Detection of Systole and Diastole Start in Cardiac Output and Arterial Pressure Recordings

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Abstract

In coronary artery bypass graft patency research, the quality of the graft is often quantified by the mean graft flow, pulsatility index (PI) and diastolic filling (DF). Calculation of PI and DF requires segmentation of the heart cycle into systolic and diastolic intervals. In this paper we present two methods to identify systolic and diastolic intervals from arterial pressure and cardiac output (pulmonary flow) signals. The methods were evaluated by comparing the start of the systole and diastole in measurements from 6 pigs undergoing bypass surgery. Furthermore, we compared DF and PI calculated using the timings from the two different signals. We obtained a mean difference between systole start of $-2.76\,\mathrm{ms}$ *(*$\pm$ $18.26\,\mathrm{ms}$*) and* $59.59\,\mathrm{ms}$ *(*$\pm$ $81.17\,\mathrm{ms}$*) for diastole start. Finally, we obtained a correlation of* $95.96\,\%$ *for PI and* $60.30\,\%$ *for DF. The use of more than one recording type can be used to ensure more stable results when performing coronary graft patency quality assessments.*

1. Introduction

During coronary bypass surgery the graft patency can be assessed using the graft flow, electrocardiogram, cardiac output and arterial pressure signals. From these signals the diastolic filling (DF) and the pulsatility index (PI) can be estimated. The mean graft flow together with the DF and PI measurements gives an indication of the graft patency [1, 2].

To estimate the DF and PI it is necessary to know, when the systolic and diastolic phases in the heart cycle occur. They can be located using the electrocardiogram, by detection of the Rpeak and the end of the T-wave [2, 3]. The systolic and diastolic phases can also be located from other types of signals, e.g. cardiac output and arterial pressure signals, which can be necessary if the electrocardiogram is not recorded or is of a poor quality. Furthermore, it could be hypothesized that the measurement of DF and PI could depend on the used signal type, as there is a delay between the start of the systole and diastole in the different signal types. This is due to the fact that the electrocardiogram describes the electrical activity of the heart, while cardiac output and arterial pressure describe the vaso-mechanical properties.

Different methods to detect the start of the systole/diastole on arterial pressure signals exists such as the wavelet-based [4], calculation of an auxiliary signal and applying decision rules [5, 6], using deriviatives [7, 8] or filter banks [9]. To the best of our knowledge, no efforts has been made to detect the systole or diastole start on the cardiac output signal.

In this paper, we present a method to detect the start of the systole and diastole from cardiac output (pulmonary flow) and compare it to a simple deriviative based method that uses the arterial pressure signal to detect the start of the systole and diastole. We investigate the bias between them as well as the stability. Furthermore, we investigate the correlation between DF and PI obtained using the two different signals.

2. Methods

2.1. Study population

Recordings from 8 pigs undergoing coronary bypass surgery were obtained. The signals include simultaneously measured electrocardiogram, central venous pressure, cardiac output (pulmonary flow), arterial pressure and graft flow, and were obtained from the VeriQ VQ4122 (Medistim A/S, Oslo, Norway).

For each pig a set of measurements exist, each $60\,\mathrm{s}$ long, and the total data set included 338 measurements. Each measurement were measured under varying conditions such as varying heart rate or blood pressure. If either the cardiac output or arterial pressure signal in a measurement contained noise, the measurement was removed.

To avoid over-training during the algorithm develop-

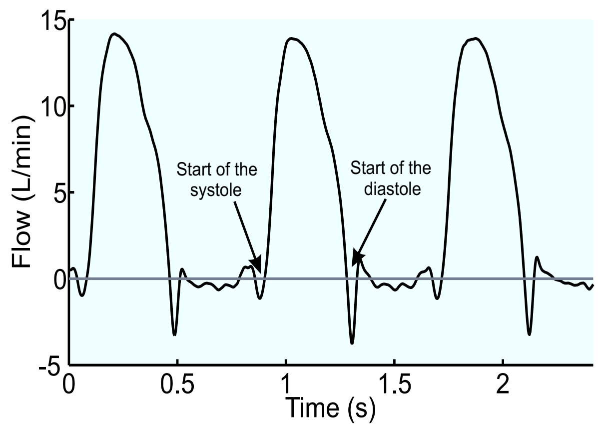

Figure 1: The start of the systole and diastole on the cardiac output (pulmonary flow) signal, was located at a zero-crossing on both sides of the systolic peak.

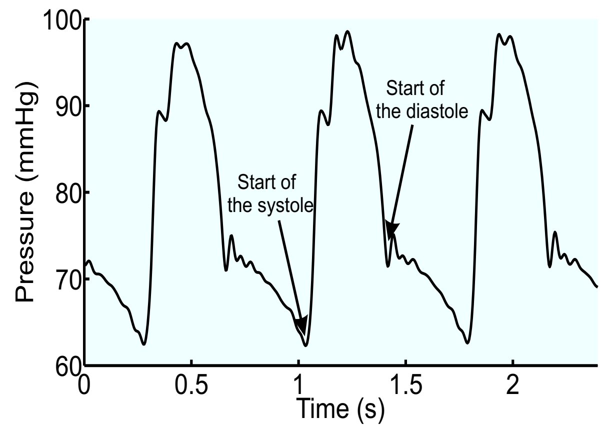

Figure 2: The start of the systole was located on the left of the systolic peak, while the start of the diastole was found at the dicrotic notch.

ment, the measurements were divided into a training (57 measurements) and test (210 measurements) set.

2.2. Detection of systole and diastole start

Cardiac output (fs = $310\,\mathrm{Hz}$) and arterial pressure (fs = $250\,\mathrm{Hz}$) signals were filtered with a high-pass bidirectional IIR filter with a cut-off frequency of $0.5\,\mathrm{Hz}$ in order to remove baseline wander. Furthermore, the signals were normalized according to their normal range ensuring robustness when noise were present.

2.2.1. Cardiac output

Initially, all maxima, exceeding a threshold of 0.5 of the normalized signal, were located. The start of the systole was defined as the first zero-crossing before a maximum, see figure 1.

For some cardiac output signals no zero-crossing was present, but a local minimum was. Therefore, the start of the systole was identified as the closest zero-crossing or minimum to the previously detected maxima. The start of the diastole was identified in a similar manner.

2.2.2. Arterial pressure

The algorithm was initiated by a search for a maximum exceeding a value of 0.025 of the normalized signal. From here a backwards search for the start of the systole was performed. In some cases the arterial pressure signals had clear artifacts near the systolic peak, and these artifacts would be found using the above mentioned threshold. To allow for a robust algorithm any maxima within $120\,\mathrm{ms}$ were discarded, and the remaining maxima were used for the backwards search for a local minimum, corresponding to the start of the systole, see figure 2.

From each maxima a search within a window for the dicrotic notch is performed. The search window is defined from the current maxima to the following systole start. Three criteria were used to identify the dicrotic notch in the differentiated signal, which was calculated using a Savitzky-Golay filter with an order of 3 and a window size of 5. In the differentiated signal the first zero-crossing, positive slope and local maximum were located. The one closest to the systolic peak of the three was selected as the dicrotic notch, i.e. the start of the diastole.

2.3. Comparison of diastolic filling and pulsatility index

The DF and PI are often used to quantify the quality of graft flow. DF is defined by [10]:

$$DF = \frac{Total\ diastolic\ flow}{Total\ diastolic\ flow + Total\ systolic\ flow}$$

where total systolic and diastolic flow were defined as the sum of graft flow during the systole and diastole. The systolic and diastolic timing is either defined by the cardiac output or arterial pressure signal. PI is defined as [10]:

$$PI = \frac{Maximum\ flow - Minimum\ flow}{Average\ flow}$$

where maximum, minimum, and average flow was defined using the graft flow, where the start and end of the cardiac cycle is defined by the cardiac output or arterial pressure signal.

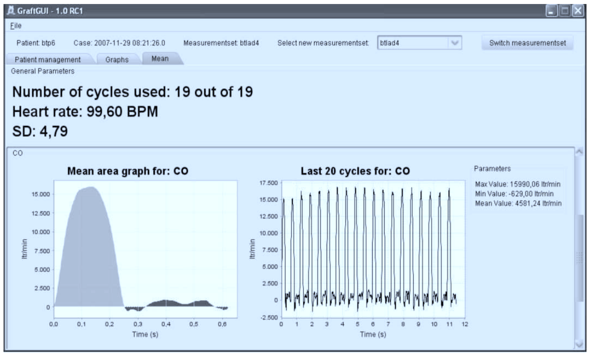

Figure 3: The described algorithms for detection of systole and diastole start on different types of signals are implemented as a part of the software framework GraftGUI, above is a screenshot of the program. The framework is freely available per request to the authors.

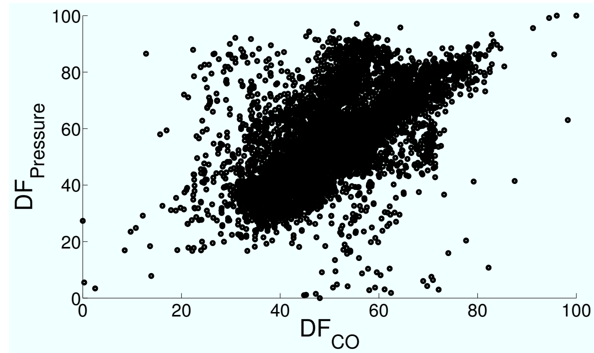

Figure 4: The diastolic filling obtained using the timings of the cardiac output (pulmonary flow) signal compared with those obtained using the timings obtained with arterial pressure. Pearson's correlation coefficient was $60.30\,\%$ ($95\,\%$ CI: $58.88\,\%$ to $61.69\,\%$). Outliers removed from the pulsatility index, was also removed from the diastolic fillings before calculating the correlation coefficient.

2.4. Implementation

The algorithms were implemented and tested using MATLAB 7.9.0 (Mathworks Inc, Natick, MA). Futhermore, the algorithms were implemented as processing modules in a software framework that facilitates statistical processing of simultaneously recorded signals. The framework is called GraftGUI, and a screenshot is shown in figure 3. The framework is freely available per request to the authors.

2.5. Statistical analysis

The difference between systole and diastole start, for the cardiac output and arterial pressure signals, was calculated and the significance of the difference was tested using a two-sided student's T-test ($\alpha = 0.05$). To quantify which signal type that had the most stable measurements of the systolic duration, the standard deviation of the systolic duration of each measurement was obtained. The difference of the standard deviations was evaluated using a two-sided student's T-test ($\alpha = 0.05$)

Finally, the PI and DF obtained using either cardiac output or the arterial pressure signal was compared using Pearson's correlation coefficient, and the significance of the correlation coefficient was evaluated using the $95\,\%$ confidence interval.

3. Results

3.1. Systole and diastole start

The difference in systole start between cardiac output and arterial pressure was $-2.76\,\mathrm{ms}$ ($\pm\ 18.26\,\mathrm{ms}$), $p = 0.04$. The difference for the diastole start was $59.59\,\mathrm{ms}$ ($\pm\ 81.17\,\mathrm{ms}$), $p < 0.01$. The mean STD of the systolic duration obtained using cardiac output was $18.17\,\mathrm{ms}$ ($95\,\%$ CI: $15.87\,\mathrm{ms}$ to $20.48\,\mathrm{ms}$) and $50.44\,\mathrm{ms}$ ($95\,\%$ CI: $45.13\,\mathrm{ms}$ to $55.75\,\mathrm{ms}$) for arterial pressure.

3.2. Diastolic filling and pulsatility index

Figure 4 shows a plot of the DF calculated based on the identified systole and diastole start on the cardiac output and pressure signals. The correlation coefficient was $60.30\,\%$ ($95\,\%$ CI: $58.88\,\%$ to $61.69\,\%$). Figure 5 shows a similar plot for the PI. The PI within a physiological level is shown, i.e. outliers are removed. The same outliers that were removed from the PI was also removed from the DF. The correlation coefficient obtained for the PI was $95.96\,\%$ ($95\,\%$ CI: $95.79\,\%$ to $96.14\,\%$).

4. Discussion and conclusions

Quantification of the quality of the graft patency is required to ensure optimal patient outcome after coronary artery bypass surgery. This is done by investigating different physiological signals, such as the mean graft flow, combined with derived parameters such as DF and PI, which are defined by the start of the systole and diastole periods. The systole and diastole start can be defined using different signals such as cardiac output (pulmonary flow) and arterial pressure, which is investigated in this study.

We obtained a difference between the systole and diastole start measured on the cardiac output and arterial pressure signals. The difference is more prominent for the diastole start, we speculate this is because of problems with identifying the dicrotic notch. To further investigate this,

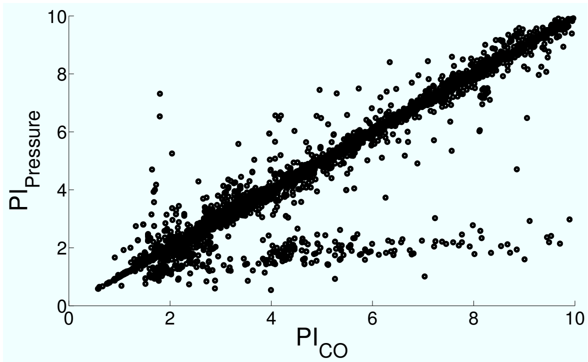

Figure 5: The pulsatility index obtained using the timings of the cardiac output (pulmonary flow) signal compared with those obtained using the timings obtained with arterial pressure. Pearson's correlation coefficient was $95.96\,\%$ ($95\,\%$ CI: $95.79\,\%$ to $96.14\,\%$). Outliers outside the physiological level were removed, before calculating the correlation coefficient.

we calculated the standard deviation of the systolic period per recording, as the duration of the systolic period is assumed to be stable for each recording due to the heart rate being kept constant during each recording. Our findings indicate that the systolic period is more unstable for arterial pressure signals, which suggests that the diastole start is not as precisely detected as the systole start. Finally, we investigated the obtained correlation coefficient between PI and DF obtained using either cardiac output or arterial pressure, to define the systole and diastole start. The obtained correlation coefficient for PI is higher than that of DF, which suggests that the PI is less affected by the location of diastole start, which makes sense with the definition of PI in mind.

The proposed algorithm for detecting the systole and diastole start in arterial pressure signals can be further improved, perhaps by using wavelets. On the contrary the algorithm to detect systole and diastole start using cardiac output is robust. Finally, we have shown that the location of diastole start affects DF more than PI, indicating that PI is a more robust measurement for graft patency.

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References

[1] Becit N, Erkut M, Ceviz M, et al. The impact of intraoperative transit time flow measurement on the result of on-pump coronary surgery. Eur J Cardiothorac Surg 2007;32(2):313–318.

[2] D´Ancona G, Karamanoukian HL, Bergsland J. Is intraoperative measurement of coronary blood flow a good predictor of graft patency? Eur J Cardiothor Surg 2001;20:1075–1076.

[3] Silbernagl S, Despopoulos A. Color Atlas of Physiology. 5 edition. Thieme, 2006; .

[4] Li BN, Dong CD, Vai MI. On an automatic delineator for arterial blood pressure waveforms. Biomed Sig Proc and Control 2010;5:76–81.

[5] Zong W, Heldt T, Moody GB, et al. An Open-source Algorithm to Detect Onset of Arterial Blood Pressure Pulses. Comput Cardio 2003;30:259–262.

[6] P. HSAA, Jansen JRC, Blom JA, et al. Detection of dicrotic notch in arterial pressure signals. J Clin Monit 1997; 13(5):309–316.

[7] Kyle MC, Klingeman JD, Freis ED. Computer Identification of Brachial Arterial Pulse Waves. Comput Biomed Res 1968;2(2):151–159.

[8] Oppenheim MI, Sittig DF. An Innovative Dicrotic Notch Detection Algorithm Which Combines Rule-Based Logic with Digital Signal Processing Techniques. Comput Biomed Res 1995;28(2):154–170.

[9] Aboy M, McNames J, Thong T, et al. An Automatic Beat Detection Algorithm for Pressure Signals. IEEE Trans Biomed Eng 2005;52(10):1662–1670.

[10] Balacumaraswami L, Taggart DP. Intraoperative Imaging Techniques to Assess Coronary Artery Bypass Graft Patency. Ann Thorac Surg 2007;83:2251–2257.

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