Reproducibility of the signal averaged P wave: time and frequency domain analysis

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Abstract

Objective—To assess the reproducibility of time and frequency domain variables derived from the signal averaged P wave.

Design—Longitudinal within patient study.

Setting—Regional cardiothoracic centre.

Patients—20 patients (10 with documented paroxysmal atrial fibrillation and 10 normal controls) were studied on three occasions to assess the reproducibility of repeated signal averaged P wave recordings. Digital P wave recordings were made on a further 10 patients on a single occasion and the recordings signal averaged twice in order to assess the reproducibility of the averaging system itself in the absence of biological variation.

Main outcome measures—P wave duration, spatial velocity, and energies contained in frequency bands from 20, 30, and 60–150 Hz of the P wave spectrum were measured after P wave specific signal averaging. Coefficients of reproducibility were calculated for paired signal averaged P waves derived by signal averaging the same digital recordings on two separate occasions, for recordings performed in the same patients immediately after each other ("back to back") and those performed one week apart.

Results—System reproducibility when the same digital P wave recordings were signal averaged on two separate occasions was high (< 11% for all variables). For P wave duration the coefficient of reproducibility was 11.4% for back to back recordings and 13.1% for those one week apart. The reproducibility of spatial velocity and P wave energy was low. Variation in P wave morphology was noted when successive P waves from the same subject were examined. If recordings with the same P wave morphology were analysed the reproducibility of spatial velocity and P wave energy improved but remained significantly poorer than that for P wave duration.

Conclusions—P wave duration is reproducible within subjects in the short and medium term. Frequency domain and spatial velocity analysis are poorly reproducible, due more to spontaneous variation in P wave morphology than to instability of the signal averaging process. This may limit the utility of signal averaged P wave variables other than duration for the prediction of atrial arrhythmia.

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Keywords: signal averaged P wave; time domain analysis; frequency domain analysis; reproducibility

Abnormalities in the signal averaged P wave appear to discriminate between patients with documented paroxysmal atrial fibrillation and controls without the arrhythmia with a reasonable degree of diagnostic accuracy when selected groups are studied.¹⁻⁴ Additionally, two recent publications have reported good predictive accuracy for this technique in identifying patients at risk of developing atrial fibrillation after cardiac surgery.^{5,6} The value of this technique in predicting the risk of atrial arrhythmia in individuals is likely to depend not only on its overall discriminant ability between different groups or in prospective trials, but also on its reproducibility when repeated measures are made in the same patients.

Analysis of the signal averaged electrocardiogram applied to the QRS complex, while giving reasonable reproducibility in parameters derived from the time domain, has shown a disturbing lack of reproducibility in frequency domain measures of ventricular activation.^{7,8} The aim of this study was to conduct an analysis of the reproducibility of both time and frequency domain variables derived from the signal averaged P wave.

Methods

STUDY DESIGN

To assess the reproducibility of repeated signal averaged P wave recordings, 20 subjects were studied: 10 normal controls drawn from medical and technical staff at our institution, and 10 patients with paroxysmal atrial fibrillation documented by 12-lead electrocardiography or Holter recordings. All subjects underwent a standard signal averaged P wave recording according to the protocol below. Immediately after the first recording, without removing the recording electrodes, a second signal averaged P wave electrocardiogram was recorded. Subjects subsequently returned for a third recording one week later. Care was taken to ensure that this third recording was performed under similar conditions to the first two recordings and subjects were scheduled to attend for the third recording at a similar time of day as for the first two. None of the patients were taking antiarrhythmic drugs at the time of any recording. The same signal averaging system was used to record all subjects.

To assess the reproducibility of the averaging

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process in the absence of biological variation, digital P wave recordings comprising approximately 600 beats were made on a single occasion on a further 10 patients, three of whom had had documented atrial fibrillation. These digital recordings were then signal averaged on two separate occasions at least four weeks apart and in random order.

SIGNAL AVERAGED P WAVE RECORDINGS

Our signal averaging and P wave analysis methods have been described before.⁹ Subjects were recorded supine and relaxed in a quiet room. A modified orthogonal lead system was used. Analogue signals were amplified between 4000 and 20 000 times and bandpass filtered between 1 and 300 Hz. A fourth, trigger signal was derived from one of the orthogonal leads and used to align P waves during signal averaging. The latter signal was bandpass filtered between 20 and 50 Hz. Analogue data were then digitised at 1 kHz with 12 bit resolution.

For analysis of system reproducibility, digitised data were stored to disk for subsequent off-line averaging from digital recordings. For assessment of repeated signal averaged recordings the digitised signal was immediately signal averaged in real time. In both cases the same signal averaging algorithms were employed.

Voltage threshold triggering using the R wave of the signal selected for the trigger channel was used to identify each electrocardiographic cycle. However, P waves were then aligned by template matching to an evenly spaced 15 point *P wave derived* template (that is, true P wave triggered averaging). An algorithm that automatically determined the most frequently occurring P wave morphology for each subject was used to select the averaging template. P waves with morphologies that failed to match this template accurately were rejected from the signal average. This technique averaged the most common P wave morphology for a particular individual to a close tolerance, ensuring high fidelity of the resultant averaged waveform. For each recording, 100 to 200 beats were averaged to give a final filtered noise level of < 0.2 µV and an estimated low pass cutoff frequency of at least 70 Hz.

After averaging, P wave duration was calculated after signals were high pass filtered at 40 Hz using a 30 term finite impulse response filter, and a vector magnitude plot was constructed. P wave limits were set automatically by an algorithm that identified the start of the P wave as the point at which the vector magnitude rose to more than three standard deviations above its baseline value, and the P wave end point as the point at which the vector magnitude fell to within three standard deviations of the baseline value of the minimum PR segment magnitude. Spatial velocity—the rate of change of the P wave voltage with respect to time—was calculated by digital differentiation of unfiltered signals between the limits defined above and the mean, peak, and ratio of peak to mean spatial velocity were measured. Spectral analysis comprised Fourier transformation of the entire unwindowed P wave after filtering at a high pass of 15 Hz.⁹ From the resultant power density spectrum the total energy contained in frequency bands from 20 to 150 Hz, 30 to 150 Hz, and 60 to 150 Hz was calculated.

Table 1 Reproducibility of the signal averaging system when averaging the same digital P wave recordings

Variable	Mean 1 (SEM)	Mean 2 (SEM)	CR	% CR
Duration	157 (6)	158 (6)	12	7
MSV	3.47 (0.44)	3.45 (0.43)	0.24	7
PSV	12.91 (1.71)	13.25(1.74)	1.12	9
RSV	3.74 (0.13)	3.85 (0.13)	0.40	11
P20	52.60 (15.3)	52.90 (15.5)	1.43	3
P30	31.53 (6.92)	31.70 (6.98)	0.82	3
P60	3.92 (0.79)	3.90 (0.77)	0.24	6

CR, coefficient of reproducibility; % CR, CR of a variable expressed as a percentage of the mean of the two values of that variable; MSV, mean spatial velocity (SV); PSV, peak SV; RSV, ratio of peak to mean SV; P20, P30, P60, energy contained in frequency bands from 20, 30 or 60 to 150 Hz.

Table 2 Reproducibility of variables from signal averaged P waves recorded immediately each other

Variable	Mean 1 (SEM)	Mean 2 (SEM)	CR	% CR	†P
Duration	139 (3)	140 (2)	15.9	11.4	—
MSV	4.63 (0.30)	4.70 (0.30)	1.44	31.2	NS
PSV	18.62 (1.46)	18.37 (1.32)	6.58	35.4	0.004
RSV	3.99 (0.12)	3.90 (0.12)	0.90	22.6	NS
P20	43.82 (5.25)	43.58 (5.33)	10.68	24.6	0.02
P30	29.80 (3.86)	28.93 (3.86)	6.00	20.1	0.03
P60	3.57 (0.36)	3.71 (0.37)	1.34	37.7	0.0001

CR, coefficient of reproducibility; % CR, CR of a variable expressed as a percentage of the mean of the two values of that variable; MSV, mean spatial velocity (SV); PSV, peak SV; RSV, ratio of peak to mean SV; P20, P30, P60, energy contained in frequency bands from 20, 30 or 60 to 150 Hz.
†P, statistical significance assessed by the Wilcoxon rank sum test.

Table 3 Reproducibility of variables from signal averaged P waves recorded immediately after each other after exclusion of subjects with P wave morphology change

Variable	Mean 1 (SEM)	Mean 2 (SEM)	CR	% CR	†P
Duration	140 (3)	140 (3)	12.5	8.9	—
MSV	4.64 (0.36)	4.71 (0.36)	0.98	21.0	NS
PSV	18.51 (1.73)	18.13 (1.50)	4.38	23.6	0.04
RSV	3.96 (0.15)	3.85 (0.13)	0.90	22.5	NS
P20	43.63 (6.33)	43.01 (6.33)	5.59	12.8	NS
P30	29.21 (4.61)	28.56 (4.56)	5.04	17.3	NS
P60	3.67 (0.43)	3.58 (0.41)	0.57	15.5	0.00

CR, coefficient of reproducibility; % CR, CR of a variable expressed as a percentage of the mean of the two values of that variable; MSV, mean spatial velocity (SV); PSV, peak SV; RSV, ratio of peak to mean SV; P20, P30, P60, energy contained in frequency bands from 20, 30 or 60 to 150 Hz.
†P, statistical significance assessed by the Wilcoxon rank sum test.

STATISTICAL ANALYSIS
Data for each recording for each signal averaged P wave variable are summarised as group mean (SEM). Reproducibility was assessed between paired signal averages of identical digital recordings, the first and second patient recordings (recorded immediately after each other) and the first and third recordings (performed one week apart). For each pair of variables the coefficient of reproducibility¹⁰ is presented, both as an absolute value and as a percentage of the mean value of the variable being examined, where:

$$Cr_{k1,k2} = 2 \times SD(k_1 - k_2)$$

Where CR = coefficient of reproducibility of two measurements k1 and k2, and:

$$\%CR_{k1,k2} = \frac{2 \times SD(k_1 - k_2)}{Mean(k_1,k_2)} \times 100$$

Where %CR is the coefficient of reproducibility expressed as a percentage of the mean value for the two measurements k1 and k2.

Statistical comparison of the reproducibility of different variables was made by comparing

Figure 1 Changes in P wave morphology between the first and second signal averaged P wave recordings in two subjects. (A) A minor change in P wave morphology observed in subject 14 (loss of notch in lead X and slightly more biphasic waveform in lead Y). (B) A major change in morphology noted in subject 16 (notice that the P wave morphology recorded one week later has reverted to that of the first recording).

Table 4 Reproducibility of variables from signal averaged P waves recorded one week apart

Variable	Mean 1 (SEM)	Mean 2 (SEM)	CR	% CR	†P
Duration	139 (3)	139 (3)	18.2	13.1	—
MSV	4.63 (0.30)	3.85 (0.33)	4.34	93.6	0.001
PSV	18.62 (1.46)	14.23 (1.40)	19.26	103.4	0.0001
RSV	3.99 (0.12)	3.70 (0.19)	1.84	46.1	0.001
P20	43.82 (5.25)	44.27 (7.77)	32.54	74.3	0.002
P30	29.80 (3.86)	28.54 (4.48)	20.96	70.3	0.002
P60	3.57 (0.36)	3.89 (0.51)	3.33	93.4	0.0001

CR, coefficient of reproducibility; % CR, CR of a variable expressed as a percentage of the mean of the two values of that variable; MSV, mean spatial velocity (SV); PSV, peak SV; RSV, ratio of peak to mean SV; P20, P30, P60, energy contained in frequency bands from 20, 30 or 60 to 150 Hz. †P, statistical significance assessed by the Wilcoxon rank sum test.

the proportional differences between pairs of recordings for each variable¹¹ using the Wilcoxon rank sum test.

Results

CHARACTERISTICS OF SUBJECTS

The overall mean (range) age of the subjects studied with repeated signal averaged recordings was 39 (25 to 68) years. Eight were female and 14 male. Normal subjects had a mean age of 32 (25 to 50) years (five female, five male). Subjects with documented paroxysmal atrial fibrillation had a mean age of 46 (32 to 68) years (one female, nine male). In five of these subjects paroxysmal atrial fibrillation was associated with structural heart disease (grade I mitral regurgitation in three (one in association with hypertension and one with mitral valve prolapse), mitral valve prolapse without mitral regurgitation in one, and sinus node disease in one); in the other five it was idiopathic.

Subjects whose digital P wave recordings were used to assess system reproducibility had a mean age of 65 (39 to 78) years (five female, five male). Three subjects had digital recordings 24 hours after successful cardioversion from atrial fibrillation. A further six subjects had sinus node disease without documented atrial fibrillation, and one patient was examined during VDD pacing for complete heart block.

SYSTEM REPRODUCIBILITY

When system reproducibility was tested by repeated signal averaging of the same series of digitally recorded P waves, the reproducibility of all P wave variables was high (table 1). There were no significant differences in reproducibility between any variables.

REPRODUCIBILITY OF FIRST AND SECOND RECORDINGS

When all subjects were analysed, P wave duration was the most reproducible variable, peak spatial velocity and frequency domain analysis of P wave magnitude being significantly less reproducible (table 2). Visual inspection of the signal averaged P waves recorded in these subjects revealed major within patient differences in the morphology of the averaged waveform in two subjects, and minor differences in a further two (fig 1). When these four subjects were excluded from the analysis the reproducibility of spatial velocity and frequency domain variables improved, although peak spatial velocity and P60 remained significantly less reproducible than duration (table 3).

REPRODUCIBILITY OF FIRST AND THIRD RECORDINGS

When recordings performed one week apart were analysed, the reproducibility of all variables except filtered P wave duration was poor (table 4). However, in this group of recordings major differences in P wave morphology between the first and third recordings were noted in three subjects, and less striking differences in a further 11 (fig 2). Reanalysis of the reproducibility of the remaining pairs of recordings in which no changes in P wave morphology

Table 5 Reproducibility of variables from signal averaged P waves recorded one week apart after exclusion of subjects with P wave morphology change

Variable	Mean 1 (SEM)	Mean 2 (SEM)	CR	% CR	†P
Duration	137 (5)	140 (7)	18.92	13.8	—
MSV	4.20 (0.54)	2.80 (0.17)	3.12	75.6	NS
PSV	16.72 (2.88)	11.75 (0.98)	16.44	98.3	0.04
RSV	3.92 (0.24)	4.20 (0.98)	1.46	36.6	NS
P20	36.41 (3.59)	34.67 (3.36)	6.66	18.3	NS
P30	24.30 (1.75)	23.42 (1.33)	6.78	27.9	NS
P60	3.25 (0.68)	3.27 (0.39)	2.02	62.4	0.04

CR, coefficient of reproducibility; % CR, CR of a variable expressed as a percentage of the mean of the two values of that variable; MSV, mean spatial velocity (SV); PSV, peak SV; RSV, ratio of peak to mean SV; P20, P30, P60, energy contained in frequency bands from 20, 30 or 60 to 150 Hz
†P, statistical significance assessed by the Wilcoxon rank sum test.

Figure 2 Changes in P wave morphology between the first and third signal averaged P wave recordings in two subjects. Similar presentation to fig 1. (A) Slight changes in P wave morphology in subject 13 (best seen in lead Y). (B) Clearly different morphologies in subject 11.

occurred revealed improvements in the reproducibility of frequency domain variables, although that of spatial velocity variables and high frequency P wave energy remained poor (table 5).

REPRODUCIBILITY IN PATIENTS WITH PAROXYSMAL ATRIAL FIBRILLATION AND NORMAL SUBJECTS

No difference in reproducibility was observed when repeated signal averaged recordings were analysed separately for normal subjects and patients with paroxysmal atrial fibrillation (table 6)

Discussion

If a technique is to be of diagnostic or predictive value in individual patients it must not only prove to be a discriminant test for a given disease process, but also be reproducible if repeated measurements are made under similar conditions. The signal averaged P wave is a discriminant test for patients with paroxysmal atrial fibrillation¹⁻⁴ and appears to have predictive value in certain groups,^{5,6} but our findings suggest that many numerical measures derived from it are not highly reproducible. The most reproducible measure is time domain assessment of filtered P wave duration. Frequency domain analysis of P wave energy is less reproducible, and spatial velocity measurements are the least repeatable measurements. Analysis of the morphology of successive P wave signals recorded from the same subjects has indicated that there are often considerable changes in P wave morphology with time, whereas when the same series of P waves was averaged on two separate occasions reproducibility was high, suggesting that change in P wave morphology rather than inconsistencies in the P wave averaging system account for the low reproducibility of spatial velocity and frequency domain variables.

The coefficient of reproducibility for P wave duration was approximately 10%. In other words if a subject has a signal averaged P wave duration of 140 ms there is a 95% probability that a second signal averaged P wave duration will lie between 126 and 154 ms (that is, within 14 ms of 140 ms) and a 68% probability that the second duration will be within 7 ms of the first. The mean difference between patients with paroxysmal atrial fibrillation and controls is only 11 ms.¹² This may explain why the diagnostic accuracy of this technique for paroxysmal atrial fibrillation is lower than might be expected from the highly significant differences in group means that have been reported. For P wave energy estimation, the coefficient of reproducibility is much worse than that for P wave duration, which is reflected in a lower diagnostic accuracy.

P wave morphology change has been noted previously by ourselves¹³ and others,¹⁴ occurring in both normal subjects and those with atrial arrhythmia. The selective P wave specific signal averaging system used for the current studies would have enhanced differences in P wave morphology, since it is designed specifically to

Table 6 Reproducibility of signal averaged P wave variables for patients and controls considered separately

Variable	Mean 1 (SEM)	Mean 2 (SEM)	% CR (1 to 2)	Mean 3 (SEM)	% CR (1 to 3)
Controls					
Duration	139 (4)	138 (4)	13.8	139 (4)	13.8
MSV	5.43 (0.43)	3.62 (0.51)	91.3	5.43 (0.43)	91.3
PSV	22.69 (2.07)	13.46 (1.98)	93.2	22.69 (2.07)	93.2
RSV	4.17 (0.17)	3.74 (0.31)	57.7	4.17 (0.17)	57.7
P20	38.23 (5.36)	38.41 (7.12)	76.3	38.23 (5.36)	76.3
P30	29.08 (4.49)	28.64 (5.80)	96.4	29.08 (4.49)	96.4
P60	3.54 (0.53)	4.29 (0.71)	84.5	3.54 (0.53)	84.5
Patients					
Duration	140 (4)	142 (3)	9.8	139 (5)	12.9
MSV	3.84 (0.25)	3.94 (0.26)	31.0	4.08 (0.45)	63.1
PSV	14.55 (1.01)	14.77 (0.96)	29.3	14.99 (2.05)	77.7
RSV	3.81 (0.16)	3.78 (0.15)	26.1	3.66 (0.23)	28.4
P20	49.4 (9.0)	48.54 (8.81)	18.5	50.10 (14.00)	75.3
P30	30.52 (6.52)	30.00 (6.41)	22.5	28.44 (7.16)	38.0
P60	3.59 (0.51)	3.58 (0.52)	20.9	3.49 (0.74)	99.7

CR, coefficient of reproducibility; % CR, CR of a variable expressed as a percentage of the mean of the two values of that variable; MSV, mean spatial velocity (SV); PSV, peak SV; RSV, ratio of peak to mean SV; P20, P30, P60, energy contained in frequency bands from 20, 30 or 60 to 150 Hz.

average together P waves with a certain morphology which it identifies as being the most prevalent at the time of each recording. If a subject presents alternative morphologies to the system, the most frequently occurring morphology at the time of the recording will be averaged. Clearly the numerical superiority of one morphology over another may vary with time. We have shown that selective P wave averaging improves the fidelity of the resultant P wave and increases the recovery of high frequency energy.¹³ A less selective approach which averages together P waves with different morphologies is clearly unsatisfactory, and would probably not improve the reproducibility of the technique, since the shape of the final waveform would still depend on the variable relative contributions of each separate morphology.

While we noted considerable improvement in the reproducibility of the signal averaged P wave when subjects with variations in P wave morphology were excluded from the analysis, reproducibility was still only modest when high frequency energy or spatial velocity (also in part a reflection of higher frequency magnitude) was considered. It has been reported that the use of data windows of variable length for spectral analysis of the terminal QRS complex introduces spurious errors into the analysis.¹⁵ However, we have shown that the use of variable data windows for analysis of the *entire* P wave is more discriminant than analysis of the terminal segment only, with a fixed data window, and less sensitive to changes in P wave end point determination.⁹ Moreover, P wave end point determination in the series of subjects reported in this paper was reproducible, since filtered P wave duration showed a low coefficient of reproducibility. Alternatively, variation in the fidelity of successive signal averages may have contributed to changes in high frequency energy. However, we ensured during each signal average that low noise levels and an adequate estimated frequency response of the signal average had been obtained. The high residual variability that we noted in apparently identical P waves may also reflect variability in the high frequency signal analogous to the changes noted in unfiltered P waves. This inherent variation in P wave morphology is difficult to address and pre-

sents a limitation to analysis of high frequency P wave content.

CONCLUSIONS

We found that the reproducibility of P wave duration when repeated measures were made in the same patients was good. Spatial velocity and frequency domain analysis were less reproducible, apparently because of biological variations in P wave morphology within patients. These variations limit the value of these analyses for predicting atrial arrhythmia in individual patients.

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