An Investigation into the Variability of Stroke Volume Using Non-Invasive Measurements

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Abstract

Beat-to-beat pulse contour stroke volume (SV) and Doppler stroke distance (SD) were determined in 13 healthy adults in supine and upright positions during spontaneous and controlled breathing. Our aim was to determine the reliability of the pulse contour method for assessing beat-to-beat changes and investigate the variability of stroke volume.

Spectral analysis showed that these parameters have very similar power spectra comprising strong respiratory frequency fluctuations under all conditions and low frequency (LF, 0.05-0.15Hz) peaks in the upright position. Beat-to-beat values of SV and SD correlated well in most recordings (mean correlation coefficient 0.63± 0.18). Coherence between SV or SD and other cardiovascular parameters (pulse interval, systolic pressure and respiration) was highly significant at respiratory frequencies for all conditions and in the LF band for the upright recordings.

1. Introduction

Beat-to-beat variability in heart rate (or pulse interval) and blood pressure and the relationship between them has been under investigation for many years. The role of changes in stroke volume in this relationship is not well defined, partly due to the difficulty of obtaining accurate beat-to-beat values by a method suitable for use on volunteer subjects. Doppler ultrasound and pulse contour algorithms using non-invasive finger blood pressure are two methods that may satisfy these requirements.

The variation of stroke volume has been investigated previously [1-3] however the spectra of the beat-to-beat-variability has not been identified until quite recently [4] and the data has not yet been integrated into models of the cardiovascular system.

The accuracy of the non-invasive methods used here is not known for this type of application. Electromagnetic flowmeters are the gold standard for real-time blood flow measurement but require direct access to the vessel concerned. Thus there is no suitable standard method against which comparisons can be made for accuracy and precision. However, the two methods used here are based on disparate physical principles, therefore agreement between the two would provide good evidence that the result reflects the true variability of stroke volume and not measurement noise or interference from other processes.

1.1. Pulse interval and blood pressure variability

Pulse interval (PI) and systolic blood pressure (SBP) are known to vary at respiratory frequencies in healthy individuals. A low frequency (LF) peak centred at approximately 0.1Hz is also present upon assumption of the upright posture. The respiratory PI variability is considered to be associated solely with parasympathetic neural activity and the LF changes are thought to be the result of baroreflex response to blood pressure changes via both parasympathetic and sympathetic efferents [5,6]. The parasympathetic response is known to be very fast and can alter the sinus rhythm within a few hundred milliseconds [7], i.e. on a beat-to-beat basis. Sympathetic changes take longer and are considered to be too slow to be involved in the respiratory frequency variations at normal breathing rates [8].

1.2. Stroke volume variability

Left ventricular stroke volume is known to vary with respiration, decreasing during inspiration, whereas right ventricular stroke volume increases and the ventricular septum moves to the left [1,9]. Current consensus would appear to be that the inspiratory reduction in intrathoracic pressure increases venous return and right heart filling and also increases the compliance of the pulmonary circulation, thus reducing left heart filling [9].

Previous measurements on the variability of left ventricular stroke volume in humans have used Doppler [1,2] and impedance [3] methods and have been restricted to the respiratory effects. To our knowledge the same information has not previously been demonstrated using a pulse contour algorithm and the presence or absence of LF variations has not been established. Power spectra and phase information have been published for the Doppler method [4] but

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coherence between stroke volume and other cardiovascular variables has not been confirmed.

2. Methods

Recordings were taken from thirteen healthy volunteers (ages 22-50yrs, 4 female). Non-invasive finger blood pressure was measured using a Finapres. Respiration frequency was monitored as changes in thoracic circumference. A 2MHz pulsed Doppler transducer was used to measure velocity in the ascending aorta (Digidop, SciMed). The directional Doppler signal, blood pressure, respiration and surface ECG were recorded onto DAT.

Five five-minute recordings were taken for each subject in the following order: two in the supine position with spontaneous breathing, one in the supine position with controlled breathing at 0.2Hz (12bpm), one in the upright position with spontaneous breathing and one in the upright position with controlled breathing. Breathing frequency was timed using a visual stimulus and was evenly cycled between inspiration and expiration. For the upright measurements following a few minutes adaptation to the upright position the subject either stood resting against a wall for support or was tilted to 70°. These positions were considered to be identical for the purpose of the study.

2.1. Data analysis

Custom-built Matlab software was used to mark the Doppler pulses and calculate stroke distance using the velocity-time integral of the intensity-weighted mean frequency (IWMF) envelope. This derived frequency is proportional to mean velocity of flow [10] and is also less susceptible to noisy profiles. The pulse contour analysis was carried out using a Matlab version of the Beatfast algorithm [11].

Beat-to-beat values were synchronised as occurring at the start of each Doppler pulse and then interpolated to 5Hz using a cubic spline. Spectral analysis was performed using a 512-point FFT, 20% cosine data window and 15% subrecord overlap. For most recordings this produced four subrecords to be averaged for the periodogram. Due to technical difficulties and non-stationarities seven recordings were shorter than five minutes and only provided three subrecords for averaging. Power and cross spectra were averaged with a moving five-point triangular window to produce spectral estimates with approximately 30 degrees of freedom. The LF band is defined from 0.05-0.15Hz.

2.2. Coherence estimates

One thousand pairs of data records (simulated using a Gaussian random distribution) were subjected to the spectral analysis procedure. Of these data pairs (which had a true coherence of zero) 95% had a calculated coherence of 0.2 or less. For three subrecords the value was 0.25. This value was then taken as the limit for significant coherence.

3. Results

3.1. Power spectra

Some subjects demonstrated spontaneous breathing rates that fell within the LF band during both supine and upright recordings. As expected subjects had significant LF and respiratory frequency power in PI and SBP spectra during both supine and upright recordings. Respiratory peaks dominated the supine recordings and were increased by controlled breathing. The upright recordings were dominated by the LF peak, which tended to be reduced by controlled breathing.

Pulse contour SV spectra were dominated by respiratory frequency peaks and showed virtually no LF power in the supine position (Fig 1). A significant LF peak developed in the upright stance for most subjects, although much smaller than the increase for PI or SBP. Doppler SD spectra were remarkably similar to SV with some differences in peak areas, e.g. SV spectra tended to have larger LF peaks than SD in the upright stance.

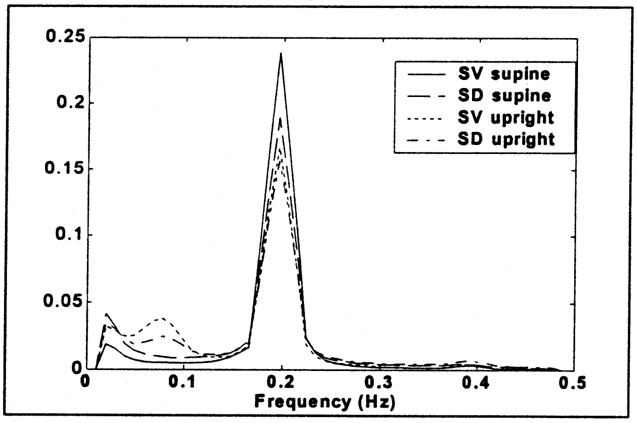

Fig 1: Mean stroke volume power spectra – controlled breathing

3.2. Correlation of beat-to-beat values

Correlation coefficients between pulse contour stroke volume and Doppler stroke distance are summarised in Table 1. The two methods correlate better during controlled than during spontaneous breathing.

Table 1: Correlation coefficients between SV and SD

Condition	Mean	Std Dev	Range	
Overall	0.63	0.18	-0.04	0.89
Supine, spont.	0.56	0.21	-0.04	0.82
Supine, contr.	0.68	0.18	0.31	0.89
Upright, spont.	0.64	0.11	0.48	0.82
Upright, contr.	0.70	0.10	0.44	0.84

Two recordings for the same subject had the lowest correlation coefficients of –0.04 and 0.17, both in the supine position with spontaneous breathing. The next lowest value was 0.31. No identifiable reason for these recordings to have such poor correlations could be ascertained (e.g. noisy Doppler signals, variable shape of Finapres signal). If these two values are removed (as they are more than two standard deviations below the overall mean value) the overall mean correlation coefficient becomes 0.65 ± 0.15 and that for the supine, spontaneous group increases to 0.60 ± 0.15.

3.3. Coherence

Coherence was examined as respiration versus each of PI, SBP, SV and SD; PI vs. SBP; SV and SD vs. PI; SD vs. SBP. Although the lower limit for significant coherence was defined as 0.2 (for four subrecordings) almost all the coherence peaks reached values of 0.5 or more. As expected, significant peaks in the coherence spectra between PI and SBP exist at respiratory and LF frequencies under all conditions (the LF peak is higher for upright recordings). All combinations that included respiration demonstrated high coherence values at the breathing frequency and at the first harmonic (0.4Hz). The coherences between respiration and SBP and respiration and SV being especially strong (mean peak coherence >0.9 for supine and >0.8 for upright positions, Fig 2).

Significant coherence peaks existed at respiratory frequencies between the stroke volume measurements and the other cardiovascular variables (PI and SBP) for all recordings, and in the LF band for the upright recordings (Fig 3). The relationship between SV and SBP was not tested because the pulse contour algorithm uses the area under the systolic part of the pressure signal. Therefore high values of coherence are to be expected and would provide no useful information.

Peak coherence values were higher for controlled breathing than for spontaneous breathing for all combinations, and for supine rather than upright for all combinations except PI vs. SBP. For the controlled breathing conditions the coherence peaks at the respiratory frequencies extended beyond the sharply defined peak in the respiratory spectrum. Also, significant peaks occurred for some subjects at higher harmonic frequencies (0.3Hz and 0.4Hz) even where no respiratory power appeared to exist.

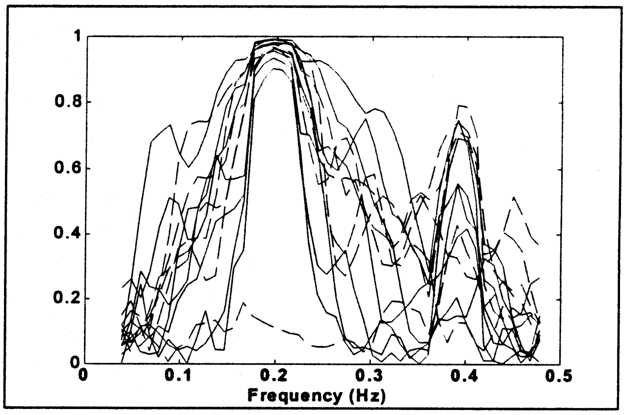

Fig 2: Individual coherence spectra between respiration and pulse contour stroke volume for controlled breathing, supine[1]

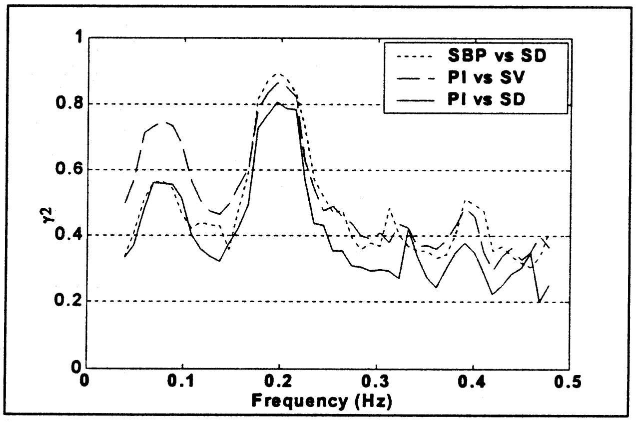

Fig 3: Mean significant coherence spectra between stroke volume and other variables for controlled breathing, upright

4. Conclusion

We have shown for the first time that that there is an acceptable correlation between beat-to-beat values of pulse contour stroke volume and Doppler stroke distance in most healthy subjects. The large discrepancy between these values in one subject during spontaneous breathing in the supine position (R^2 of –0.04 and 0.17) is currently unexplained but the power spectra remain very similar. Fig 4 shows the comparison of pulse contour SV and Doppler SD power spectra for the recording with the poorest correlation (Subject A; supine, spontaneous breathing) and for that with the best correlation of 0.89 (Subject B; supine, controlled breathing).

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[1] The single line that shows no coherence at the respiratory frequency was found to demonstrate a phase shift between respiration and other cardiovascular variables approximately one third of the way throught the recording.

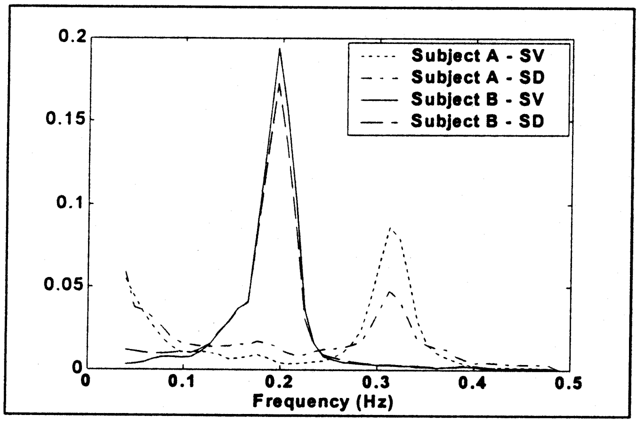

Fig 4: Similarity of SV and SD spectra.

The respiratory frequency variability of stroke volume shown here agrees with previously published results. We have also shown that left ventricular stroke volume as measured by pulse contour and Doppler methods demonstrates significant low frequency (0.05 – 0.15Hz) power in the upright position (Fig 1). The dissimilar physical basis for the two methods and the close correspondence of the results indicates that this a real physical phenomenon.

Previous studies involving coherence measures have taken an arbitrary value of 0.5 to denote a lower limit for significance [12]. We have used random data to establish that, for the spectral analysis procedure used here, 95% of unrelated data pairs (i.e. true coherence of zero) would have a calculated coherence of 0.25 or less (for recordings with 4 subrecords). This value was used for the lower limit of significant coherence although the graphs show that in the frequency bands of interest the coherence peaks reached values much higher than this.

We have also demonstrated for the first time the high coherence values at respiratory frequencies between stroke volume and both pulse interval and systolic blood pressure. Low frequency peaks also exist during the upright stance. The phase relationships between stroke volume changes and those of other cardiovascular variables remain to be identified. Further work includes the use of intravascular blood pressure and the use of a modelling method for the derivation of stroke volume (Modelflow [13].

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