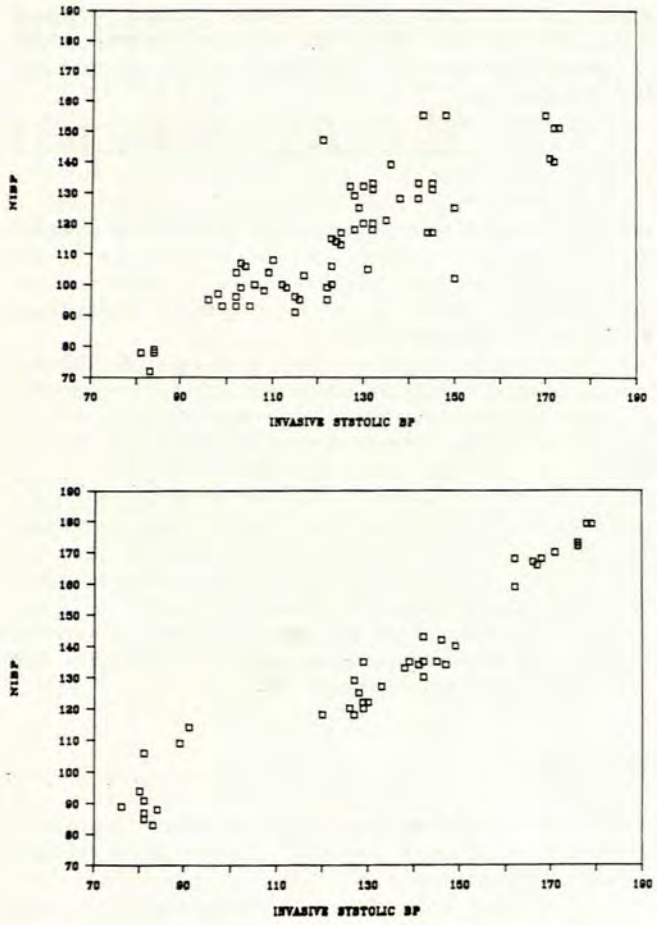

Fig. 3. Correlation between the invasive and non-invasive systolic blood pressures in group A (above) **and group B** (below).

Similar larger scatters were found for the mean blood pressures in group A compared with group B (Fig. 4.)

The average systolic blood pressure in group A and the average systolic and mean blood pressures in group B showed intercepts, which were significantly higher than zero. The average slopes, however, were all less than unity. This implies that in this study the non-invasive monitor tended to indicate higher values at lower pressures and lower values in the higher blood pressure ranges. This point requires further investigation in a study specifically designed to analyse this relationship.

As shown in Table II, patients with type A pulse pressure contours had a lower average invasive systolic blood pressure (mean ± SD — 123 ± 22,5 mmHg) than the patients in group B (131,0 ± 32,5 mmHg) although this difference was not statistically significant due to the wide scatter of values. The mean and diastolic invasive blood pressures of group A were also significantly lower than group B (Table II).

The non-invasive monitor showed significant differences between group A and group B in all measurements (Table II).

A comparison of the invasive v. non-invasive blood pressure measurement in group A (Table II) showed a significant difference only in the systolic measurement — the invasive method yielding a higher average blood pressure of 123,7 ± 22,5 mmHg compared with the non-invasive of 113,4 ± 20,7 mmHg.

The average of the differences between the individual invasive and non-invasive measurements in both groups is shown in Table III. There was a significantly larger difference between the systolic blood pressure measurements in group A compared with group B. The range of differences for each measurement in both groups is also shown in Table III. The maximum systolic difference in type A was 48 mmHg and in type B 13 mmHg. There were 3 patients in each group in whom the systolic blood pressure fluctuations due to respiration exceeded 5 mmHg.

The number of patients in each group with differences between invasive and non-invasive systolic blood pressure measurements equal to or larger than 11 mmHg (median

TABLE II. COMPARISON BETWEEN INVASIVE AND NON-INVASIVE MEASUREMENTS (mmHg ± SD)

	Type A (N = 65)	Type B (N = 40)	Significance Type A v. Type B	
			t	P
Invasive				
Systolic	**123,7 ± 22,5**	**131,0 ± 32,5**	**1,4**	**NS**
Mean	**84,0 ± 11,8**	**97,4 ± 27,8**	**3,44**	**0,01**
Diastolic	**65,3 ± 9,2**	**77,6 ± 24,2**	**3,67**	**0,01**
Pulse rate	**113,1 ± 12,1**	**105,1 ± 9,5**	**3,58**	**0,01**
Non-invasive				
Systolic	**113,4 ± 20,7**	**131,1 ± 28,3**	**3,69**	**0,01**
Mean	**85,5 ± 15,9**	**97,5 ± 25,1**	**3,01**	**0,01**
Diastolic	**68,3 ± 13,5**	**79,0 ± 26,0**	**2,39**	**0,02**
Pulse rate	**111,6 ± 12,0**	**104,3 ± 9,4**	**3,31**	**0,01**

Significance: invasive v. non-invasive

	Type A		Type B	
	t	P	t	P
Systolic	2,76	0,01	0,01	NS
Mean	0,6	NS	0,01	NS
Diastolic	1,4	NS	0,24	NS
Pulse rate	0,7	NS	0,36	NS

Student's t-test; NS = not significant ($P > 0,05$)

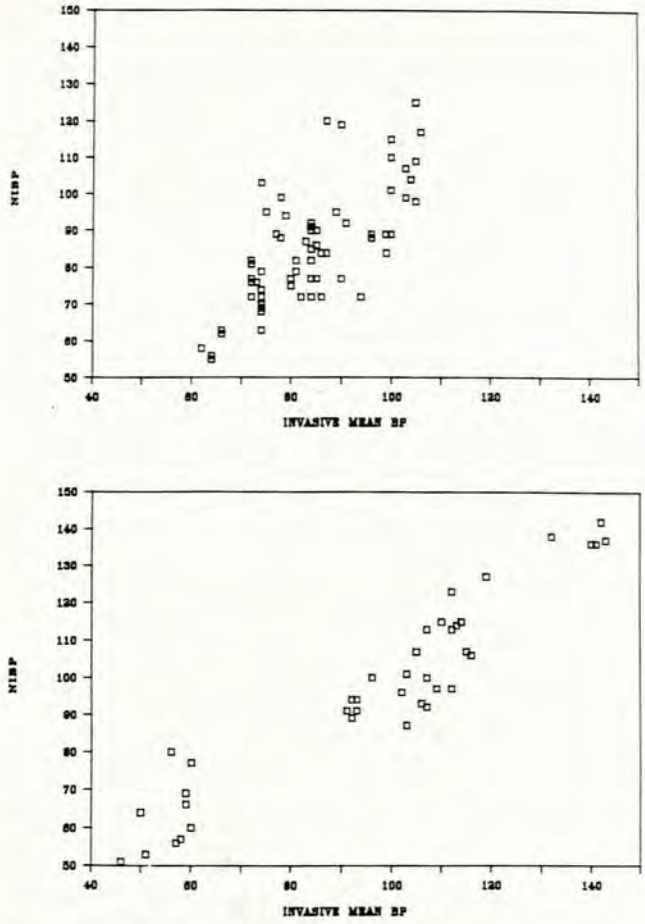

Fig. 4. Correlation between the invasive and non-invasive mean blood pressures in group A (above) **and group B** (below). **Note the wider scatter in group A compared with group B.**

value) is shown in Table IV. Ten out of 13 patients in group A had larger differences than the median whereas 7 out of 8 patients in group B had a smaller difference. This distribution is statistically significant (Fisher's exact probability test; $P < 0{,}025$). There were no significant differences between group A and group B in relation to the number of patients with differences between invasive and non-invasive mean and diastolic pressures that were greater than the median (Table IV).

TABLE IV. NO. OF PATIENTS IN EACH GROUP WHERE THE MAXIMUM DIFFERENCE BETWEEN THE SYSTOLIC, MEAN AND DIASTOLIC BLOOD PRESSURES MEASURED INVASIVELY AND NON-INVASIVELY EXCEEDED THE MEAN VALUE

	Type A	Type B
Systolic blood pressure*		
⩾ 11 mmHg	**10**	**1**
< 11 mmHg	**3**	**7**
Mean blood pressure†		
⩾ 6 mmHg	**7**	**3**
< 6 mmHg	**6**	**5**
Diastolic blood pressure‡		
⩾ 5 mmHg	**6**	**5**
< 5 mmHg	**7**	**3**

* $P < 0{,}025$; median test and Fisher's exact probability test.
† Difference not significant.
‡ Difference not significant.

Discussion

Although many investigations and comparisons of invasive and non-invasive blood pressure measurements have been published,[1-3] none has enabled the clinician at the bedside to predict the presence and direction of a difference or suggested which method of blood pressure measurement should be used.

This trial was designed to investigate what clinicians do in practice. It was found that not only this unit but most other intensive care units do not and cannot test frequency response, i.e. damped natural frequency (DNF) and damping factor (DF) either by the step method[5,6] or the frequency sweep method.[2] The clinician would see the so-called ringing, search for an air bubble, flush the system and — failing to find a major change in the readings — accept the invasive blood pressure reading and respond mainly to the systolic reading basing his therapy on what we consider to be false readings.

The invasive arterial blood pressure is usually taken as the gold standard for comparison with other methods. The group correlations are usually statistically highly significant but the clinician using the two methods often finds gross individual discrepancies leading to a distrust of the non-invasive measurement.[4] A method of predicting when large differences can be expected has two advantages; firstly, when the difference is expected and then found, the clinician can believe both measurements to be true reflections of the physical phenomena being measured thereby sustaining confidence in both methods; and, secondly, when unexpected differences are present the apparatus may require checking or recalibration.

The results of this investigation support the hypothesis that the inotropic pressure pulse[7] is a pressure impulse with a minimal component of volume displacement. The peak pressure pulse is therefore detected and measured by the invasive method but not by the cuff in the non-invasive monitor. The first peak shown in the arterial pulse tracing was called the 'inotropic' phase by Bruner,[7] and it was thought to be caused by an inertial pressure impulse termed the pressure pulse (to

TABLE III. DIFFERENCES BETWEEN INVASIVE AND NON-INVASIVE (MEAN ± SD, RANGE)*

	Type A (N = 65)	Type B (N = 40)	Significance t	Significance P
Systolic	**10,3 ± 11,8 (48 - −26)**	**−0,1 ± 9,1 (13 - −25)**	**4,77**	**0,01**
Mean	**−1,5 ± 10,9 (22 - −33)**	**−0,1 ± 8,6 (16 - −24)**	**0,8**	**NS**
Diastolic	**−3,0 ± 9,8 (23 - −30)**	**−1,4 ± 6,1 (11 - −12)**	**0,9**	**NS**
Pulse rate	**1,5 ± 2,0 (10 - −1)**	**−0,8 ± 2,6 (7 - −8)**	**1,6**	**NS**

*Student's t-test; NS = not significant ($P > 0{,}05$).

differentiate the phenomenon from the pulse pressure) (see Fig. 2). The second peak is part of the ejection phase and was postulated to correlate better with methods of determining blood pressure that are dependent upon flow (such as cuff occlusion techniques with distal flow detection). Ladin *et al.*[8] also investigated patients with what they termed a 'systolic spike' and found that the difference between invasive and non-invasive pressure exceeded 10 mmHg in 4 of their patients.

The possibility that these differences (and the inotropic pressure pulse) were due to an underdamped invasive catheter system with a low-damped natural frequency was considered but rejected for the following reasons:

1. If underdamping with ringing causing overshoot was the sole explanation for the higher invasive systolic blood pressures in group A, then the average systolic blood pressure in group A should have exceeded that in group B where underdamping was not present. This study found that group A patients had a lower average systolic blood pressure than group B patients.

2. Differences in frequency response and damping of the pressure measurement systems as an explanation would require group A to have a lower natural frequency and group B to have a higher damping factor. The catheter manometer systems were standard and the only method of altering the natural frequency or damping would then be the presence of air bubbles leading to increased damping and a lower natural frequency. The presence of a spiked waveform in group A, a dichrotic notch in group B and exclusion of damped-looking traces from the trial also negate air bubbles as an explanation. (Measurement of the frequency response and damping factor was not possible due to the lack of a high speed recorder.)

3. A separate study of type A traces[9] using Fourier and power-density spectrum analysis followed by digital filtering indicates that the inotropic pressure pulse contains both high- and low-frequency components with the low-frequency components representing the inotropic pressure pulse generated in the cardiovascular system.

4. The type of pulse pressure contour can change from type A to type B within a few pulse beats by factors decreasing the inotropic state such as a Valsalva manoeuvre. The opposite has also been observed over a few minutes (type B to type A) with the use of inotropic agents. No alteration could have occurred in the resonant state (DNF and DF), such as addition and removal of air bubbles.

5. A study of clinically used catheter transducer systems[8] with measured DNF ranging from 11,6 Hz to 18,5 Hz and DF ranging from 0,16 to 0,27 using frequency-domain analysis showed that: 'The systolic spike observed in 4 of the 7 patients did not originate in the pressure tubing or in the amplifier system.'

Movement artifacts are probably the single most common cause for large discrepancies between invasive and non-invasive measurements. Repetitive measurements, observation of the patient and the close correlation of the pulse rates measured by ECG and non-invasive monitors (as in this trial), largely exclude movement artifacts as the main cause of any difference.

The possibility that respiratory fluctuations were the main cause of the observed difference was excluded by repeating the measurements 5 times. The start of the pumping cycle of the non-invasive monitor occurred at a random period relative to the respiratory cycle. Fluctuations in blood pressure due to respiration may be exaggerated by high inspiratory pressures or by low central venous pressures. The latter were minimised by the trial design, which required a cardiovascular status that could be predicted to be stable for the study period.

The expectation that mean blood pressures measured by invasive and non-invasive monitors would correlate better than the systolic pressures was also noted to be unfounded (see Fig. 4 and Table I). The scatter of mean blood pressures for both groups was greater than the systolic scatter and is supported by the correlation co-efficients (Table I) for mean blood pressures.

The practical application of this work depends on the ability of the clinician to recognise type A invasive pressure contours and realise that the highest pressure measured by the monitor is displayed as systolic pressure. We believe that this specific pressure is due to a pressure impulse and does not represent a pressure-generating forward flow. The clinician should, under these circumstances (type A pressure contours), ignore the invasive 'systolic' blood pressure and use the mean blood pressure or use a flow detection method such as a non-invasive monitor to measure systolic blood pressure. The differences between these methods can be considerable, e.g. the highest difference measured by one of us (W.B.M.) was 100 mmHg where invasive measurement indicated a systolic blood pressure of 180 mmHg compared with a non-invasive value of 80 mmHg. The latter was consistent with the clinical assessment of a thin, thready pulse and was therefore accepted as the basis for further management. The highest difference in this study was 46 mmHg, which we consider to be a clinically important difference.

Patients with type B pressure pulse contours can be managed with information from either invasive or non-invasive measurements, since the differences are small and the correlation can be satisfactory — as demonstrated in this study.

A further pointer to clinical relevance was that the differences between the groups were statistically significant in such a small group of patients. Investigating a larger number of patients will increase the level of statistical significance rather than alter the clinical relevance.

An important point not predicted by the inotropic pressure pulse hypothesis was the discovery of blood pressure readings where the non-invasive monitor exceeds that of the invasive arterial pressure. We postulate that pressure and flow are not in phase in the peripheral arterial vascular systems (an analogy is the effect of capacitance and impedance in an alternating current circuit). In addition to the capacitance and impedance of the vascular system, the phase difference is also due to pressure reflections from the periphery[7,9] leading to a summation of forward and reflected pressure waves that are measured by the invasive monitor (measuring pressure) but not by the non-invasive monitor, which measures volume displacement or flow. The flow and pressure signals do not have the same pattern or shape and are therefore expected to have different peak, mean and minimum values.

Conclusion

While the cause of the initial peak of the arterial waveform may be largely unknown and the terminology controversial, the resulting difference between invasive and non-invasive measurements is striking. The difference should not be seen as an error, since each apparatus measures a different physical phenomenon. However, incorrect clinical use of the different measurements may cause inappropriate patient therapy based on the value generated by a measuring device which can only measure the physical process for which it was designed. The clinician needs to interpret the measurement in the light of the patient's clinical condition rather than follow an isolated blood pressure value. We believe that in patients with type A pressure contours the use of invasive systolic blood pressure measurements should be specifically avoided. It is preferable to use mean blood pressure measured by invasive methods (since the scatter, although quite wide, is less for the mean blood pressure in group A compared with the systolic blood pressure) in these patients or, alternatively, to determine systolic blood pressure by the non-invasive method.

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