# Effect of high-pass filtering on ECG signal on the analysis of patients prone to atrial fibrillation

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**Summary.** The aim of this study was to assess the effect of filtering techniques on the time-domain analysis of the ECG. Multi-lead ECG recordings obtained from chronic atrial fibrillation (AF) patients after successful external cardioversion have been acquired. Several high-pass filtering techniques and three cut-off frequency values were used: Bessel and Butterworth four-pole and two-pole bidirectional and unidirectional filters, at 0.01, 0.05 and 0.5 Hz low cut-off frequency. As a reference, a beat-by-beat linear piecewise interpolation was used to remove baseline wander, on each P-wave. Results show that ECG filtering affects the estimation of P-wave duration in a manner that depends upon the type of filter used: particularly, the bidirectional filters caused negligible variation of P-wave duration, while unidirectional ones provoked an increase higher than 8%.

*Key words:* atrial fibrillation, digital signal processing, electrocardiography.

**Riassunto** *(Effetto del filtro passa-alto del segnale ECG sull'analisi dei pazienti predisposti alla fibrillazione atriale)*. Scopo di questo studio è di valutare l'effetto delle tecniche di filtraggio del segnale ECG sull'analisi dell'onda P nel dominio del tempo. L'analisi è stata svolta su registrazioni ECG multi-derivazione ottenute da pazienti sottoposti a cardioversione per fibrillazione atriale cronica. Sono state analizzate diverse tecniche di filtraggio passa-alto e 3 valori di frequenze di taglio: filtri Bessel e Butterworth a 4 e 2 poli, bidirezionali e unidirezionali, a 0.01, 0.05 e 0.5 Hz. Un'interpolazione lineare battito-battito effettuata su ciascuna onda P è stata usata come tecnica di riferimento per la rimozione delle oscillazioni della linea di base. I risultati mostrano che il filtraggio dell'ECG incide sulla stima della durata dell'onda P in modo dipendente dal tipo di filtro usato: in particolare, i filtri bidirezionali provocano una variazione trascurabile della durata dell'onda P, mentre quelli unidirezionali causano un aumento dello stesso parametro anche maggiore dell'8%.

*Parole chiave:* fibrillazione atriale, elaborazione dei segnali, elettrocardiografia.

## INTRODUCTION

Atrial fibrillation (AF) is the most common arrhythmia encountered in the clinical practice (about 4.5 million people in European Union): its prevalence is estimated between 0.4% and 1% in the whole population, which increases with age (5% for patients older than 65 years and 8% for older than 80 years) [1-5]. Although it is not a lethal disease, AF may increase mortality up to 2-fold, primarily due to embolic stroke. Indeed, the lack of coordinated atrial contraction leads to unusual fluid flow states through the atrium that could favor the formation of thrombus at risk to embolize, especially after return to normal sinus rhythm.

When normal cardiac impulse travels through atrial myocardium, surface ECG recordings show the P-wave. If the atrial depolarization patterns are different from the normal, P-wave may appear prolonged and highly variable. Abnormal P-waves have been observed in patients prone to AF and the analysis of P-wave from surface electrocardiogram has been extensively used to identify patients prone to atrial arrhythmias, especially AF [6-9].

In this context, P-wave analysis is usually performed following both the conventional 12-leads ECG approach and the three bipolar orthogonal leads one, used to construct a P-wave vector magnitude [10-14]. Given the relatively low P-wave amplitude respect to background noise, both approaches use signal averaging technique to obtain a P-wave template.

The quantitative analysis of the P-wave template turned out to be a discriminative test for patients at risk of developing AF or with paroxymal AF with high sensitivity and specificity. The most reproducible parameter seems to be the P-wave duration [13].

Indeed, slowed conduction velocity in several atrial regions together with different cell refractory periods, are believed to be the electrophysiological conditions provoking and maintaining AF [14].

Such atrial conduction abnormalities result in prolonged and highly variable P-waves, detectable by surface ECG. However, the estimation of P-wave

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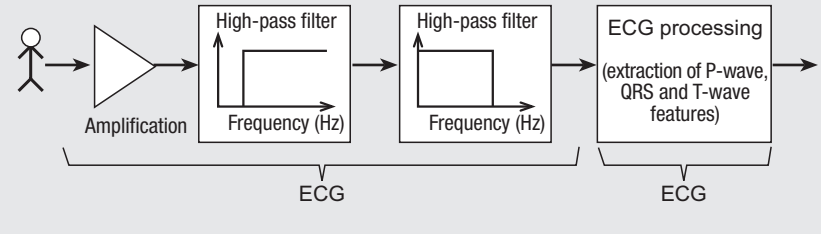


**Fig. 1** | *General scheme of an electrocardiograph equipment.*

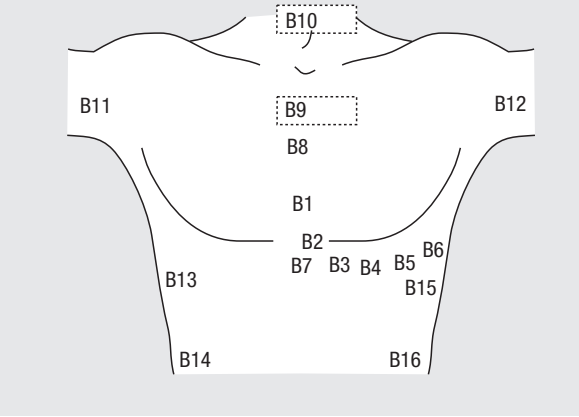


**Fig. 2** | *Electrodes position used for the multi-lead ECG acquisition. Electrodes are indicated with the letter B prefix. Electrode B9 and B10 (dashed line box) are positioned on the back.*

duration, performed either manually or automatically, can be affected by the preprocessing procedure applied to the ECG signal (*Figure 1*) [15, 16].

Standard for ECG signal processing is compulsory when complex morphological and time-domain analysis of the P-wave is attempted. Such feature extraction can be highly affected by the high-pass filters implemented, in different ways, in every electrocardiographic equipment. Such filters, used to suppress (low-frequency) baseline wander, can affect the estimation of P-wave features, given the low-frequency components characterizing the P-wave [17-21]. ECG acquisition and processing systems differ mainly for the type of filters and filtering frequencies used before the signal processing for the extraction of quantitative variables. Review of high-pass filter settings on various modern electrocardiographs shows that manufacturers provide a number of different options, in terms of cut-off frequency, filter order and filter type.

The aim of this study was to assess the effect of filtering techniques on the time-domain analysis of the P-wave.

## METHODS

We analyzed multi-lead ECG obtained from 10 AF patients prone to AF. We used a mapping system for high-resolution biopotential measurement (ActiveTwo, Biosemi, The Netherlands), sample frequency 2 kHz, 24 bit resolution, 0-400 Hz bandwidth.

The system is made of a battery powered AD box that digitises the signals and transfers them to a PCI receiver on computer through fiber optic connection.

Particularly, the 16-lead configuration showed in *Figure 2* has been used. ECG recording lasted 5-minute, with the patient laying on the bed in resting position.

### *High-pass filtering*

To simulate the analogue filters implemented in the most widely used ECG commercial devices, we designed digital high-pass filters, which we applied to the raw ECG recording obtained by the DC-coupled ECG acquisition system used in this study.

Bessel and Butterworth four-pole and two-pole bi-directional and unidirectional filters were used at the tree cut-off frequency values of 0.01, 0.05 and 0.5 Hz. The list of the tested filters is showed in *Table 1*.

**Table 1** | *List of implemented filters*

| Filter | Type | Uni/bi directional | Cut-off frequency (Hz) | Order |
|---|---|---|---|---|
| BeU01_2 | Bessel | Uni | 0.01 | 2 |
| BeU01_4 | Bessel | Uni | 0.01 | 4 |
| BeU05_2 | Bessel | Uni | 0.05 | 2 |
| BeU05_4 | Bessel | Uni | 0.05 | 4 |
| BeU5_2 | Bessel | Uni | 0.5 | 2 |
| BeU5_4 | Bessel | Uni | 0.5 | 4 |
| BeB01_2 | Bessel | Bi | 0.01 | 2 |
| BeB01_4 | Bessel | Bi | 0.01 | 4 |
| BeB05_2 | Bessel | Bi | 0.05 | 2 |
| BeB05_4 | Bessel | Bi | 0.05 | 4 |
| BeB5_2 | Bessel | Bi | 0.5 | 2 |
| BeB5_4 | Bessel | Bi | 0.5 | 4 |
| BuU01_2 | Butterworth | Uni | 0.01 | 2 |
| BuU01_4 | Butterworth | Uni | 0.01 | 4 |
| BuU05_2 | Butterworth | Uni | 0.05 | 2 |
| BuU05_4 | Butterworth | Uni | 0.05 | 4 |
| BuU5_2 | Butterworth | Uni | 0.5 | 2 |
| BuU5_4 | Butterworth | Uni | 0.5 | 4 |
| BuB01_2 | Butterworth | Bi | 0.01 | 2 |
| BuB01_4 | Butterworth | Bi | 0.01 | 4 |
| BuB05_2 | Butterworth | Bi | 0.05 | 2 |
| BuB05_4 | Butterworth | Bi | 0.05 | 4 |
| BuB5_2 | Butterworth | Bi | 0.5 | 2 |
| BuB5_4 | Butterworth | Bi | 0.5 | 4 |

Bidirectional filter was implemented by filtering the signal in the forward direction and then filtering again in the reverse direction. In this way the magnitude of the frequency response is the same for each direction, while the phases are opposite in sign. When the two directions are combined, the magnitude becomes squared, while the phase cancels to zero.

As a reference, a beat-by-beat linear piecewise interpolation was used to remove baseline wander, on each P-wave. Fiducial points for linear interpolation were taken from TP and PQ tracks of each beat. Beat-by-beat regression line estimated over such fiducial points were subtracted from each P-wave (*Figure 3*).

### *P-wave pre-processing*

After ECG filtering, every lead signal was pre-processed and analysed to extract the average P-wave (P-wave template): after P-wave detection, a coherent averaging procedure is applied by aligning the P-waves according to the lag at which the cross-correlation function between the current averaged P-wave and each single P-wave shows its maximum. The coherent averaging procedure went on until 200 beats were included. If the residual noise level remained at more than 1 μV even after averaging of 200 beats, averaging procedure continued until the noise level reached a value lower than 1 μV. If it was impossible, the lead was excluded from the study. Residual noise was measured in the isoelectric segment before the P-wave (TP track).

### *P-wave duration*

P-wave duration has been automatically calculated by using the algorithm described in [19, 20]. Briefly, P-wave duration is defined as the time between the onset and the offset of the P-wave. P-wave onset is automatically computed as the first point, among 20 consecutive points, higher than 3 times the residual noise standard deviation. Offset is analogously defined considering the first point, among the last 20 consecutive samples going backward from the QRS, being above the same threshold. Residual noise was measured in the isoelectric segment before the P-wave, as for the coherent averaging procedure stop criteria.

### *P-wave morphology*

P-wave morphological analysis was based on a Gaussian fit, *i.e.* P-wave is modelled by the sum of up to 8 Gaussian functions [21]. The number of Gaussian functions needed to model the P-wave (model order, N), the number of zero crossings (NZ) and the sum of relative maxima and minima (MM) of the model have been defined as morphological parameters of the P-wave.

## RESULTS

A total of 154 P-waves were analyzed in terms of P-wave duration and morphological parameters.

Results show that ECG filtering affects the estimation of P-wave duration and morphology. Such effects occur in a manner that depends upon the type of filter used.

Particularly, the cut-off frequencies tested in this study, seems to affect the P-wave duration in similar manner. As for the filter order, we found that the 2-pole filters provoke the P-wave duration to be 1-2 ms longer than the 4-pole ones, and thus affect the P-wave duration estimation in a negligible manner.

Respect to the not-filtered P-wave, the bidirectional filters caused a not significant variation of P-wave duration, while unidirectional ones pro-

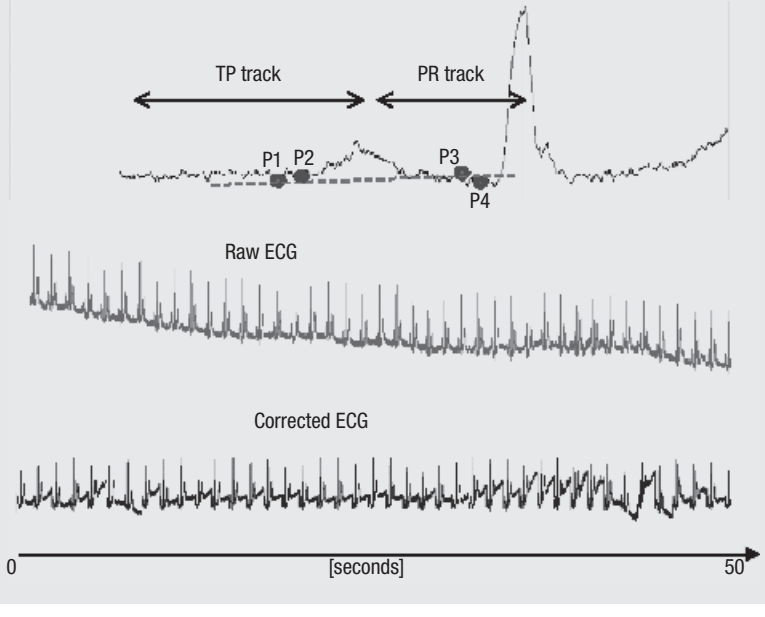


**Fig. 3** | *Beat-to-beat linear piecewise interpolation (upper panel) and its effect of entire ECG (lower panel).*

**Table 2** | *Results obtained for P-wave duration: percentage variation respect to linear piecewise beat-to-beat interpolation is reported*

| Filter | P-wave duration variation (%) |
|---|---|
| BeU01_2 | 3.8 ± 1.5 |
| BeU01_4 | 3.2 ± 2.1 |
| BeU05_2 | 4.1 ± 2.2 |
| BeU05_4 | 4.9 ± 3.3 |
| BeU5_2 | 8.8 ± 5.2 |
| BeU5_4 | 8.7 ± 6.1 |
| BeB01_2 | 2.6 ± 1.3 |
| BeB01_4 | 2.5 ± 2.1 |
| BeB05_2 | 3.1 ± 2.2 |
| BeB05_4 | 2.9 ± 2.3 |
| BeB5_2 | 5.8 ± 4.6 |
| BeB5_4 | 5.7 ± 4.1 |
| BuU01_2 | 3.4 ± 1.5 |
| BuU01_4 | 3.3 ± 2.5 |
| BuU05_2 | 4.0 ± 212 |
| BuU05_4 | 4.4 ± 3.1 |
| BuU5_2 | 7.8 ± 5.2 |
| BuU5_4 | 7.9 ± 5.1 |
| BuB01_2 | 2.8 ± 1.4 |
| BuB01_4 | 2.3 ± 2.0 |
| BuB05_2 | 3.0 ± 2.3 |
| BuB05_4 | 2.2 ± 1.3 |
| BuB5_2 | 3.8 ± 4.3 |
| BuB5_4 | 3. 7± 4.0 |

voked longer P-waves. The average increase of P-wave duration for the BuU5_4 filter was 8.7% ± 6.1%. Similar results have been obtained for the other filters. *Table 2* shows the results obtained for the P-wave duration, in terms of variation respect to the baseline wander removal by linear beat-by-beat interpolation.

Not all the morphological parameters turned out to be affected by high-pass filters. NZ was not affected at all, and the model order N resulted to be lower in filtered ECG but not in a significant way. MM resulted lower in filtered ECG than in original ECG in a high percentage of analyzed ECG.

## DISCUSSION AND CONCLUSIONS

A number of papers stated that the quantitative analysis of the P-wave can be used to discriminate patients at risk of developing AF. Atrial conduction abnormalities and atrial impulse propagation delays provoke the P-wave to be prolonged and fragmented when in sinus rhythm [22-25].

However the quantitative analysis of the P-wave is often performed without taking into account important technical aspects of the ECG acquisition and processing: different acquisition settings and processing algorithms used in different clinical realities cause the results to be incomparable.

In addition, many techniques used to extract quantitative indexes concerning the P-wave prolongation or complexity are still based on manual indication by visual inspection.

Particularly, for the estimation of the P-wave duration, various filtering techniques and algorithms are used for the detection of the onset and offset of the P-wave.

Given the low-amplitude of the P-wave portion of the ECG, the detection of such fiducial points is crucial. Thus it becomes necessary to investigate the effect of ECG acquisition and pre-processing procedure on the detection and estimation of the P-wave characteristics.

This issue has been investigated for the signal-averaged ECG systems by Valverde *et al*. [16]. They found that high pass filters usually implemented in SAECG systems (with cut-off frequencies at 29 Hz and 40 Hz) affects the P-wave duration estimation in a manner that depended on the filters used. In particular, they showed that each filter gave different values of sensitivity and sensitivity for the discrimination between paroxymal AF patients and a control group.

In this study, we investigated the effects of several high-pass filters applied to conventional ECG on the P-wave characteristics. To do this, we used ECG acquired by a DC-coupled acquisition system, which do not provide any analogue filter.

High-pass filter to the signal. The raw signals have been processed by 24 digital high pass filters.

We found that ECG filtering affects the estimation of P-wave duration in a manner that depends upon the type of filter used. In particular we found that the unidirectional filter have the major effect on the P-wave duration estimation. High-pass filters resulted to affect the estimation of morphological parameters, which have been recently demonstrated to provide additional and crucial information about the atrial conduction in patients prone to AF. Particularly, the number of peaks and valleys can be significantly reduced by high-pass filtering, producing misleading results. Our data show that a correct and reliable estimation of P-wave duration requires care to the technical aspects of P-wave pre-processing. An error of almost 9% for P-wave duration – obtained as worst case in the present study – corresponds to a variation of more than 10 ms, that is unacceptable in investigations aimed at discriminating patients at risk of developing AF by using cut-off values of P-wave duration.

Indeed, different cut-off values for P-wave duration, dispersion and variance have been found. P-wave duration cut-off, from 110 ms [9, 26] to 120 ms [27] have been suggested for 12-lead ECG recordings, and from 110 ms [28] to 155 ms [22] for the P-wave vector magnitude. Such a proliferation of cut-off values may in part depend on the lack of a standard for the acquisition and processing of the P-wave, including high-pass filtering, signal averaging techniques and alignment of P-wave before

averaging. The reported bias on the estimation of P-wave features can introduce relevant diagnostic error for the discrimination between patients at high and low risk of developing AF and thus poses an obstacle to the clinical use of time-domain P-wave analysis.

A direct practical implication of such study is that high pass filters used in conventional electrocardiographs should be taken into consideration when estimating P-wave duration and morphology to discriminate patients at risk of developing AF. Automatic filtering and preprocessing can indeed affect the quantification of P-wave features, either manual by visual inspection or automatic by a proper software, thus decreasing diagnosis accuracy.

The beat-to-beat linear piecewise interpolation implemented in this study and used as the reference signal, provokes only the TP and PQ track to become iso-electric (on the baseline). Since this time-domain technique is more respective of the P-wave morphology, this technique could be suggested to remove baseline wonder when P-wave characteristics estimation is concerned.

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