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1 Introduction

The objective of this series of exercises is to apply different methods for the estimation of power spectral density on real signals in order to understand their ability to extract relevant information about signals. The first exercise is more orientated to the technical evaluation of the influence of the parameters of the Welch algorithm when the two other exercises are more oriented to the interpretation of the results from bio-medical point-of-view.

2 Ex. 01, Welch algorithm for the estimation of power spectral density of the ECG

The objective of this exercise is to study the influence of the length of the window used to evaluate the power spectral density using the Welch algorithm. The input signal is an ECG measurement with a 50 Hz perturbation. The signal is sampled at 500 Hz and 4 seconds of recording are provided resulting in a length of 2000 samples. The Welch algorithm has been evaluated for window lengths of 100, 500 and 2000 samples. The results are displayed in figure 1.

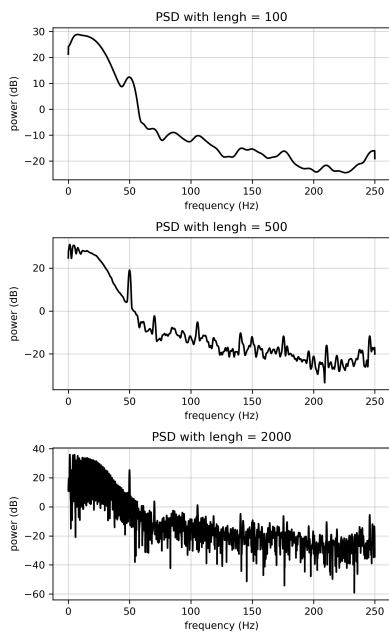


Figure 1: Power spectrum density of a noisy ECG using different window lengths.

The input parameters of the Welch algorithm include the length of the window (`nperseg`) and the overlap (`noverlap`) between consecutive windows. By default (when not specified) the overlap parameter is fixed to one

half of the length of the windows. This means that the number of FFTs used to average the power spectral density is given by the length of the input signal minus the half of the length of the window divided by the half of the length of the analysis window:

- length = 100 → averaging of $\frac{2000-50}{50} = 39$ FFTs
- length = 500 → averaging of $\frac{2000-250}{250} = 7$ FFTs
- length = 2000 → averaging of $\frac{2000-1000}{1000} = 1$ FFTs

On the other side, the spectral resolution for a window length (independently of the windows applied) can be approximated as twice the sampling frequency divided by the length of the window used (width of the first lobe of a rectangular window). This lead that the spectral resolution for windows of 100, 500 and 2000 samples the spectral resolution are, respectively, of 10, 2 and 0.5 Hz.

The results presented in figure 1 validate the expected results, for a windows length of 100 samples the signal is smooth because of the averaging that reduce the noise but the spectral resolution is not sufficient to clearly show the 50 Hz peak, for a window length of 2000 samples the spectral resolution is maximal but no smoothing the noise is observed, the length of 500 samples offers a adequate compromise by reducing significantly the noise but still providing a sufficient spectral resolution to highlight the 50 Hz perturbation.

3 Ex. 02, study of the control of the autonomic nervous system before and after alcohol consumption

The objective of this exercise is to study the effect of alcohol consumption on the control of the autonomic nervous system (ANS). In order to highlight the effects of alcohol consumption three signals are analyzed, the cardiac interbeat intervals extracted from the time interval between consecutive R peaks of an ECG measurement, the mean blood pressure obtained with a finger counter pressure finger system and the breathing volume obtained with impedance measurement. Figure 2 presents the temporal plot of these signals. The cardiac interbeat intervals exhibits slow and spike like variations that are related to the baroreflex regulation of blood pressure (some of the spike like variations are also present in the mean blood pressure). Superposed to the variation one can observe that a respiration synchronization takes place. These variations shows that ANS control (more specifically the vagal regulation) is operating correctly. Indeed the respiration, due to variations of pressure inside the thorax, modulate the venous blood return. In order to avoid that blood pressure

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is modulated by respiration the vagal control modulates the beat-to-beat intervals in order to keep the blood ejection volume from the heart constant and thus keeping the blood pressure constant.

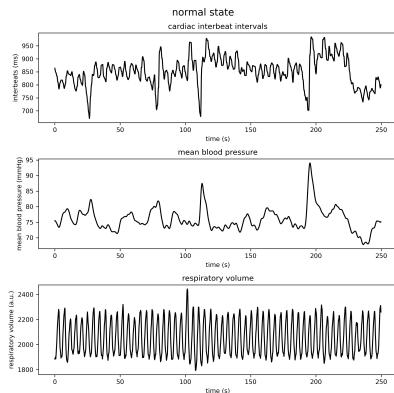


Figure 2: Temporal plots for cardiac interbeat intervals, mean blood pressure and respiration before alcohol consumption.

The mean blood pressure clearly shows that no respiration related oscillations are present in the signal, highlighting that the ANS regulation is operating correctly. The oscillation that are observed are related to the normal regulation of the baroreflex control.

The respiration signal exhibits a normal respiration at a constant frequency. The peak-to-peak variations are related to normal breathing variations.

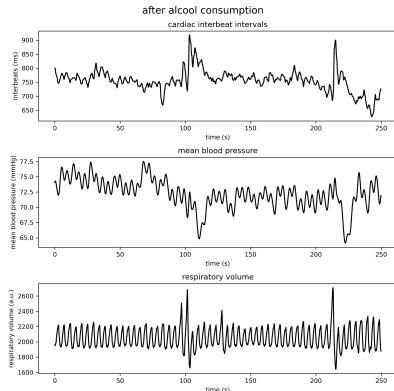


Figure 3: Temporal plots for cardiac interbeat intervals, mean blood pressure and respiration after alcohol consumption.

Figure 3 presents the temporal plots of the same signals after alcohol consumption. On the cardiac interbeat intervals one can observe that the baseline of the signal exhibits less slow variations meaning that the blood pressure control is less active (baroreflex control). The sec-

ond observation is that fast variations are damped (a fast change is followed by a slow return to the baseline value) that are also an indication of the reduction of the ANS control. The third observation is a reduction of the components that are related to the respiration. The reduction of these components means that the variations of the venous blood pressure return are no more compensated, or at least indefectibility compensated. The mean blood pressure shows that oscillations that are related to respiration appears, confirming that the regulation of sinus arrhythmia does not function correctly. Compared to the mean blood pressure observed before alcohol consumption the slow variations have disappeared, or at least are strongly attenuated. This means that not only the control of sinus arrhythmia by the vagal control is affected by alcohol consumption but the whole control of the ANS is affected. The analysis of the respiration signal shows that the respiration is stable except two events that take place around 100 and 200 seconds where the subject has taken deeper breathes. These events have impacted both the cardiac interbeat intervals and the mean blood pressure. The clear relationship with the is difficult to describe without information about the context but we can observe that return to the baseline value is slower than in the signals before alcohol consumption meaning that the ANS control is affected.

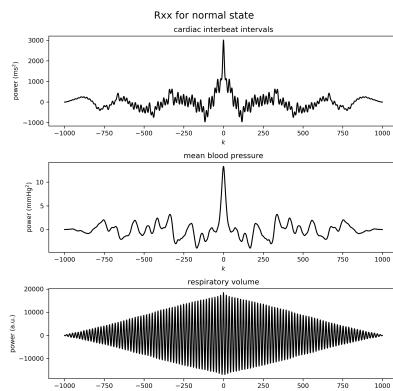


Figure 4: Autocorrelation functions for the different signals before alcohol consumption.

Figure 4 shows the autocorrelation of the different signals before alcohol consumption. The analysis of the plot for the cardiac interbeat intervals shows mainly two components, one of fast frequency that corresponds to the regulation of variation induced by modulation of venous blood return and one of slower frequency that corresponds to the baroreflex regulation of blood pressure. The mean blood pressure signal contains only slow variations and the absence of respiration related components shows that vagal control is effective. The plot of the autocorrelation of the breathing signal does not provide information ex-

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cept the linearly decaying amplitude that shows that the breathing signal is close to a deterministic oscillation.

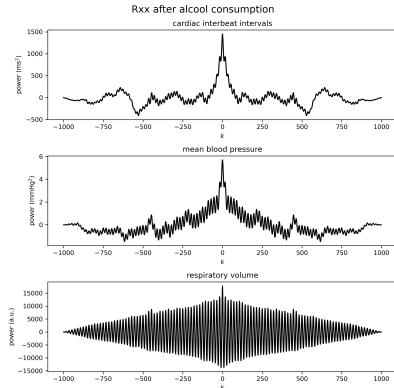


Figure 5: Autocorrelation of the different signals after alcohol consumption.

Figure 5 shows the autocorrelation for the same signals after alcohol consumption. The analysis of the cardiac interbeat intervals confirms that the variations related to the respiration are strongly reduced when compared with same signal before alcohol consumption. The slow oscillation that corresponds to the baroreflex regulation is also attenuated. The signal for the mean blood pressure shows the respiration related oscillations that confirms that the vagal regulation of sinus arrhythmia is not effective. One can also observe that the autocorrelation exhibits a slower exponential decaying of the values of the autocorrelation function and that most of the values of the autocorrelation are positives. The lack of negative values in the autocorrelation function means that no negative feedback takes place in the regulation and thus variations due exogenous factors return to baseline by itself but without regulation of the ANS. The autocorrelation of the respiration is similar to those of the signal without alcohol consumption.

Figure 6 presents the power spectral densities (PSD) of the signals computed from the autocorrelation function. The cardiac interbeat intervals PSD shows different distributions of power. Below 0.04 Hz the observed power distribution corresponds to slow regulation (ULF and VLF) that corresponds to circadian and hormonal regulation, however these values are of little interest in the current case because the length of the signals is too short to evaluate them reliably. Within 0.04 and 0.15 Hz (LF) the regulation of the ANS takes place. On can observe a peak at 0.08 Hz that corresponds to the baroreflex regulation. In the higher frequency bands (0.15 to 0.5 Hz, HF band) corresponds to the regulation of the vagal system to compensate for the sinus arrhythmia. The observation of the power spectrum of the respiration shows a spectral peak at the same frequency that validates that the peak observed corresponds to the variations of beat-to-beat inter-

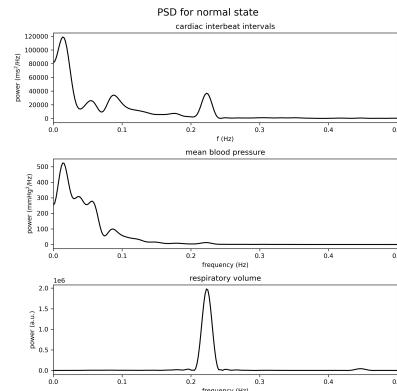


Figure 6: Power spectral density of the different signals before alcohol consumption.

vals aiming in counter-balancing the variations of venous blood return. The mean blood pressure shows the same behavior in the lower frequencies but no, or very small, is observable meaning that the compensation of respiratory induced variations are correctly compensated.

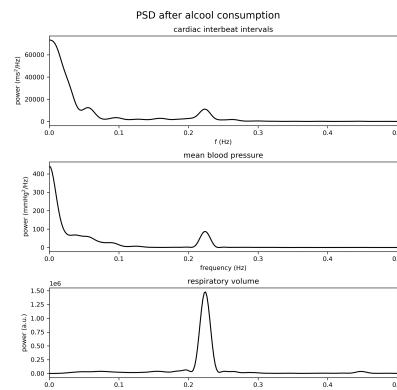


Figure 7: Power spectral density of the different signals after alcohol consumption.

Figure 7 shows the power spectral densities for the different signals after alcohol consumption. On the cardiac interbeat intervals one can observe a reduction of the respiratory peak that highlights the reduction of control of the vagal system. Controversy a peak appears at the respiration frequency in the mean blood pressure signal, confirming that the control is defective and thus respiration related variations appears.

Figure 8 compares the power spectral densities of the different signals before and after alcohol consumption. The previous observations concerning the respiration frequency are confirmed and clearly shows that alcohol consumption significantly affects the regulation. It can also be observed that all the regulation of the ANS is effected

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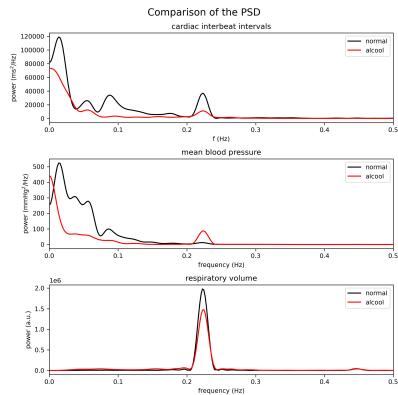


Figure 8: Comparison of the power spectral densities of the different signals before and after alcohol consumption.

by alcohol consumption. Both for cardiac interbeats and mean blood pressure the consumption of alcohol completely reduce the regulation of ANS.

In conclusion during this exercise several representation of the signal have been used to analyse the effect of alcohol on the regulation of ANS. Both the temporal and autocorrelation representation of the signals can be used to analyze the signals but the phenomenon are easier to observe and analyze in the power spectral domain.

4 Ex. 03, atrial fibrillation

The objective of this exercise is to study the p-waves during atrial fibrillation in order to highlight segments where repolarization loops take place in the atria repolarization (p-waves).

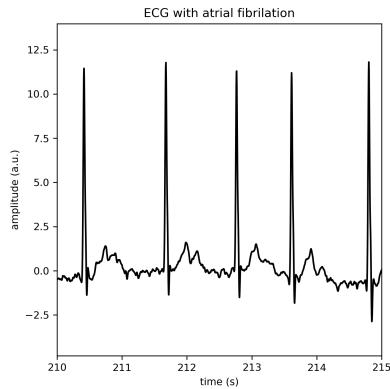


Figure 9: ECG signal with atrial fibrillation.

Figure 9 shows an ECG measurement when atrial fibrillation (AF) is present. On this signal the p-waves are no more synchronous to the other waves (QRST) because of

the fibrillation. The intervals between the R waves is also irregular due to AF. This figure shows that it is difficult to analyse the p-waves due to the presence of the other complexes.

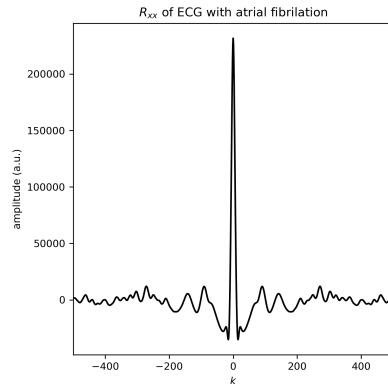


Figure 10: Autocorrelation of an ECG during AF.

Figure 10 present the autocorrelation of the previously present ECG. No clear structure can be observed because of the fibrillation and the varying R to R intervals. The autocorrelation is not suitable for the analysis of the p-waves because the other complexes mask the information.

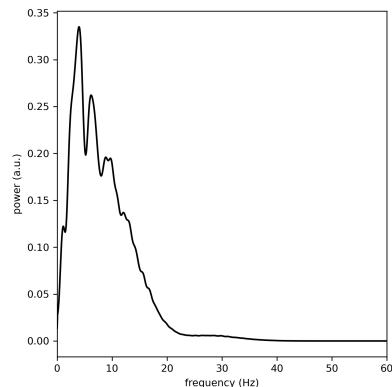


Figure 11: Power spectral density of an ECG signal during AF.

Similarly, the power spectral density of the ECG signal containing AF presented in the figure 11 does not permit to analyse the p-waves signals because all the relevant information is masked by the variability of the beat-to-beat intervals.

The direct analysis of the signal in the time, autocorrelation and spectral domains does not provide sufficient information to study the nature of the AF because the information is masked. To overcome this limitation the ECG has been pre-processed in order to remove the QRST complexes. This removal has been obtained by detecting the

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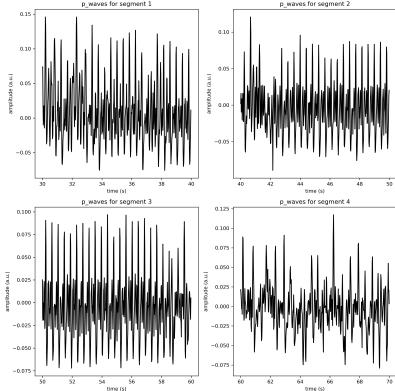


Figure 12: Four different segments of the p-wave only signal.

R peaks and by computing an averaged QRST complex waveform. This waveform template is then subtracted for each R peak and the resulting signal contains only the p-waves. Figure 12 presents four different segments of the p-wave only signal. When the AF signal contains clean repolarization loops one can expect that the observed signal is periodical. The first observation is that the three first segments are more rhythmical when the last one exhibits more a noise like structure. A more detailed analysis shows that the first one exhibits sustained oscillation of around two seconds mixed with transitions. The second segments exhibits a sustained oscillation of around 8 seconds. Finally the third segment exhibits the more stable oscillation.

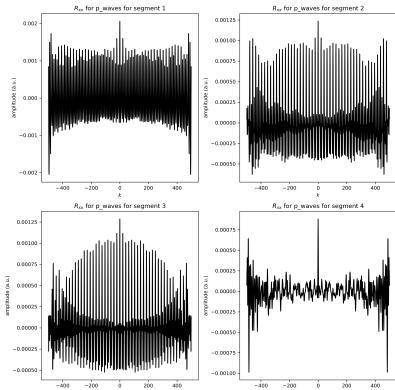


Figure 13: Unbiased autocorrelation of four different segments with p-wave only.

Figure 13 depicts the autocorrelation of the four segments of the p-wave signal. As the unbiased autocorrelation function has been used for these analyses it is straightforward to see that the three first segments exhibit sustained oscillations when the last one has a very fast de-

cay around the value of $k = 0$ meaning that the segment is noise like. For the three segments with sustained oscillation it is difficult to determine which one corresponds to the more stable oscillation.

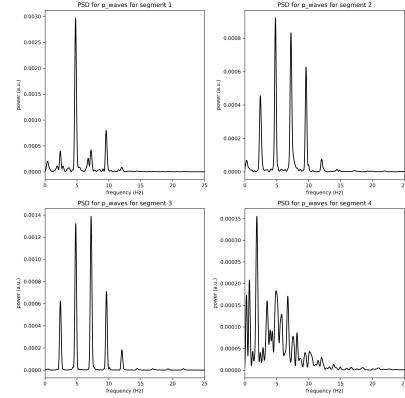


Figure 14: Power spectrum density of the four different segments with p-wave only.

Figure 14 shows the power spectral density of the four segments. With the power spectral density it is straightforward to see that the third segment is the one exhibiting the most stable oscillation because the power spectrum consists only in well defined peaks. The second segment exhibits also a stable oscillation but some low amplitude noise can be observed. The first one shows a deteriorated oscillation because the signal consists in mixed peaks of different frequencies and noise. Finally the fourth segment is the more noisy.

In conclusion the study of the atria repolarization cannot be observed directly from the ECG measurement. In order to permit such analysis the QRST complexes have to be first removed from the signal. The time and autocorrelation analyses permit some investigations about the stability of the oscillation but the power spectral density is a more suitable method to study the stability of repolarization loops during AF.

5 Conclusion

During this laboratory several signals have been analyzed with Welch, autocorrelation and estimation of the power spectral density using the FFT transform of the autocorrelation. The autocorrelation permits to analyze the organisation of the signal (deterministic vs noise like) by analysing the decay around $k = 0$ but the power spectrum density obtained either by calculating the FFT of the autocorrelation or by using the Welch algorithm permits to highlight periodical estimation in the signals.