



Norwegian University of
Science and Technology

A System for the Acquisition and Analysis of Invasive and Non-invasive Measurements used to quantify Cardiovascular Performance

Ole Øvergaard Omejer

Master of Science in Engineering Cybernetics

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Supervisor: Hans Torp, ITK

Co-supervisor: Lasse Løvstakken, ISB

Problem Description

At the Department for comparative medicine at NTNU, different instruments from different vendors are providing measurements related to cardiac function for physiological research in large animals. There is a need for a centralized tool for acquisition, calibration and synchronization of the different measurements sources. The purpose of this thesis is to develop a system that can fulfill these requirements. Functionality for calculating and comparing different parameters related to cardiac function will also be included in the system.

An important motivation for the development of this system is to allow for comparison of invasive and non-invasive measurements. Invasive measurements produces more accurate indicators of cardiac function, but is often not available in the clinical setting. Non-invasive measurements is more readily available, but is less accurate. The system will have a possibility for comparing parameters calculated from invasive and non-invasive measurements, and thus aiding the development of more accurate measures of cardiac function based on non-invasive measurements.

The system will be developed in close cooperation with a team of doctors, and will be tested out during operations on living pigs.

Assignment given: 10. January 2011

Supervisor: Hans Torp, ITK

Abstract

Invasive measurements of cardiac functioning allows for more accurate measures of cardiac functioning than non-invasive measurements. However, invasive measurements is often not available in clinical settings. By comparing invasive and non-invasive measurements collected in an experimental context, better relationships between non-invasive measurements and cardiac functioning may be found. This master thesis describes the development of two computer applications for simultaneous acquisition, calibration and synchronization of these measurements. The developed applications were tested out during operations on pigs with all measurement sources connected. The results shows that all the desired measurements were successfully acquired by the system. Calibration of the measurements were also achieved. Different methods for synchronization were tested out during the experiments, and it was possible to achieve synchronization of all clocks present in the system. It was concluded that synchronization based on a common ECG altered by a pacemaker was better than synchronization by electrical noise generated by a diathermy.

Preface

This masters thesis is written at the Department of Engineering Cybernetics (ITK) of the Faculty of Information Technology, Mathematics and Electrical Engineering (IME) of the Norwegian University of Science and Technology (NTNU). The work was carried out at the Department of Circulation and Medical Imaging (ISB) of the Faculty of Medicine (DMF). The formal supervisor for this thesis is professor Hans Torp, but the daily supervision has been carried out by researcher Lasse Løvstakken.

The master thesis is a continuation of my project thesis performed the autumn of 2010. During the project thesis, a framework for collection of invasive measurements was created. The first part of this master thesis has been to investigate and implement solutions to challenges discovered during the project work. New functionality related to user-friendliness has been included and several of the algorithms for calculating parameters has been improved. The tool has been expanded with the possibility for analyzing ultrasound images and comparing them to the invasive measurements.

As this thesis is written to be read independently, some topics covered in the project thesis is treated here as well. This report is intended to be detailed enough to be read as a users manual for the developed applications.

Acknowledgments

I wish to thank my supervisor Lasse Løvstakken for his very helpful assistance and feedback.

I would also like to thank medical student Audun Eskeland Rimehaug and the other members of the clinical team, for all help and input.

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Trondheim, June 13

Ole Øvergaard Omejer

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List of Abbreviations

ADC Analog to Digital Converter
DICOM Digital Imaging and Communications in Medicine
ECG Electrocardiography
EA Effective Arterial Elastance
EES End-systolic Elastance
ES End Systole
LVP Left Ventricular Pressure
LVV Left Ventricular Volume
PV Loop Pressure-Volume loop
PRF Pulse repetition frequency
PWR Cardiac Power
SW Stroke Work
TDM Technical Data Management
TDMS Technical Data Management Streaming
TVI Tissue Velocity Imaging
VI Virtual Instrument, Labview's equivalent of a program/subroutine

Introduction

At the Dept. of Circulation and Medical Imaging, research efforts are made to uncover fundamental relationships that influence cardiovascular function. Treating the heart as a pump, its function is at a higher level related to the contractile properties of the myocardium, as well as to arterial and pulmonary loading conditions, called afterload and preload respectively. A wide range of diseases can lead to alterations in the myocardial abilities, or change the afterload or preload which influence performance and which may lead to remodelling of the heart. Basic cardiovascular performance can be summarized by a pressure-volume loop when measured inside the ventricle. This measurement is however not available in clinical practice, where non-invasive measurements must be used. There are currently no non-invasive tools available that are able to measure the contractility directly, or absolute pressure inside the ventricle for that matter, and therefore surrogate parameters that can be related to these basic properties are used. One approach could be to estimate aortic pressure using a tonometric system in the peripheral arteries, another to use ultrasound imaging to quantify the deformation of the myocardium (strain / strain rate imaging). In clinical research there is an increasing list of parameters currently being debated for their abilities to quantify the true contractile properties of the myocardium, without being affected by loading conditions. Therefore, an understanding of the complex relationship between these parameters is needed. But as they are not easily available for measurements in humans, animal experiments must be used where invasive measurements otherwise not available during human treatment can be performed. This may be for instance of pressure, flow and volume which can relate to the parameters above and hence cardiac function. Presently, different instruments from different vendors are providing these measurements in the animal lab at NTNU. This master thesis describes the development of a centralized tool where data can be synchronized and analyzed. The analysis tool also links these invasive measurements to current non-invasive surrogate parameters under investigation. This tool would potentially be used to enhance clinical studies in many future projects.

The tool developed enables semi-automatic calibration of the different measurements. Of pivotal importance is synchronization of the different signals. Synchronization based on common ECG, electromagnetic noise and control of the heart rate is investigated. The system has been tested out during operations on living pigs. The data from these operations is used to present the systems functionality.

The developed tool consists of two applications. The first is an appli-

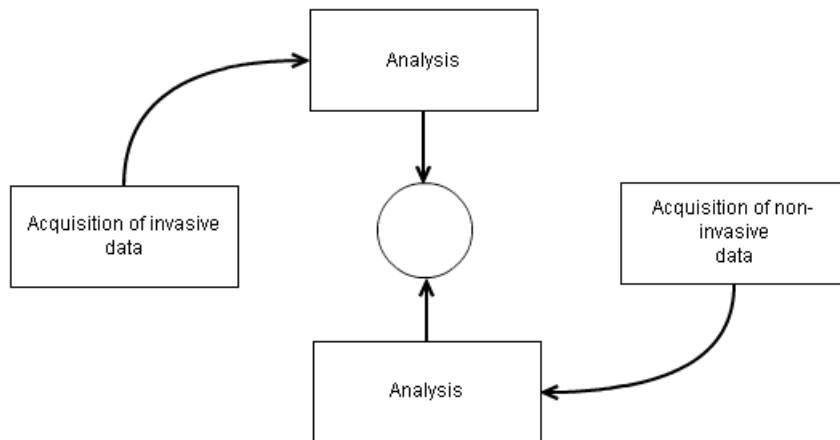


Figure 1: A high level overview of the main components in the developed system.

cation for collecting invasive measurements and a PW-Doppler signal. This application is implemented in the programming language Labview, and is called the *Labview application* for the rest of this thesis.

In addition to the Labview application, an plug-in to the existing tool GcLab were developed as part of this thesis. This tool is called *GcLab plug-in* in this thesis. GcLab enables analysis of ultrasound images, and the developed application allows for comparison of data from ultrasound images and invasive measurements.

Thesis outline

This thesis is consists of four main parts; Background and Theory, Methods, Results, and Discussion and Conclusion.

The Background and Theory section presents the theory necessary to understand the functionality of the developed applications. Theory on the instruments used for data acquisition is included if it is of importance to the applications. Further is some basic theory on the physiology of the heart and circulatory system included.

In the Methods part, the functionality and structure of the applications is described. The lab equipment is briefly introduced. Special emphasis is put on the synchronization of the different data sources. The algorithms for calculation of the desired parameters is presented.

The results part presents the final applications, the measurements collected during the experiments and the parameters calculated.

Theory

Cardiac- and Hemodynamics

The heart and the blood vessels are connected in two circulatory systems, the systemic circulation and the pulmonary circulation system. In the systemic circulation, blood flows from the heart, through the body and back to the heart. In the pulmonary circulation, blood flows from the heart, through the lungs and back to the heart.

The heart consists of four chambers, the left and right atrium and the left and right ventricle. The right atrium receives the blood returning to the heart from the systemic circulation. Blood then flows from the right atrium into the right ventricle. The right ventricle ejects blood into the pulmonary circulation. The blood returning from the pulmonary circulation flows into the left atrium. From the left atrium the blood flows into the left ventricle, and is then ejected into the systemic circulation. The heart chambers works in cycles. The cycle consists of the phases systole and diastole. In systole, the chamber contracts and bloods flow out of the chamber. In diastole, the chamber relaxes, and blood flows into the chamber. Valves between the chambers and the blood vessels prevent backflow of blood. [1].

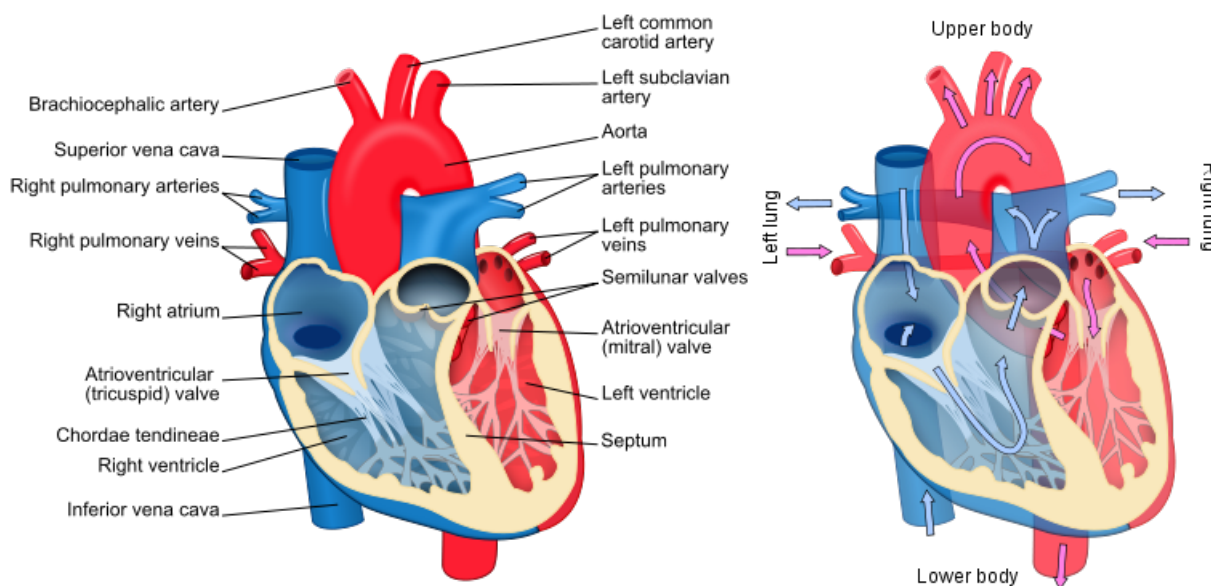


Figure 2: To the left is an illustration of the major parts of the heart. To the right is an illustration of blood flow in the heart.[2][3]

The following discussion on the cardiac cycle is based on the left ventricle. However the right ventricle works in a similar manner.

The left atrium receives blood from the Pulmonary veins. Between the left atrium and the left ventricle is the mitral valve. From the left ventricle blood flow through the aortic valve into Aorta. The start of systole is defined as the closure of the mitral valve. The heart muscles contracts and ventricular pressure is rising. This phase is called *Isovolumic ventricular contraction*, which means that the volume of the ventricle is constant during this phase. When the pressure in the ventricle is higher than the aortic pressure, the aortic valve opens, and blood starts flowing from the ventricle into the aorta. When the ventricle ceases to contract, the aortic valve closes due to the blood in aorta. This is the end of systole and start of diastole. After the closure of the aortic valve the mitral valve is still closed, while the ventricle relaxes. This phase is called *Isovolumic ventricular relaxation*, and the ventricular volume is constant. Pressure in the left ventricle continues to drop, and when it becomes lower than the pressure in the left atrium, the mitral valves opens. The ventricle then starts to contract, and pressure is rising. When the pressure in the ventricle is higher than the pressure in the atrium, the mitral valve closes, and the diastole ends.

The end-diastolic ventricular pressure (LVP) is also called preload. Afterload can be described as the end-systolic LVP [4].

The Pressure-Volume loop is created by plotting the corresponding pressure and volume data in a plot with volume along the horizontal axis and pressure along the vertical axis. In this project the PV loop will be applied to illustrate the relationship between the left ventricle volume (LVV) and left ventricle pressure.

The lower right corner in this PV loop is the start of the systole and end of diastole. The upper left corner is the end of the systole and start of diastole [5].

Contraction of cardiac muscle tissue is initiated by electrochemical signals. This signals generate an electric field that can be detected by electrodes on the surface of the body. The Electrocardiography (ECG) signal is a recording of the hearts electrical events. A characteristic pattern can be seen in the ECG signal, with the R wave as its highest point. The R wave is a part of the QRS complex, which originates from the electrical signal causing the ventricular contraction[1]. Figure 5 illustrates the regions usually found in an ECG signal.

In a healthy heart these signals are provided by the heart's natural pacemaker. An artificial pacemaker can generate signals that dominate over the natural ones and altering the heart rate.

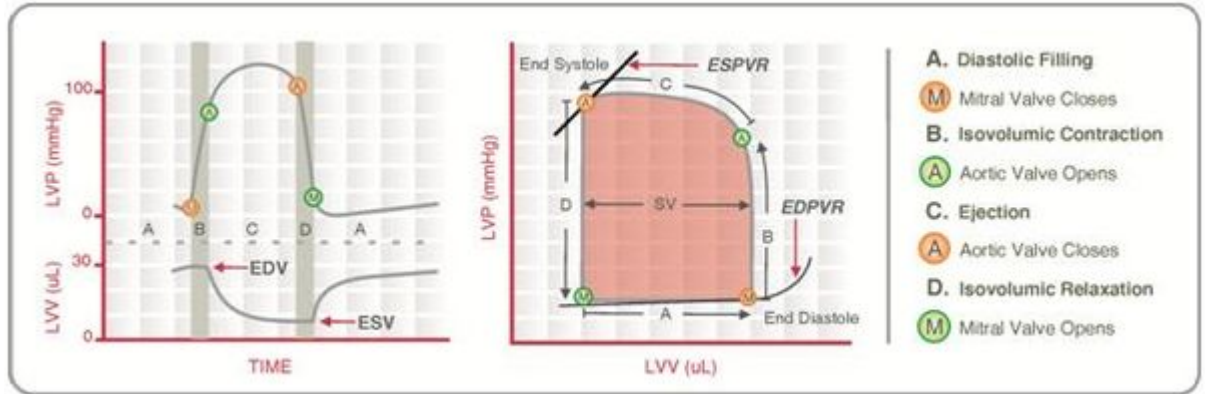


Figure 3: Left ventricle pressure and volume from a cardiac cycle is presented in the left plot. The right plot presents the corresponding Pressure-Volume loop. The major events during the cardiac cycle are listed at the right [6].

Heart Work

Mechanical work is defined as the product of a force on an object and the movement of the object. For a fluid this correspond to the product of the pressure and the volume moved. To calculate the mechanical work done by the heart in a time period, for instance a heart cycle, the integral of the product of the pressure and volume flow in aorta may be used:

$$W = \int P \cdot Q dt$$

Here P is the aortic pressure and Q is the blood flow. The instantaneous product of aortic flow and pressure is called cardiac power (PWR) . The integral of the PWR over a heart cycle is a measure of the hearts stroke work [9].

The area enclosed the Pressure-Volume loop (PV loop) for the left ventricle is a another measure of the hearts stroke work (SW).

End-systolic elastance

By varying the load of the cardiac contraction, a series of PV loops with decreasing end systolic pressure and volume is created.

End-systolic elastance (Ees) is defined as the slope of a line through the end systole pressure and volume points in a series of PV loops. Ees is reflects the contractility of the chamber, and is measured in units of elastance [10].

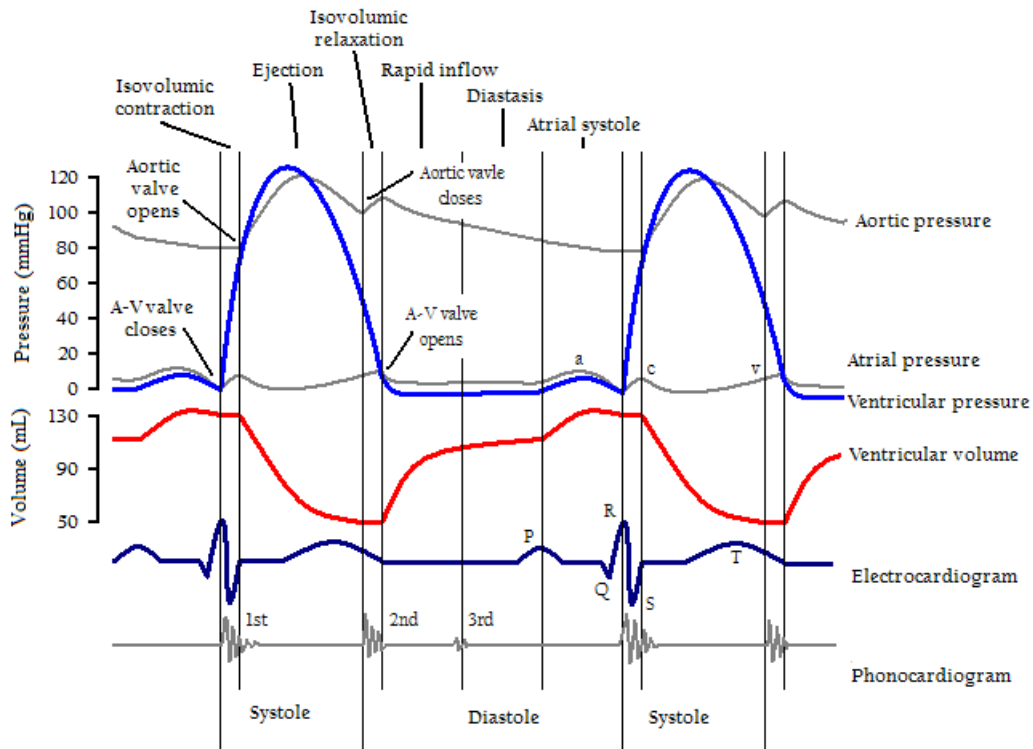


Figure 4: The main events in the cardiac cycle. [7]

Effective arterial elastance

Effective arterial elastance (E_a) is another measure of the heart function, and is also measured in units of elastance. E_a is defined as the slope of the line from the point $(Volume_{max}, 0)$, to the point $(Volume_{end_systole}, Pressure_{end_systole})$ in a single PV loop [10].

Ultrasound

Medical ultrasound technology is based on sending sound pulses with frequencies in the ultrasound specter into the body, and measuring the sound reflected from the tissue. Information on depth is found by the time the reflected pulse arrives. An image is created by sending pulses in several directions in sequence from the probe [11].

Different ultrasound methods is used to obtain different information.

Brightness-Mode (B-Mode) ultrasound produces an image where the brightness of a pixel represents the strength of the received echo from this point. This gives an image of the structures of the tissue. Doppler mode ultrasound

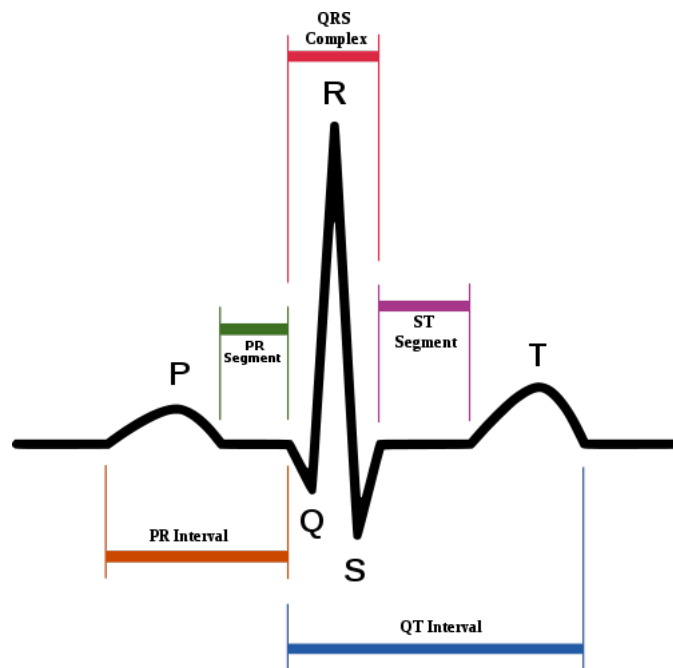


Figure 5: ECG pattern with the major events indicated. [8].

gives information on velocities of blood or tissue.

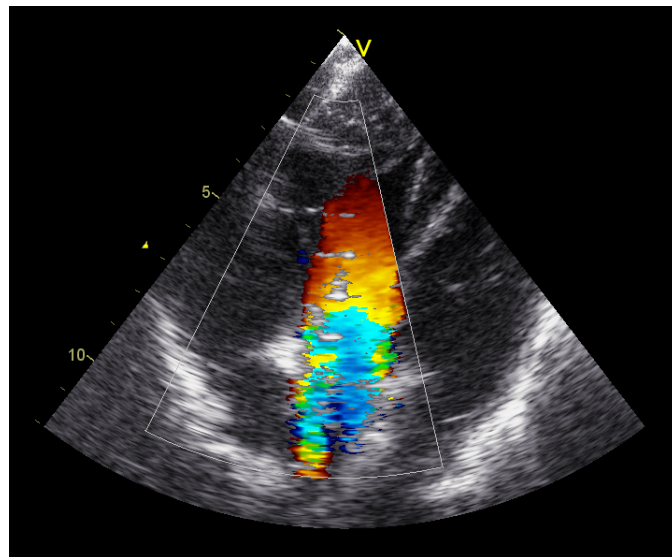


Figure 7: B-mode ultrasound image with color Doppler flow

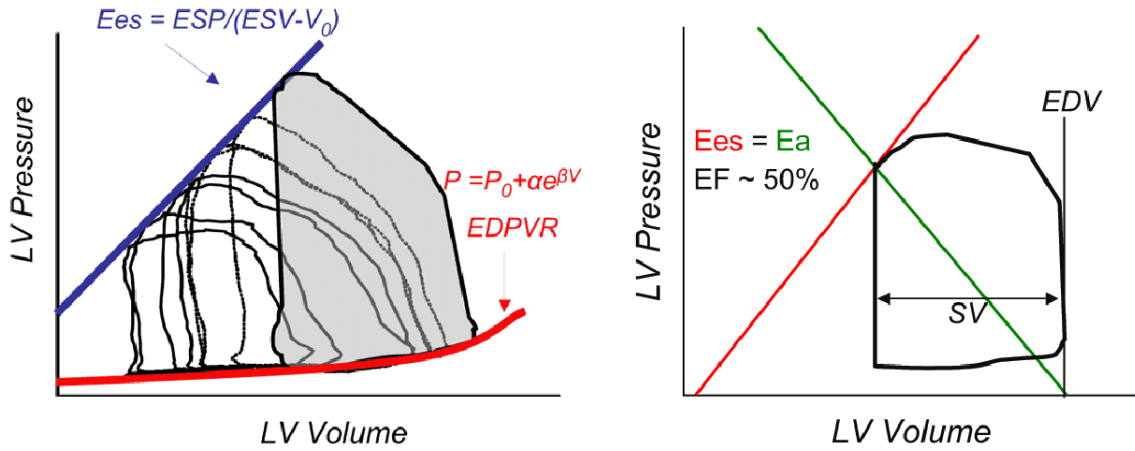


Figure 6: On the left is a series of PV-loops with varying load is displayed. The E_{es} is created by drawing a line through the points of end systole. On the right E_a is displayed for one PV-loop. The figure is taken from [10].

Doppler

When sound waves with a given frequency is reflected from a moving target, the frequency of the reflected sound will be higher or lower depending on whether the target is moving towards the source of the sound or away from it. This is analogous to a boat hitting more waves as it travels towards the waves than in the direction of the waves. This is the Doppler effect, and can be used to estimate the velocities of tissue in the body. By sending ultrasound with a known frequency into the body, and measuring the frequency of the received sound, the velocities of the objects reflecting the sound can be estimated.

Blood velocity can be measured by Doppler ultrasound. Pulses with a known frequency are sent into the body, and the Doppler frequency shift in the received signal is used to estimate the speed [12]. The change in frequency from one pulse to the next is denoted the Doppler shift, and is given by the equation:

$$F_d = 2 \cdot f_0 \cdot \frac{v \cdot \cos(\theta)}{c}$$

F_d is the frequency of the Doppler shift, c is the speed of sound in the tissue, f_0 is the frequency of the transmitted signal and v is the velocity of the blood flow. θ is the angle between the direction of the ultrasound beam and the direction of the blood flow.

The velocity v is found according to the equation:

$$v = \frac{F_d \cdot c}{2 \cdot f_0 \cdot \cos(\theta)}$$

Only velocities in the direction of the ultrasound beam can be measured by Doppler ultrasound.

Pulsed Mode

Pulsed mode Doppler means that the transducer sends out a pulse, and then waits for the received echo. Only echoes with a defined time delay is used, enabling positioning of a sample volume along the beam [12]. The received pulses is IQ-demodulated [13]. The IQ demodulated signal consists of an real and an imaginary part. Every pulse is represented by one complex sample. The frequency shift is estimated by taking the fast Fourier transform (FFT) of a window surrounding each sample in the IQ signal. The resulting specter is displayed horizontally. When this is performed for subsequent samples, a specter can be displayed. The brightness of the pixel values indicates the power of the frequency in the received signal.

Tracing The velocity may be estimated from the specter by producing a trace of the highest velocity with a value above a given threshold. This methods is depending on the blood having a flat velocity profile, which may be a valid assumption for blood flow close to the ventricle.

Autocorrelation Doppler speed can also be calculated by taking the autocorrelation of the IQ signal with lag 1:

$$R1(n) = \text{conj}(z(n)) \cdot z(n + 1)$$

Next the signal is averaged over N samples. The speed is then calculated by the equation:

$$V = \frac{\text{angle}(R1)}{2 \cdot \pi \cdot PRF}$$

PRF is the pulse repetition frequency.

The autocorrelation is detecting the mean velocity from the Doppler velocities that is measured.

Electromagnetic interference

Electrical currents moving through a conductor generated an electromagnetic field [14]. This field may create disturbances in other electrical devices if strong enough. Electromagnetic radiation moves with the speed of light, and can therefore be assumed to affect all equipment in an operation room simultaneously. This can be used for synchronization of different instruments.

Cardiac power project

The first project using the application will be comparing PWR to SW. The following measurements need to be collected in this project:

- Aortic flow measured by Doppler ultrasound
- Aortic flow measured by transit time ultrasound.
- Aortic pressure measured by a Millar catheter
- Aortic pressure measured by a fluid-filled catheter.
- Left ventricular volume measured by a conductance catheter.
- Left ventricular pressure is measured by a pressure transducer.
- Electrocardiography (ECG)

The aortic pressure measurement with Millar catheter is used to validate the measurement with the fluid-filled catheter. The aortic flow measured by transit time ultrasound will be used to validate the flow measurements by Doppler ultrasound and the measurements of ventricle volume. ECG will be measured by two different systems separately, and be used to synchronize data from different sources.

The PV loops will be calculated based on the measurements of left ventricular volume and pressure. SW will be calculated based on the PV loops. Four different PWR parameters will be calculated based on aortic flow measured by Doppler and transit time ultrasound and aortic pressure measured by fluid filled catheter and Millar catheter. The calculated PWR numbers will be compared to the SW.

The first project using the application will investigate the possibility for measuring the cardiac reserve based on PWR instead of SW. PWR requires less invasive measurements than SW, and is therefore more suited to clinical applications [9]. The developed applications main functionality is acquisition,

calibration and synchronization of the necessary measurements. Further is there a need for a tool for validation of the measurements and calculation of parameters like PWR and SW.

Comparison of invasive measurement and ultrasound imaging

Another project is comparing invasive measurement with information extracted from ultrasound images. The following measurements needs to be acquired in addition to the measurements from the cardiac power project:

- Ultrasound images with possibility for extracting TVI curves.
- ECG from the Ultrasound scanner.

The programming language Labview

The first application was developed in the program Labview. Labview is a development environment for the graphical programming language G. Both Labview and G are developed by National Instruments. Labview is assumed to be well suited for data acquisition tasks, such as the one in this project. Another reason for choosing Labview was that the NI USB-6251 BNC board is also produced by National Instruments. It were assumed that programming in Labview would give the easiest implementation of data acquisition from this board.

Basic features

The basic building blocks of Labview are virtual instruments (VI) and basic structures like while- and for-loops. A VI is Labview's equivalent to functions in text based programming languages. A VI can contain other VIs and basic structures.

The VIs and the other structures are connected through data wires. The blocks perform operations on the data that is coming from the wires connected to it. Execution of Labview code is data driven. A Labview block is executed when it has received data on all its input wires. This is a major difference from text based programming languages, where the execution usually is sequential.

Event structures is Labview way of implementing interrupts. The event structure awaits an event, and executes the associated action whenever the event occurs.

When several data is passed together they are grouped as clusters. A cluster in Labview allows the different data to be accessed by name.

Another basic structure in Labview is the tab control, for the rest of this thesis called a tab. A tab is a collection of one or more pages. The pages can for example display graphs and buttons. If there are several pages on one tab, the user can select the desired page on top of the tab. The tab and the individual pages on the tab can be set invisible.

Methods

The system consists of different instruments connected to a laptop computer. The measurements is acquired through an analog to digital converter (ADC), the laptops serial port and the sound card input.

The inputs from the serial port, the ADC and the sound card is acquired through the Labview application. The GcLab plug-in reads files recorded at the ultrasound scanner. Figure 8 gives an overview of the major hardware parts of the system.

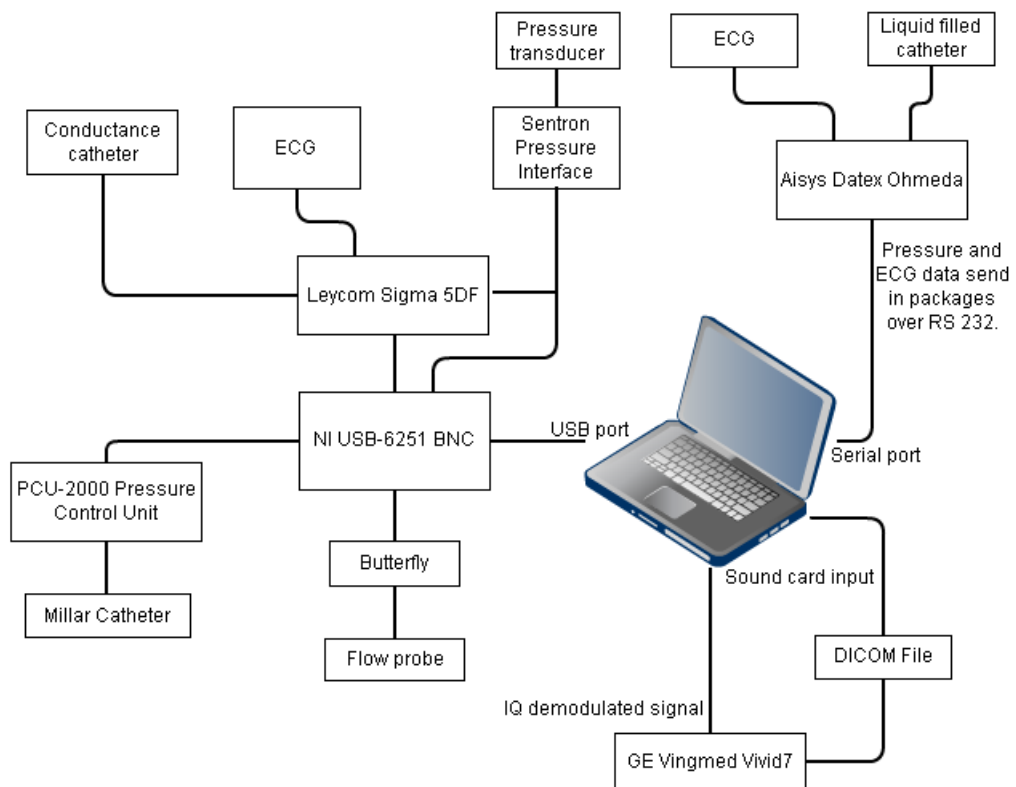


Figure 8: Block diagram of the major components in the system.

Input

Analog to digital converter

The analog inputs is acquired by an ADC named NI USB-6251 BNC produced by National Instruments. This device is connected to the laptop through a USB connection.

The NI USB-6251 BNC contains 8 BNC analog inputs and 2 BNC analog outputs. In this project NI USB-6251 BNC performs sampling and analog to digital conversion of the analog input signals. The input and output range is from -10 to 10 volt. NI USB-6251 BNC is connected to the laptop through a USB connection. The developed application uses Labview's specialized block for communication with NI data acquisition (DAQ) devices named *DAQ Assistant* VI. This block takes the sampling rate and the number of samples to be read per iteration as parameters. When the block is called in a while loop it returns the specified number of samples in each iteration.

Serial Port

The laptops serial port is used for communication in the RS-232 protocol, which is required for receiving data from Aisys Datex Ohmeda.

The communication over RS-232 in Labview is performed by a group of Labview VIs with the prefix VISA. These VIs are Labview's implementation of the VISA language, which is a language for instrumentation programming. The setup of the connection is performed by the *VISA ConFigure Serial Port* VI. This block takes the baud rate, the number of data bits, the parity type, and the number of stop bits as input parameters. The block also takes the input buffer size and the timeout for the reading of the buffer as input parameters. The content of the buffer is read in every iteration of the while loop by the *VISA Read* VI. When the acquisition is stopped the *VISA Close* VI closes the session.

Sound card input

The IQ demodulated signal from the ultrasound scanner is acquired through the sound card input on the laptop. To set up the a sound acquisition session in Labview the *Sound Input Configure* VI is used. This VI takes the sampling rate and the number of samples to read in each iteration as input parameters. In each iteration of the while loop the *Sound Input Read* VI reads the specified number of samples. The *Sound Input Clear* VI closes the sound acquisition session. The sound card input is sampled at 44100 Hertz,

and resampled to the actual sampling rate. Resampling of the sound card input is performed by Labview's *Resample Waveforms (continuous)* VI. The resampling uses the linear interpolation method.

DICOM files

The data from the ultrasound scanner can be saved in the Digital Imaging and Communications in Medicine (DICOM) file format. In this project the DICOM files will contain B-Mode ultrasound images, Color Doppler images, Doppler specters and ECG measured at the ultrasound scanner. Not all information will be present in the same files. The DICOM files will be saved at the scanner, and transferred to the laptop for analysis.

Instruments

Leycom Sigma 5DF

The Leycom Sigma 5DF instruments is connected to a conductance catheter, an ECG device and a pressure interface. The conductance catheter is used to measure the volume of the left ventricle. Five segmental volumes and the total volume is output from Leycom Sigma 5DF. All outputs are in voltages [15]. The total volume and the ECG is taken as an input on the NI USB-6251 BNC.

Sentron Pressure Interface

A pressure transducer sensor is connected to the Sentron Pressure Interface. This transducer is measuring the pressure in aorta. The Sentron Pressure Interface provides an analog voltage output through a BNC connector. This output is connected to the Leycom Sigma 5DF and the NI USB-6251 BNC [16].

CardioMed CM-4000 Flowmeter

A flow measurement probe is connected to the CardioMed CM-4000 Flowmeter. This probe is used to measure flow in aorta. The CardioMed CM-4000 provides an analog voltage output through a BNC connector taken as an input on the NI USB-6251 BNC.

Millar catheter

Aortic pressure is measured by a Millar catheter. This sensor is connected to the PCU-2000 Pressure Control Unit. This instrument gives the pressure as a voltage into NI USB-6251 BNC [17].

GE Vingmed Vivid7

This ultrasound scanner performs B-mode imaging and Doppler measurements. The scanner also provides the IQ demodulated PW-Doppler signal as a aux stereo signal.

In this project the IQ-demodulated signal is taken as an input on the sound card input on the laptop. The DICOM files is read by the existing application GcLab, and synchronized and displayed together with the data acquired by the Labview application.

Aisys Datex Ohmeda

A fluid-filled catheter for measuring blood pressure and an ECG measurement instrument is connected to the Aisys Datex Ohmeda machine. Data is transferred between this peripheral and the laptop through a RS-232 connection. RS-232 is a communication protocol for transmitting serial data. The RS-232 connection is connected to the laptops serial port, located at the laptops docking station.

Aisys Datex Ohmeda can transmit several different types of data. This includes among others respiratory data, blood gas data and anesthesia data, but in this project only the waveform data of invasive pressure and ECG is interesting. This data consists of continuous samples taken at a constant sample rate. Aisys Datex Ohmeda can record and transmit three different ECG channels and eight different invasive pressure channels. The user has to choose which ECG channel and pressure channel to use. The total number of samples per second (S/s) than can be transmitted is limited to 600 S/s. The invasive pressure channels each consists of 100 S/s and the ECG channels consists of 300 S/s. As it is not given which channel the pressure and ECG signal of interest is connected to, all 11 channels can be requested in the application.

Every sample is a signed 16 bit value. The sample value is transferred as two bytes in little endian format. [18]. The specification for communication with Datex Ohmeda 19200 bit/s baud rate, 8 data bits, even parity and 1 stop bit[19].

The data from Aisys Datex Ohmeda is sent in packages. Each packages contains one or more waveforms, and related information. Every package also contains the start time of the waveforms, given as seconds passed since 1.1.1970. Different waveforms from the same package is synchronous. The start time of the waveforms acquired from Aisys is set to be the start time given in the first package. See Appendix B for details on how the packages from Aisys Datex Ohmeda is handled.

Calibration of measurements

The measurements is acquired by different instruments, and sent to the laptop. The developed system is dependent on correct calibration of the instrument. There is also a need for calibration of the transmitting from the instruments to the laptop. An interface enabling this calibration is developed.

The received values is calibrated according to the equation:

$$y = a \cdot x + b$$

Where y is the calibrated value, x is the received value and a and b is the calibration parameters.

The values of a and b is found through the equations:

$$a = \frac{c_1 - c_2}{x_1 - x_2}$$

$$b = c_2 - x_2 \cdot \frac{c_1 - c_2}{x_1 - x_2}$$

Here c_1 and c_2 are the correct values for two points in time, while x_1 and x_2 are the corresponding received values. c_1 and c_2 has to be set manually for all measurements. x_1 and x_2 can either be given set manually or found from the incoming measurements. One method for finding x_1 and x_2 sets them to be the minimum and maximum values of the incoming data. The other method sets the value of either x_1 or x_2 to be the average of the last received samples. This methods will be named method 1 and 2 respectively in the following discussion. The calibration procedures for the different instruments is listed below:

- Aortic pressure by fluid-filled catheter: The maximum and minimum of the received data is displayed on the screen of the Aisys Datex Ohmeda. This leads to calibration by method 1.

- Aortic pressure by Millar catheter: The PCU-2000 Pressure Control Unit has a calibration functionality, that generates a output representing a constant 25 mmHg or 100 mmHg pressure [17]. This values will be used as comparison values. This leads to calibration by method 2.
- Aortic flow by transit time ultrasound: The CardioMed CM-4000 Flowmeter has the possibility for producing output voltages representing known flow levels. This values will be used as comparison values, and the instrument will be calibrated by method 2.
- Left ventricular volume by conductance catheter: Leycom Sigma 5DF has a calibration module that can be used to generate an output voltage representing a fixed volume [14]. This signal will be used as comparison value, and method 2 will be used.
- Left ventricular pressure by pressure transducer: The Sentron Pressure Interface has two buttons used to generate outputs representing constant pressures of 0, 10 mmHg and 100 mmHg [16]. This leads to calibration by method 2.

Synchronization

Three different clocks is present in the system, producing a need for synchronization. The measurements collected with NI USB-6251 BNC and the sound card input is given the timestamp of the current time of the laptop clock when the data is acquired in Labview. The other clocks are synchronized to this time.

Laptop clock

- LVV from Leycom Sigma 5DF
- LVP from the Sentron Pressure Interface
- Blood flow from the CardioMed CM-4000
- Aortic pressure from the Millar catheter
- IQ demodulated signal

It is assumed that delays in the different instruments is negligible.

Aisys Datex Ohmeda clock

- ECG
- Fluid Filled Catheter pressure measurement

The start time of the measurements from Aisys Datex Ohmeda is set based on the start time in the first package received. As the different measurements in the same package are synchronous, the correct synchronization depends on both the ECG and the pressure measurement to be present in the first package arrived. If this is not the case the application will give an error message.

GE Vingmed Vivid 7 clock

- DICOM file

The data in the DICOM files is assumed to be synchronous.

Methods for synchronization

Diathermy

Use of the diathermy creates electromagnetic noise. By adjusting the time offsets for the different measurements until the spike occurs simultaneously, synchronization is achieved. This requires that all measurements is affected by the diathermy at the same time instant. All measurements affected by the diathermy can be used for calibration, but the default is set to be the ECG measurements.

Pacemaker

By altering the heart rate through a pacemaker, a period of changed heart rate is induced in all ECG measurements. By comparing the ECG, this area can be matched. This enables synchronization of all three clocks.

Load change

Changing the preload or afterload results in a detectable effect on the psychological measurements. Especially the aortic pressure measured by the fluid filled catheter and the Millar Catheter. Used together with ECG measurements this enables synchronization of the laptop clock and Aisys Datex Ohmeda.

The DICOM files can not be synchronized in this way because they does not have pressure data saved..

Calculation of parameters

Cycle Detection

Cycles is detected based on the ECG measured by Leycom Sigma 5DF. The start of the systole is defined as the peak of the R-wave for this application. For details on the heart cycle detection see Appendix B.

The ECG from Leycom Sigma 5DF is considered to be the most suitable for heart cycle detection because the ECG from Aisys Datex Ohmeda often experiences drifting.

Stroke Work

SW is defined as the area under the PV loop. Equation 1 for calculation of SW was developed as a part of the project thesis preceding this work. This equation calculates SW by iterating over all pair of subsequent points on the loop. The area beneath a straight line between the points is calculated according to the equation:

$$A_i = \frac{1}{2} \cdot (V_i - V_{i+1}) \cdot (P_i + P_{i+1}) \quad (1)$$

If the value of V_1 is smaller than V_2 , the area is negative. If V_1 is larger than V_2 , the area is positive. By summation over all subsequent points on the PV loop, SW is obtained. This gives the area under a counterclockwise loop. If the loop were clockwise, the area would be negative. However, the characteristic of heart function always creates a counterclockwise loop.

Doppler velocity

The spectrogram of the Doppler frequencies is calculated by taking the fast Fourier transform (FFT) as a sliding window over the IQ-data. In the following discussion the window size is called N. For every sample, the $\lfloor \frac{N}{2} \rfloor$ samples before the sample, the sample and the $\lceil \frac{N}{2} \rceil - 1$ samples after the sample is used for the FFT. The timestamps of the resulting spectrogram and speed estimates is adjusted accordingly. In order to prevent the computing time from becoming unacceptable high, the calculation is only performed for a subset of the samples with an equal distance in between. This increment is chosen by the user.

$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$
$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$
$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$

Table 1: Example of a 2D smoothing filter. In this case the dimensions is set to be 3x3.

After the spectrogram has been created, it is smoothed by a filter. A 2D filter with symmetric coefficients are applied to all pixels in the spectrogram. The size of the filter is set by the user. Table 1 illustrates a 2D filter.

Several algorithms for producing a velocity trace in the spectrogram were investigated in the project thesis preceding this work. The algorithm described here was decided to be the most suited for this application.

The algorithm starts at the position of the highest frequency in the spectrogram. It then iterates downward until it reaches a frequency with a value above a given percentile. This frequency is set to be the Doppler shift for that timestamp.

This algorithm find the maximum of the measured Doppler speeds. This is correct if we assume that the velocity profile is “flat”. In this case the mean velocity is approximately equal to the maximum velocity.

If the algorithm detects a sharp drop to zero frequency shift, the output is set to the frequency detected at the last timestamp.

An limitation to the measurements of blood velocity based on spectrogram is that the spectrum has a limited bandwidth.

In the application the spectrogram is displayed with the velocity estimate is overlaid on the spectra. The velocity estimates is also returned as an array.

The timestamp t_{out0} of the first sample in the velocity estimate array is set by the equation:

$$t_{out0} = t_{in0} - \left(FFT_size - \left\lfloor \frac{FFT_size}{2} \right\rfloor \right) + \left(\left\lfloor \frac{smoothing_filter_size}{2} \right\rfloor - 1 \right) \cdot increment \cdot dt$$

t_{in0} is the timestamp of the first sample in the incoming data. FFT_size is the number of samples used for the FFT. $increment$ is the distance between the samples used for the analysis. dt is the time increment in the sampling interval.

The estimated velocity is smoothed by a mean filter.

Tissue Velocity Imaging

The Tissue Velocity Imaging (TVI) is calculated from the Doppler images in the DICOM file. For a sequence of image frames the value of an individual pixel is taken. This data can be used as in the *Autocorrelation* method described in the *Theory* part to produce a velocity curve.

End Systole

The point i of the end systole is found from the equation:

$$\max(P_i - C \cdot V_i)$$

P and V is the left ventricle pressure and volume for the heart cycle investigated.

C is a scaling constant from the equation

$$C = \frac{P_{max} - P_{min}}{V_{max} - V_{min}}$$

This equations maximizes the pressure and minimizes the volume. This gives an end systole detection based on the start of the isovolumetric contraction.

The equations were developed by Audun Eskeland Rimehaug in the clinical team.

End-systolic elastance and effective arterial elastance

Ees is defined as the slope of a line through the end systole pressure and volume of a series of PV loops. In order to create this parameter, a series of PV loop must be created. These loops need to be identified by the user.

Ees is calculated by minimizing the function:

$$\frac{1}{N} \sum_{i=0}^{N-1} (f_i - y_i)^2$$

N is the number of points used, f_i is the i 'th element of the linear fit, and y_i is the i 'th end systole point. This is done by Labview's *Linear Fit VI*.

Effective arterial elastance (Ea) is defined as the slope of the line from the point $(V_{max}, 0)$, to the point $(V_{end_systole}, P_{end_systole})$ in the PV loop.

Cardiac power

The PWR is calculated by taking the integral of the instantaneous product of the aortic pressure and the aortic flow. The PWR will be calculated for each heart cycle detected. The integration of the instantaneous product will be performed by the *Numeric Integration VI* block in Labview. This block takes the values of the samples, the sampling interval and the chosen method of integration as inputs, and returns the integral value. In this project the trapezoidal method is used for integration.

Filtering

The users have an option for low-pass filtering of the received measurements. The filter used is a FIR filter with coefficients found from the Parks-McClellan algorithm. This filter is implemented through Labviews *Filter VI*.

Developed Applications

To achieve the acquisition, calibration and synchronization of the desired measurements, the two applications described in the introduction were developed. Figure 9 displays how data is passed between the applications and saved to files.

Labview Application

Acquisition of the invasive measurements and the PW-Doppler is performed by the Labview application. This application provides the interface for selection, calibration and calculation of parameters from the invasive measurements. Synchronization between the measurements from Aisys and NI USB-6251 BNC are also performed in this application.

At startup, the Labview application is in the Main VI, illustrated in Figure 10. An event structure waits for the user to name a project. If the project already exists, the user is asked whether to open the existing project or to cancel. After a project is opened a menu is displayed enabling the user to choose either to enter the acquisition state, the analyze state or to exit.

Acquisition

The application has two different states it can enter in the acquisition mode. In the Set Parameters state, the user can set the parameters for calibration,

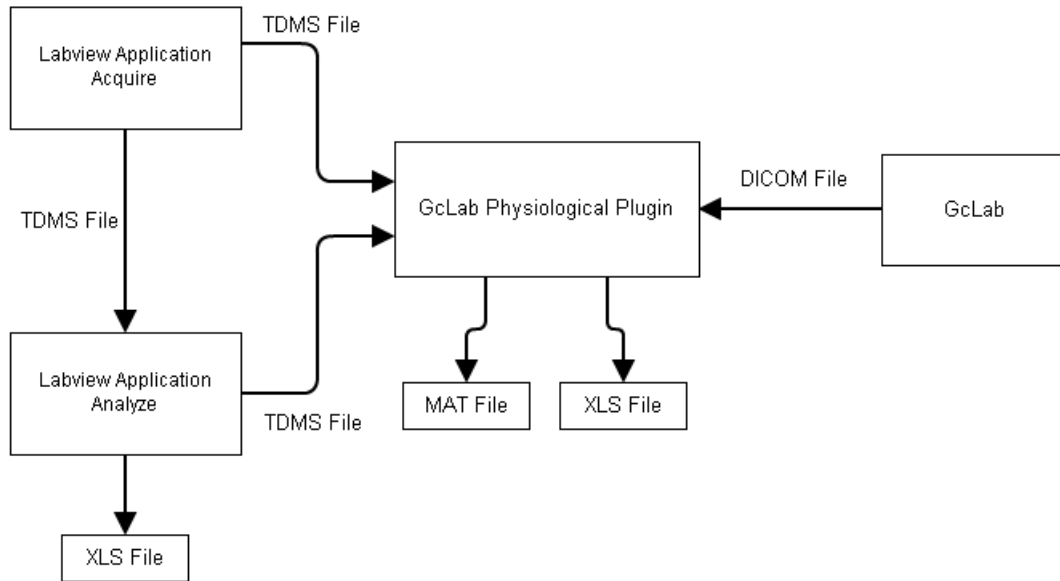


Figure 9: The data flow between the different modules of the system.

synchronization and analysis of the acquired measurements. In the Acquire state, the user can watch the received data and save to file.

The Acquisition mode is implemented with one main while loop polling the buttons for entering the different states. When one of these is pressed, the program starts acquiring data. This is implemented with separate while loops for acquisition and processing of data running in parallel, a so called producer-consumer design [20].

The producer loop performs the data acquisition, and passes the data to the consumer loop through queues. All processing and saving of the acquired data is taking place in the consumer loop.

Collected measurements is on Labview’s waveform format, with includes information on start time, name and sampling rate in addition to the samples.

Analyze

In the analyze mode the user can view the measurements acquired and the calculated parameters. The analyze mode loads and presents the contents of one TDMS file at the time. When the analyze mode is entered, the last saved TDMS file in the project folder is loaded. The user can load any saved TDMS afterward, and the graphs and displays are updated. All the parameters can be recalculated. Whenever a parameter is recalculated, all

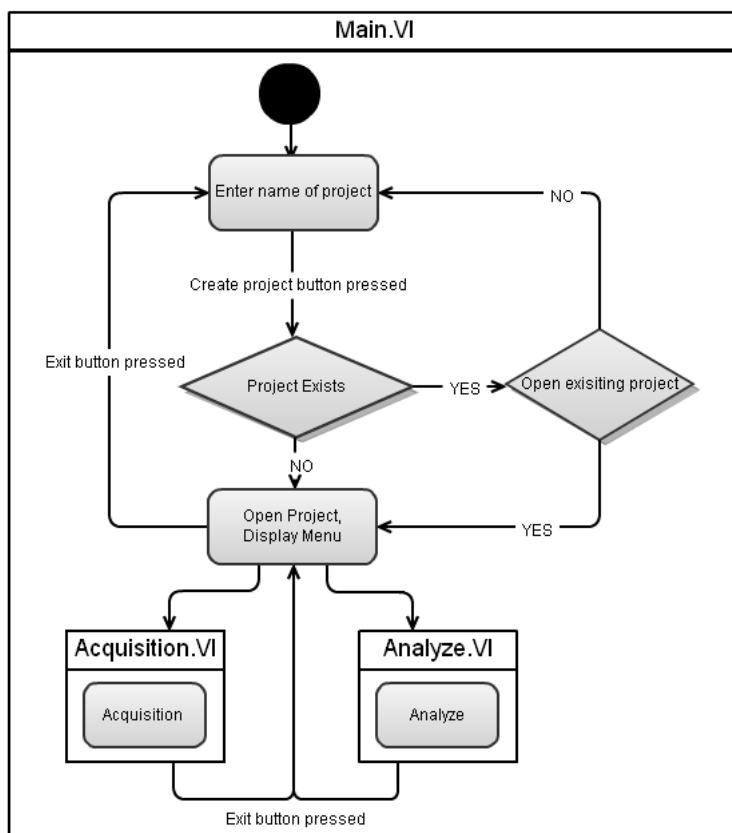


Figure 10: The Main Vi of the Labview application.

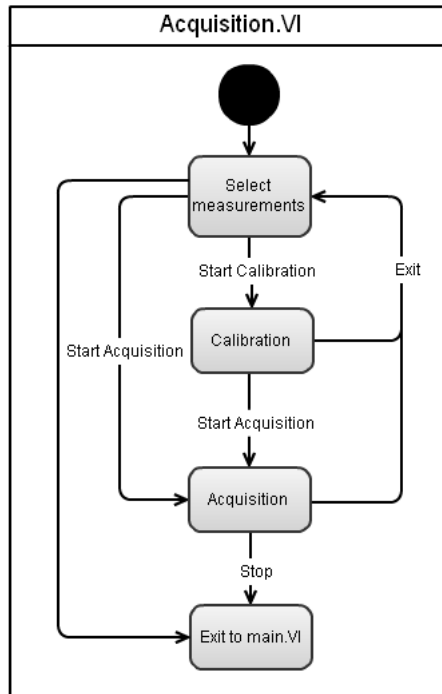


Figure 11: The acquisition state.

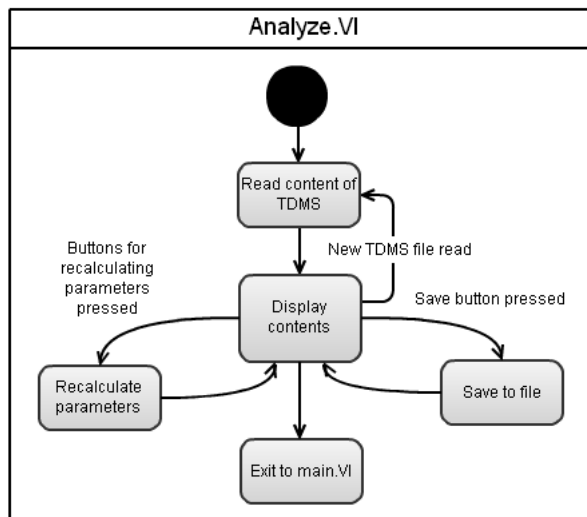


Figure 12: The analyze state.

the other parameters depending on this parameter is also calculated anew, and the displays are updated. From the analyze mode data can be saved as TDMS files or XLS files.

Structure of files and folders

The final application is placed in a folder at the desktop. When the user creates a new project, a folder with the given project name appears in this folder. The project folder contains the saved measurement files, in the TDMS format.

TDMS files

TDMS files is Labview's file format. Data is divided as groups consisting of one or more channels. In this application, the TDMS files created is intended to be read both by the Labview application and by the GcLab plug-in.

The TDMS files created for a measurement series, has the following groups:

- **IQ demodulated data** The unprocessed IQ-demodulated data from the sound card input.
- **Active Signals** An cluster of boolean values is created indicates which measurement that is chosen and parameters that is to be calculated. This cluster controls which measurements that will be collected, which pages will be visible on the tabs, what parameters that will be calculated.
- **Aisys Names** The names given to the Aisys Datex Ohmeda measurements. This information is necessary to recognize the Aisys Datex Ohmeda data when the measurements is synchronized.
- **Measurement.** Waveforms for all measurements collected.
- **Cycle Data** Several channels consisting of arrays of equal length. Each index in every array represent data for the same heart cycle.

The group **Cycle Data** consists of the following channels :

- **Start Timestamp** The start time of the heart cycle
- **Final Timestamp** The final time of the heart cycle
- **SW** The stroke work calculated from the PV loop.

- **ES Position** The position of the end systole in samples from the first sample
- **PWR Doppler Flow and Fluid Filled Catheter**
- **PWR Doppler Flow and Millar Catheter**
- **PWR Probe Flow and Fluid Filled Catheter**
- **PWR Probe Flow and Millar Catheter**
- **Ea** Effective arterial elastance

XLS files

After discussion with the clinical team, it was decided to implement the possibility of saving to spreadsheets in the XLS file format. This is the file format associated with the program Microsoft Excel. This choice was made because this tool is familiar to most users. The possibility of saving files in the .XML format was also investigated. However, this turned out to be slow and memory demanding, causing the application to crash.

Files in the XLS formats has a maximum size of 65 536 rows and 256 columns. Every channel of data has a header consisting of name, sample rate and start time in the first three rows. The data is divided into segments of 60 000 samples. Every segment occupies a variable number of columns, depending on its length. The matrix with cycle information is placed first in the spreadsheet. According to clinical team, it will be sufficient with one XLS file for data lengths of interests.

Plug-in for GCLAB

GcLab is an analysis program for ultrasound data, implemented in Matlab. In GcLab, files in the DICOM file format can be displayed and analyzed. GcLab gives the opportunity to create plug-ins. As a part of this master work, a plug-in with the possibility for combining measurements collected with the Labview application with data from GcLab were developed. A plug-in for GcLab is created by placing a Matlab class file in the folder with the location *GcLab\+plug-ins*. This class needs to inherit the *GcLab.toolbox* class, and follow a defined structure. The plug-in is displayed as a menu in the GcLab window, consisting of elements given in the file. In this system the developed plug-in has buttons for opening a second window. This window displays and synchronizes the measurements from the Labview application and the DICOM files.

Reading TDMS files in Matlab

The data collected in Labview is stored as TDMS files. To read the TDMS files from Matlab, a Dynamic link-library (DLL) nilibddc.dll together with a C-header file provided by National Instruments is used [21].

The DLL provides several functions for reading and writing data and properties of TDMS files from Matlab. However, it is not possible to read the sampling rate and start time of a waveform. Reading the description field of the TDMS channel is however possible, so the solution is to write information on start time and sampling rate as a text string in the description field.

Time format

In Labview the timestamp variable measures time in second passed from 1904-01-01 00:01:00. In Matlab, the time is measured as days passed since 0000-00-00 00:00:00. All time data is converted to the Matlab time format before it is displayed or saved.

Reading of DICOM

In GcLab, an activex object is created to read the DICOM file. When this activex object has the correct parameter set to the value of a DICOM file, the contents of the file is displayed in the object on the screen. The contents of the DICOM file can then be accessed by calling functions on the activex object. In the program designed in this master work, the contents of the DICOM files is accessed through the interface provided by the class udthandle included in GcLab.

Synchronization of measurements

The data from the DICOM and the TDMS files is synchronized based on the ECG signals. The synchronization is dependent on the presence of a recorded ECG measurement in the DICOM file. The time adjustment is calculated to adjust the time of the data in the DICOM file.

Heart Cycle Based Synchronization A time adjustment minimizing the difference between the ECG signals can be calculated based on detection of heart cycles. First the R-waves in both measurement are detected, then the ECG signals with the lowest number of peaks is found. The match between peaks in this ECG and every possible set of subsequent peaks in the other ECG is found. Then the match giving the lowest difference between the two sets is chosen, and the time adjustment is set. This method is dependent

on detectable changes in the in the heart rate, i.e. from a pacemaker. If the heart rate is constant, the algorithm will not be able to find the correct match.

Manual time adjustment The time delay may also be set manually. This allows for synchronization based on diathermy.

Results

Three operations on pigs were conducted to test the system. The operations were conducted by a team of clinical personnel, including aestheticians and surgeons. All operations were approved by the Regional Ethical Committee.

In every operation, the measurements listed in the Sections *Cardiac power project* and *Comparison of invasive measurement and ultrasound imaging* were acquired:

- Aortic flow measured by Doppler ultrasound through the GE Vingmed Vivid7 ultrasound scanner.
- Aortic flow measured by transit time ultrasound by CardioMed CM-4000
- Aortic pressure measured by a Millar catheter through
- Aortic pressure measured by a fluid-filled catheter through Aisys Datex Ohmeda
- Left ventricular volume measured by a conductance catheter through Leycom Sigma 5DF
- Left ventricular pressure is measured by a pressure transducer through the Sentron pressure interface.
- Doppler flow measured by GE Vingmed Vivid7 ultrasound scanner.
- B-Mode ultrasound images and tissue Doppler measured by GE Vingmed Vivid7 ultrasound scanner.
- ECG measured from Leycom Sigma 5DF, Aisys Datex Ohmeda and GE Vingmed Vivid7.

In the third operation, the conductance catheter could not be inserted properly, and no appropriate measurement of left ventricular volume was acquired.

There was also a problem with the ECG connected to the Leycom Sigma 5DF in this operation. The ECG measurement was corrupted by noise and was reversed. In order to use the data in this report, the ECG measurement was filtered and inverted.

The image in Figure 13 displays the laptop and some of the instruments in the operation room.

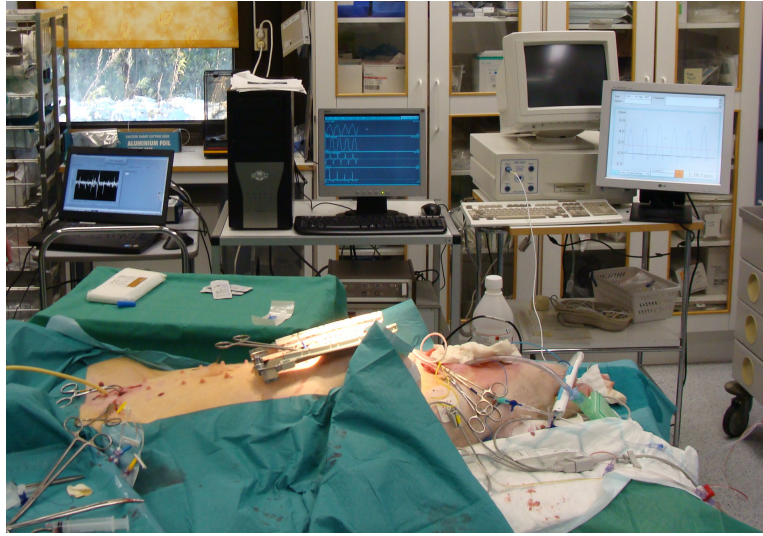


Figure 13: To the left is the laptop with the Labview application running. In the middle is the Leycom system. To the right is the CardioMed CM-4000 flowmeter.

Instruments and inputs

Noise were present in many of the analog measurements acquired by NI USB-6251 BNC. This may be due to NI USB-6251 BNC having little electrical insulation. In order to remove the noise, a possibility for low pass filtering is included in the application. As the PV loops is strongly affected by the noise, the effect of the filtering is illustrated by the LVV, LVP and the resulting PV loops. Figure 15, 14 and 16 displays the unfiltered and filtered measurements and the corresponding PV loops.

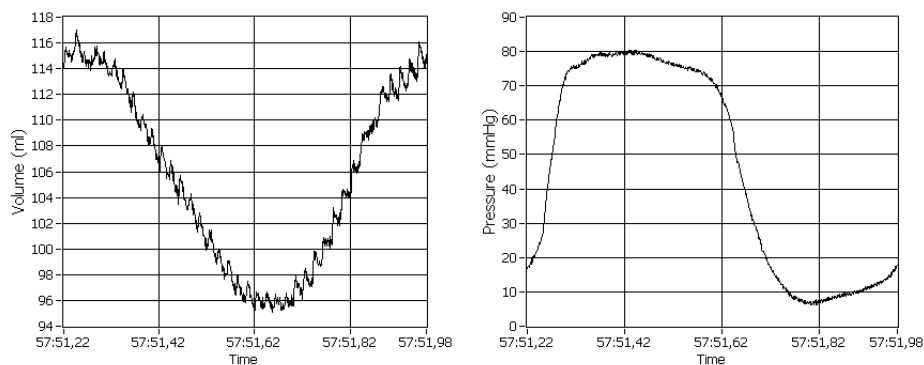


Figure 14: Unfiltered measurements of LVV to the left and LVP to the right.

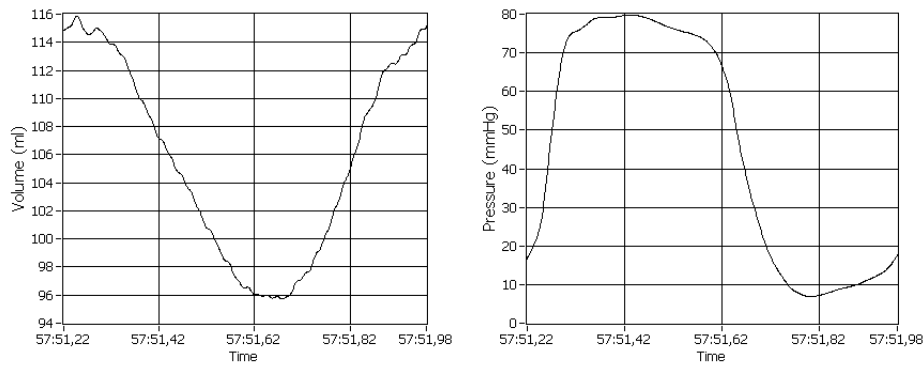


Figure 15: Filtered measurements of LVV to the left and LVP to the right.

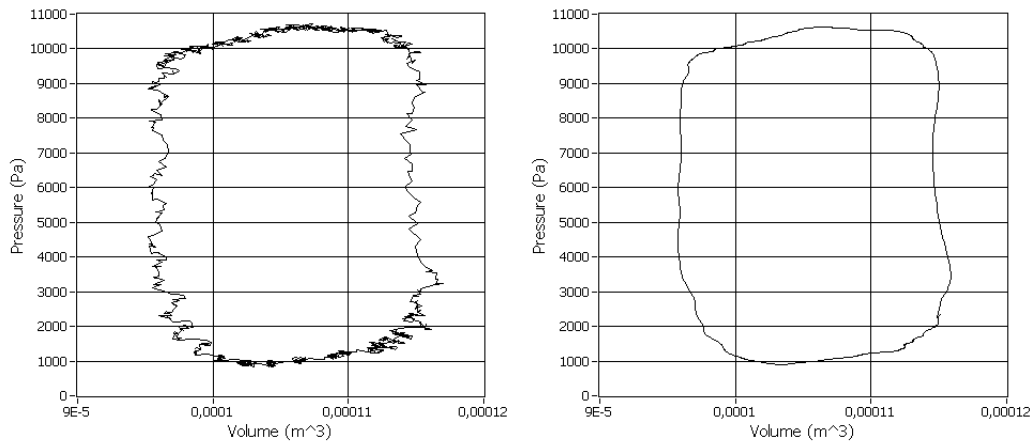


Figure 16: PV loop from unfiltered measurements to the left, and from filtered measurements to the right.

A plot of all the measurements acquired by NI USB-6251 BNC is displayed in Figure 17. The measurements makes sense from a physiological point of view. The aortic pressure and flow comes a little behind the LVP. The LVV has its lowest point at when the LVP drops below the aortic pressure, which is the end systole.

These plots indicates that the assumption on negligible delays in the instruments connected to NI USB-6251 BNC is reasonable.

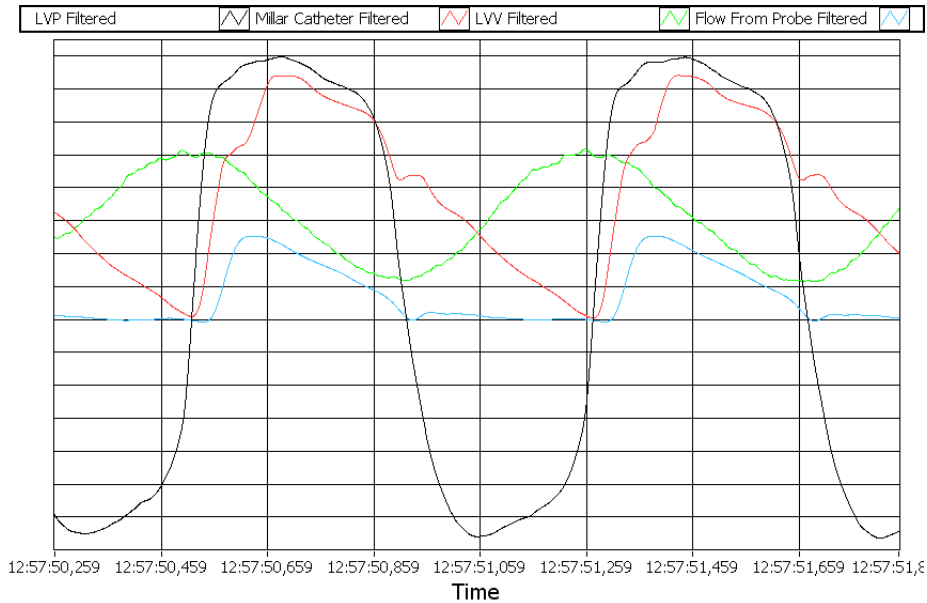


Figure 17: All the measurements acquired by NI USB-6251 BNC. The Millar catheter pressure and LVP has the same scaling. The other measurements is scaled to fit the magnitude of the pressure measurements.

Sound card input

During the analysis of the signals acquired in the project work, it became apparent that the actual sampling rate provided by Labviews sound card interface might deviate from the given sampling rate.

A VI was developed to estimate the actual sampling rate and compare it to the sampling rate given as input. By measuring the time elapsed during the acquisition of a given number of samples, the actual sampling rate can be estimated. The estimated sampling rate is then compared to the sampling rate given as input to the sound card interface, and the difference is calculated.

The results for different desired sampling rates is displayed in Table 2. As 6000 and 7000 is common values for PRF, these values were investigated.

Sound cards may be intended to operate in multiples of the CD sampling rate at 44100. Therefore the values 11025, 22050 and 44100 were tested out. As it seems, the sampling rate of 44100 gave the lowest error. It was therefore decided to sample at this value, and resample the signal in order to achieve the desired sampling rate.

Estimation of the sampling rate is dependent on acquiring the correct timestamps before and after the acquisition of the samples. A small amount

Desired Sampling Rate	Actual sampling rate mean	Deviation	Standard Deviation
6000	5997.64	-0.049 %	0.44
7000	6896.27	-1.482 %	0.50
11025	11048.16	0.210 %	0.87
22050	22189.9	0.621 %	23.69
44100	44077.48	-0.051 %	3.07

Table 2: The desired sampling rate is the sampling rate given to the function. The average of the actual sampling rate is calculated for 20 sets of 2 minutes of sampling.

of time will inevitably elapse from the acquisition of the timestamp to the start of the acquisition. Also from the time of the last sample is acquired to the stop timestamp a short time interval will elapse.

To rule out the possibility of an error in Labview, a similar program were implemented in Matlab. This program gave approximately equal results, so it is problem is probably due to the sound card of the laptop. The problem was also posted as a question on the NI forum, and the respondents concluded that the problem probably was due to the sound card.

Calibration

Calibration between the instruments and the laptop was achieved as described in the *Methods* part.

Accurate calibration is possible for the instruments with a possibility for producing a calibration value. This includes all measurements except the Aisys Datex Ohmeda. Calibration of pressure measurements from Aisys Datex Ohmeda is based on the maximum and minimum values read from the screen. If the pressure is in a stable condition, the maximum and minimum values calculated in the application will represent the one read from the screen.

As the measurement is sent from Aisys Datex Ohmeda to the laptop over a digital connection, the calibration is probably constant. However, no information on the calibration of the transmitted data was found. Figure 18 displays the interface for calibration.

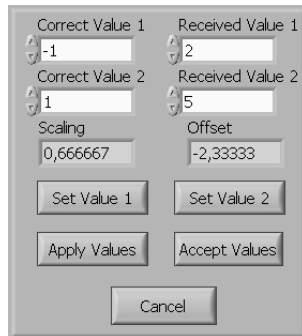


Figure 18: Calibration panel

Synchronization

In the first two of the operations, a diathermy was used to generate spikes in the measurements. The different clocks was then synchronized based on this spikes. During the last operation, a pacemaker was attached to the heart of the pig. Synchronization was then achieved by matching the areas of increased heart rate.

Diathermy

Recorded data from a measurement series with increased afterload is used to illustrate synchronization based on electromagnetic noise from a diathermy here.

Four DICOM files were recorded in sequence, at the same time as a continuous series of invasive measurements were recorded.

The effect of the diathermy spike in the different ECG measurements is displayed in Figure 19, 20 and 21. It is apparent from Figure 19 that the diathermy has a large effect on the ECG measurements from Leycom Sigma 5DF. From Figure 20 it is clear that the ECG from Aisys Datex Ohmeda has diathermy spikes that is easier to identify. Synchronization between the Labview Application and the DICOM files will therefore be based on the ECG from Aisys Datex Ohmeda. Aisys Datex Ohmeda and NI USB-6251 BNC will first be synchronized based on the first effect of the diathermy in their ECG measurements. Figure 21 displays the ECG from the first DICOM file.

Figure 22 displays the synchronization of Aisys Datex Ohmeda and NI USB-6251 BNC. Figure 23 to 27 displays the synchronization of the four DICOM files.

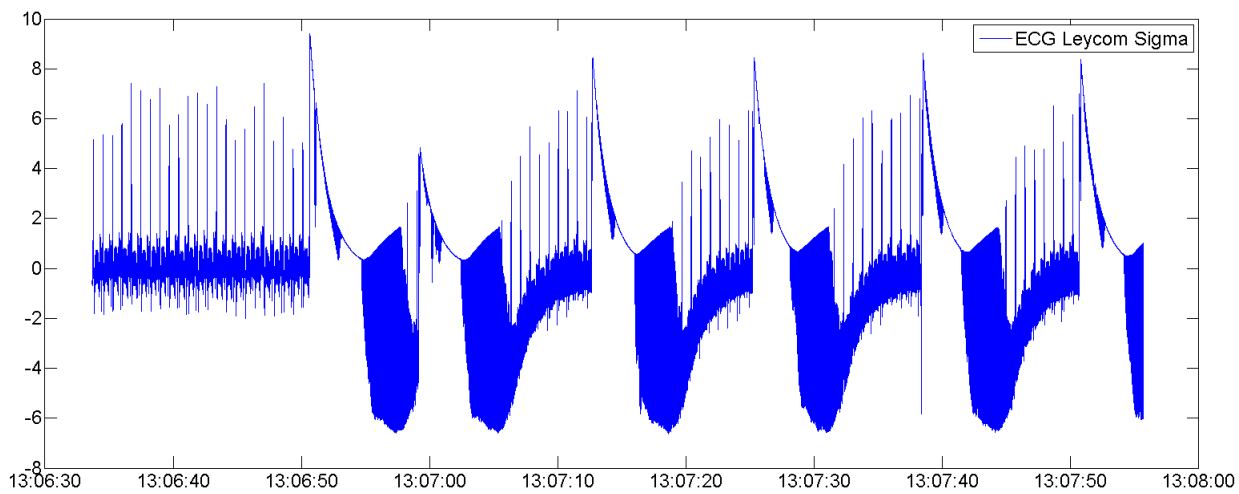


Figure 19: The ECG measurement from Leycom Sigma 5DF affected by diathermy.

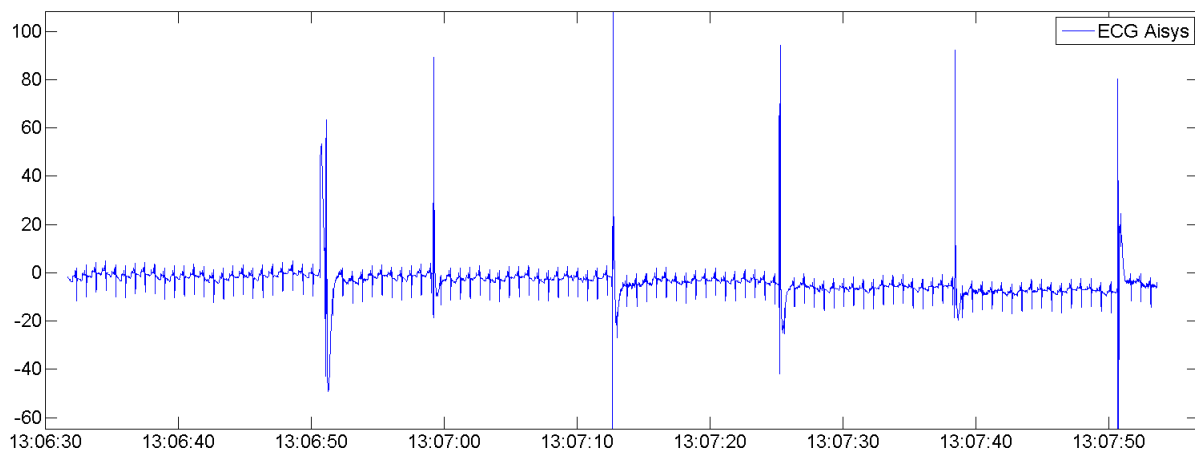


Figure 20: The ECG measurement from Aisys Datex Ohmeda affected by diathermy.

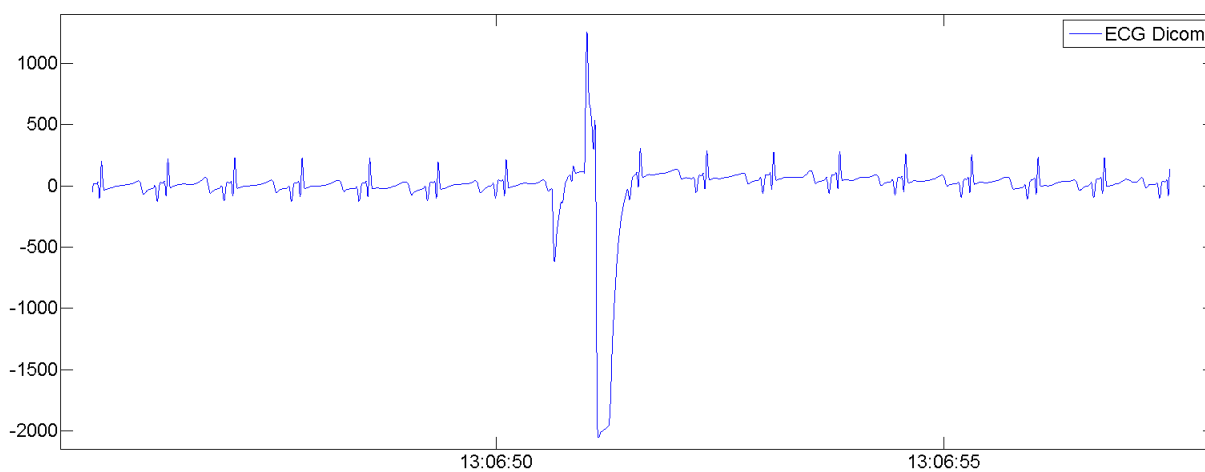


Figure 21: The ECG measurement from DICOM affected by diathermy.

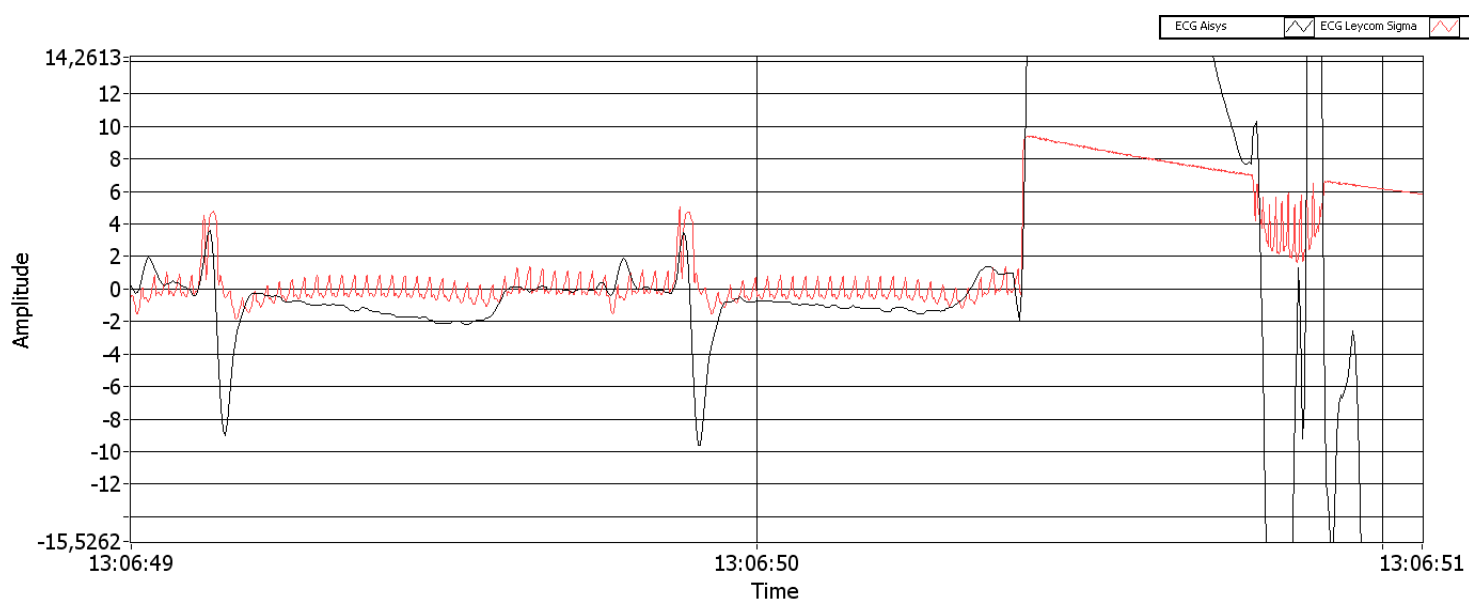


Figure 22: Synchronization of the ECG measurements from Aisys Datex Ohmeda and Leycom Sigma 5DF. A synchronization of the R waves and the diathermy spike is achieved, indicating that the synchronization is correct.

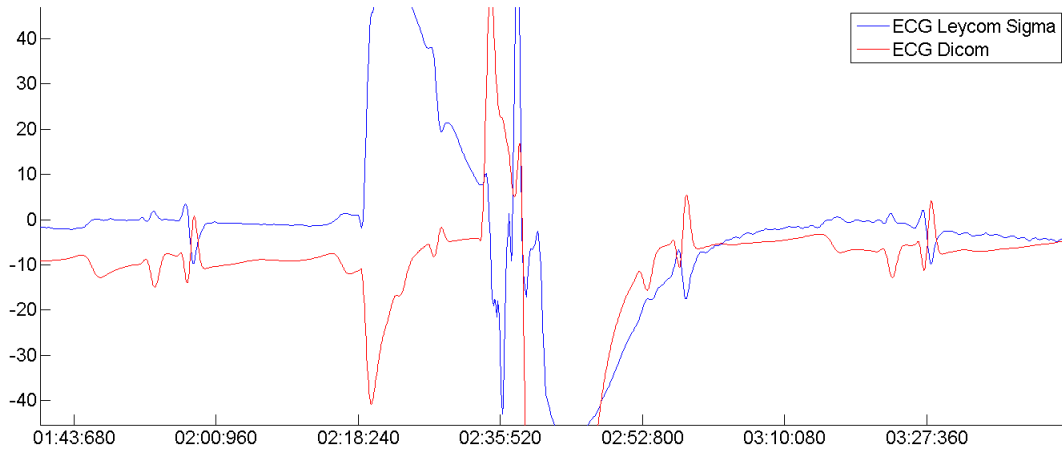


Figure 23: ECG from the first DICOM file synchronized with the first diathermy spike in the ECG from Aisys Datex Ohmeda. A synchronization of the R waves and the diathermy spike is achieved, indicating that the synchronization is correct.

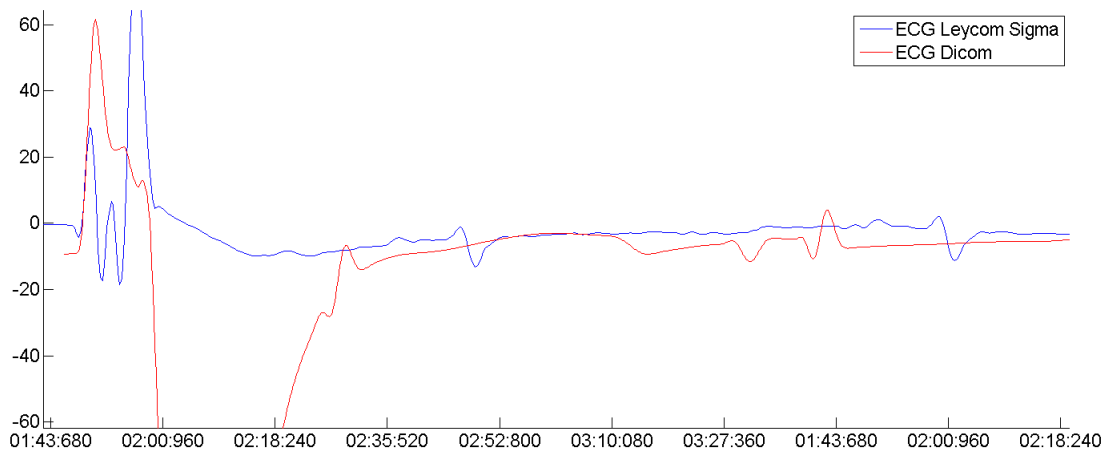


Figure 24: ECG from the second DICOM file synchronized with the second diathermy spike in the ECG from Aisys Datex Ohmeda. As a synchronization of the R waves and the diathermy spike is achieved, this synchronization is probably correct.

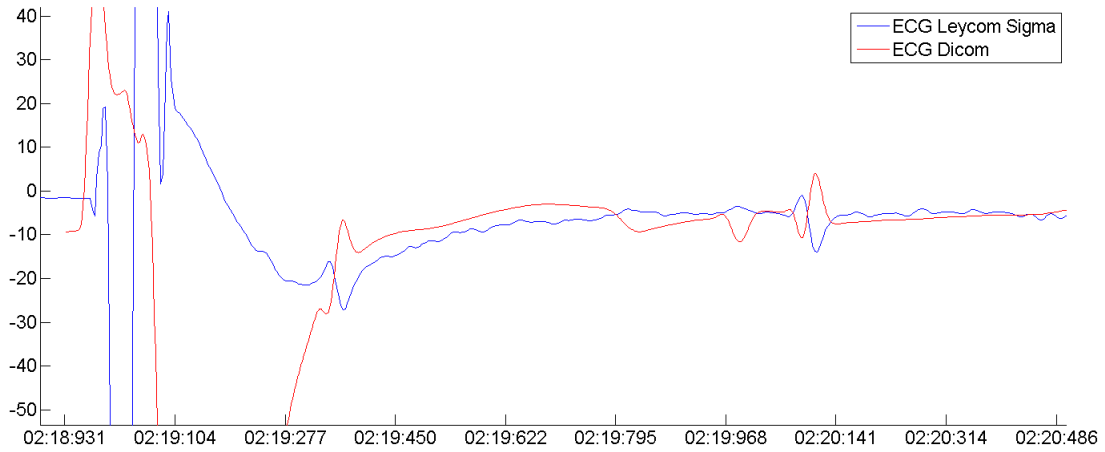


Figure 25: ECG from the second DICOM file synchronized with the third diathermy spike in the ECG from Aisys Datex Ohmeda. As a synchronization of the R waves and the diathermy spike is achieved, this synchronization is probably correct.

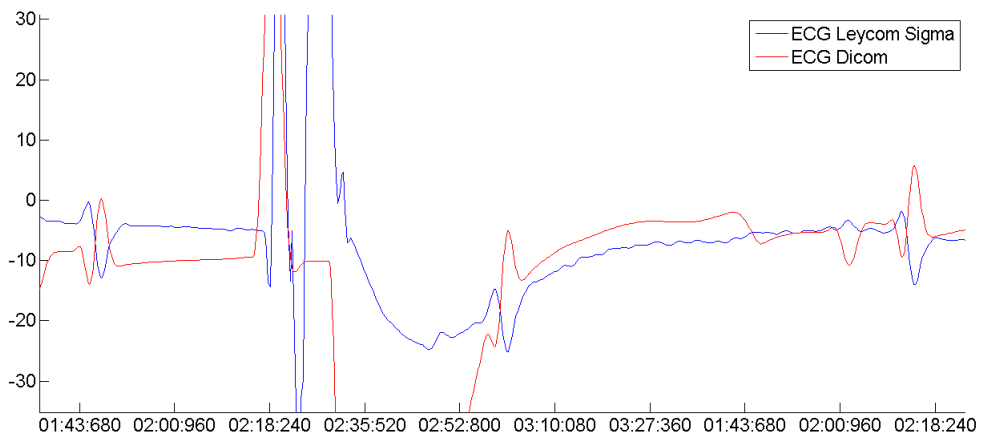


Figure 26: ECG from the third DICOM file synchronized with the fourth diathermy spike in the ECG from Aisys Datex Ohmeda. As a synchronization of the R waves and the diathermy spike is achieved, this synchronization is probably correct.

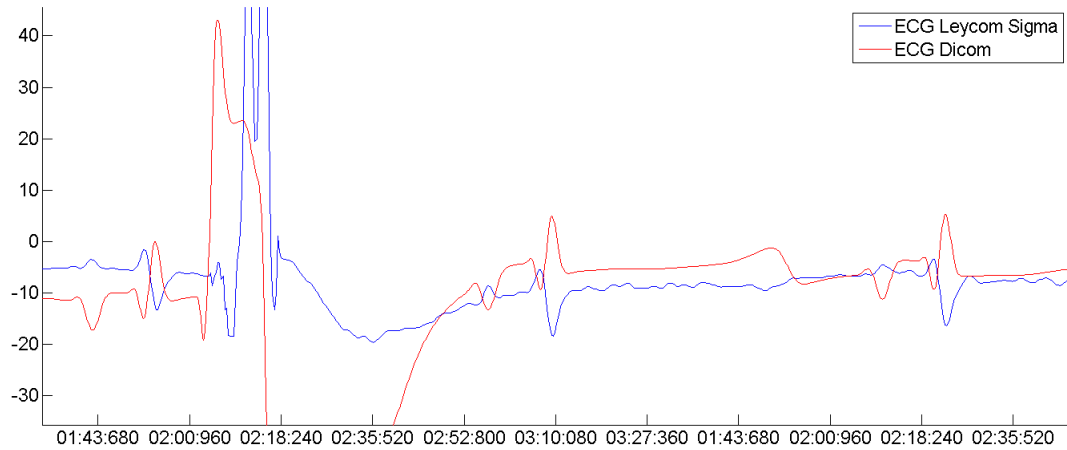


Figure 27: ECG from the fourth DICOM file synchronized with the fifth diathermy spike in the ECG from Aisys Datex Ohmeda. As a synchronization of the R waves and the diathermy spike is achieved, this synchronization is probably correct.

Pacemaker

Recorded data from a set of measurement with reduced preload is used to illustrate synchronization based on a pacemaker. Two DICOM files were recorded in sequence, at the same time as a continuous series of invasive measurements were recorded. Intervals of increased heart rate is used to synchronize the different clocks.

Figure 28 displays the synchronization of Aisys Datex Ohmeda and NI USB-6251 BNC.

Figure 29 and 30 displays the synchronization of NI USB-6251 BNC and the DICOM files.

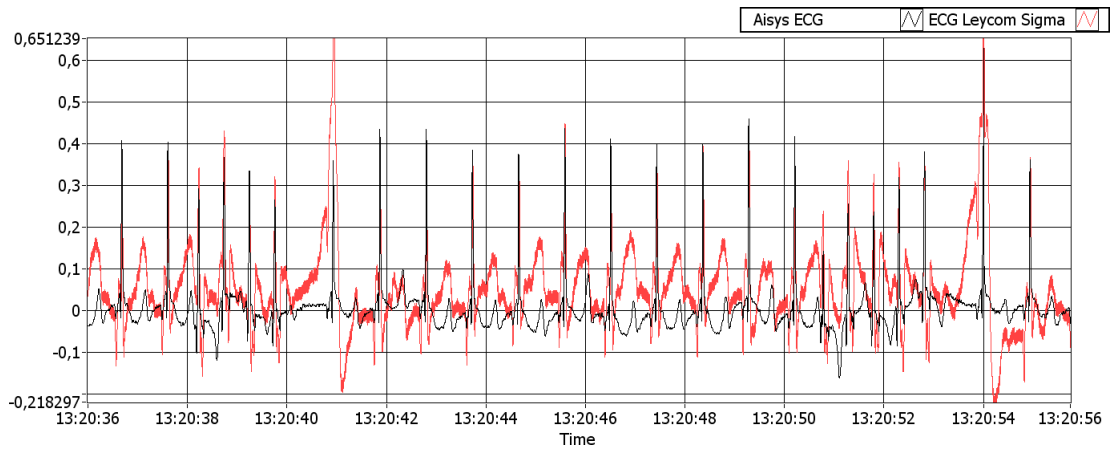


Figure 28: Synchronization of the ECG measurements from Aisys Datex Ohmeda and Leycom Sigma 5DF.

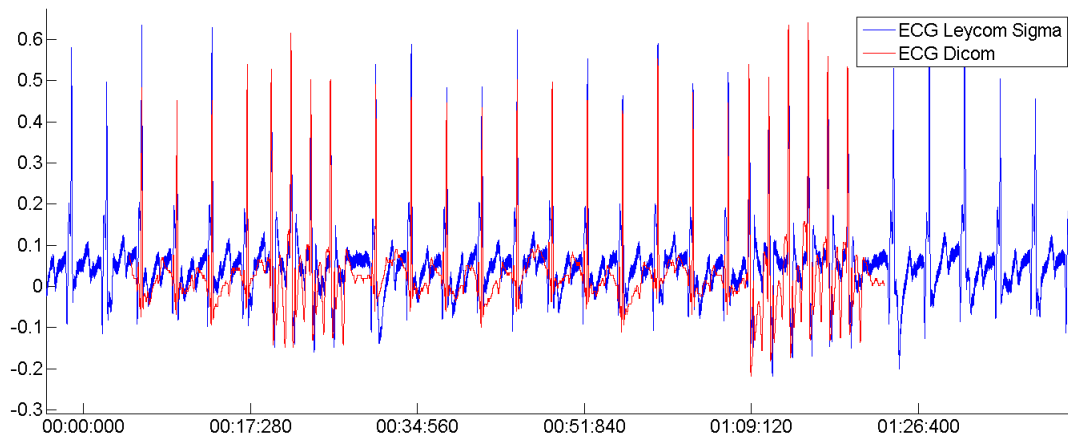


Figure 29: ECG from the first DICOM file synchronized with the ECG from Leycom Sigma 5DF.

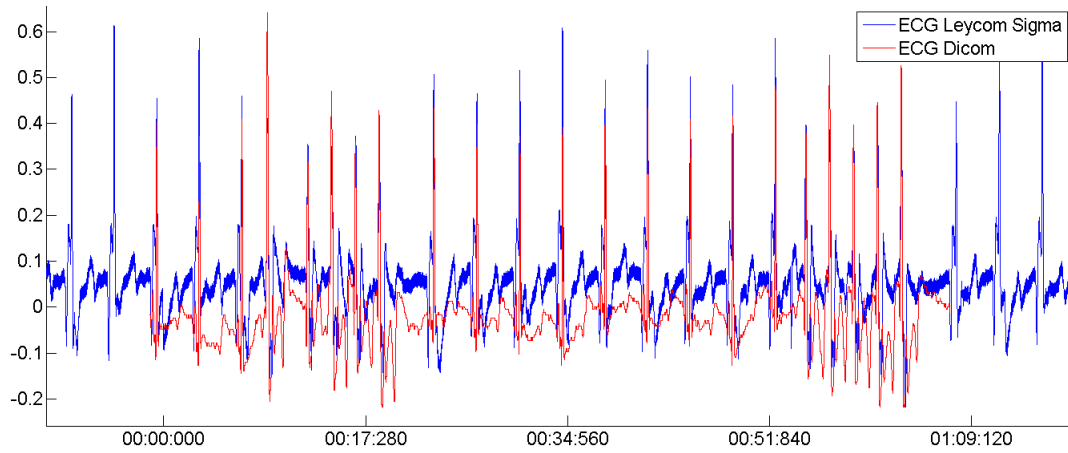


Figure 30: ECG from the second DICOM file synchronized with the ECG from Leycom Sigma 5DF.

Load change

Synchronization of Aisys Datex Ohmeda and NI USB-6251 BNC is possible by only using the aortic pressure and the ECG, without any external devices like diathermy or pacemaker. For this to be possible there must be a detectable change in both pressure measurements. Figure 31 displays the pressure measured by the fluid filled catheter and the Millar catheter adjusted so that the load change is happening synchronous. Fine tuning of the time adjustment is performed by comparing the ECG measurements, as illustrated in Figure 32.

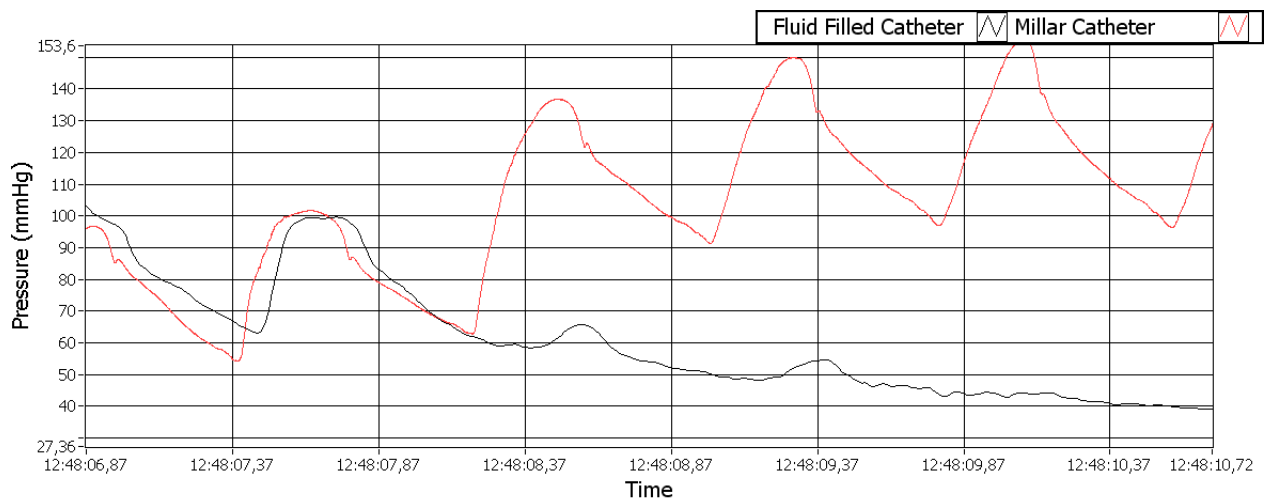


Figure 31: Pressure from the fluid filled catheter and the Millar catheter

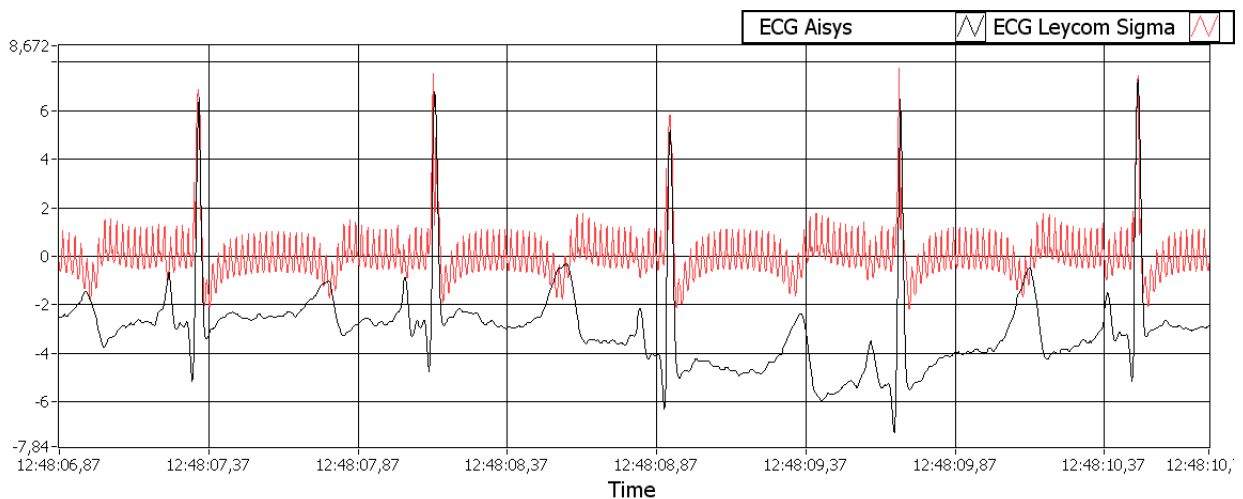


Figure 32: ECG from Aisys Datex Ohmeda and NI USB-6251 BNC.

Calculated parameters

Doppler Flow

The specter with the velocity trace is displayed next to the resulting velocity curve for measurements from the three operations in Figure 33, 34 and 35. The increment is set to 10, and the FFT size is 100. The size of the smoothing filter for the spectrogram is 10. The resulting velocity is filtered by a mean

filter with size 10. No measurements of the aortic diameter were performed in the operations, so the diameter was set to 1 in all cases. Because of this the calculated aortic flows is not accurate.

In Figure 33 and 34, sharp transitions from areas with strong specter power to areas with weak specter power is present. When the algorithm detects such a transition it sets the velocity trace to be the velocity detected before the transitions. Otherwise the velocity would have a sharp decline to zero velocity in these regions.

Figure 63 compares blood flow calculated from the Doppler specter with the flow measured by the flow probe. As no measurement of aortic diameter was performed, only comparison of magnitude and timing is relevant here.

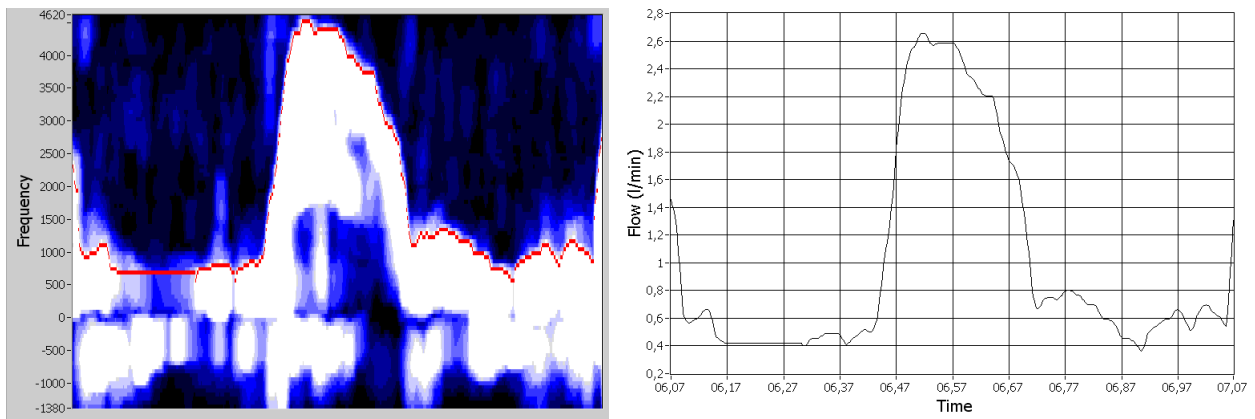


Figure 33: Doppler specter and corresponding velocity for one second of received data. The specter is shifted 25 percent down in this case.

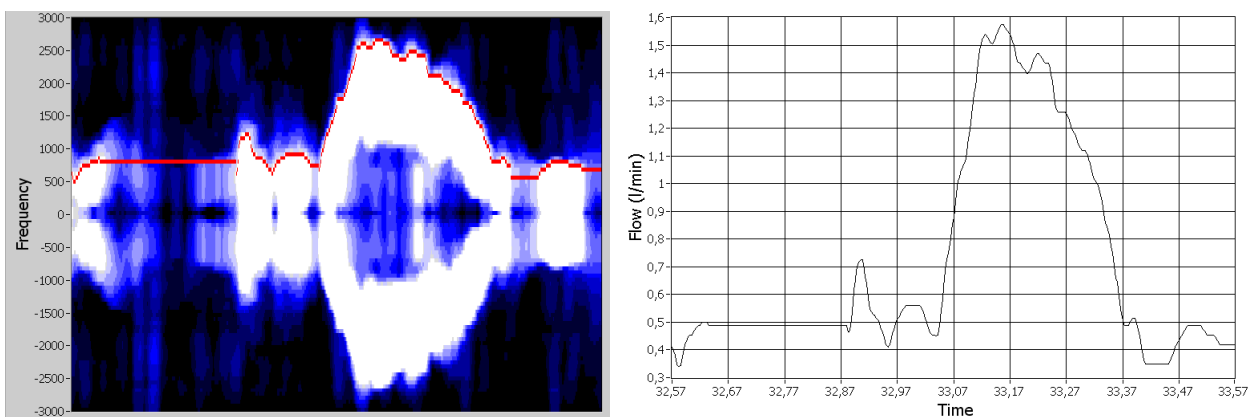


Figure 34: Doppler specter and corresponding velocity for one second of received data.

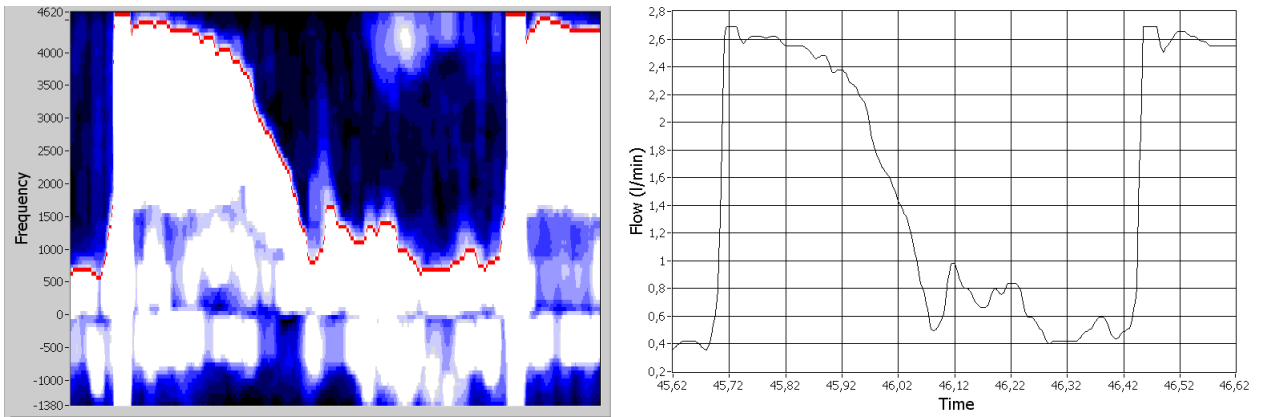


Figure 35: Doppler specter and corresponding velocity for one second of received data.

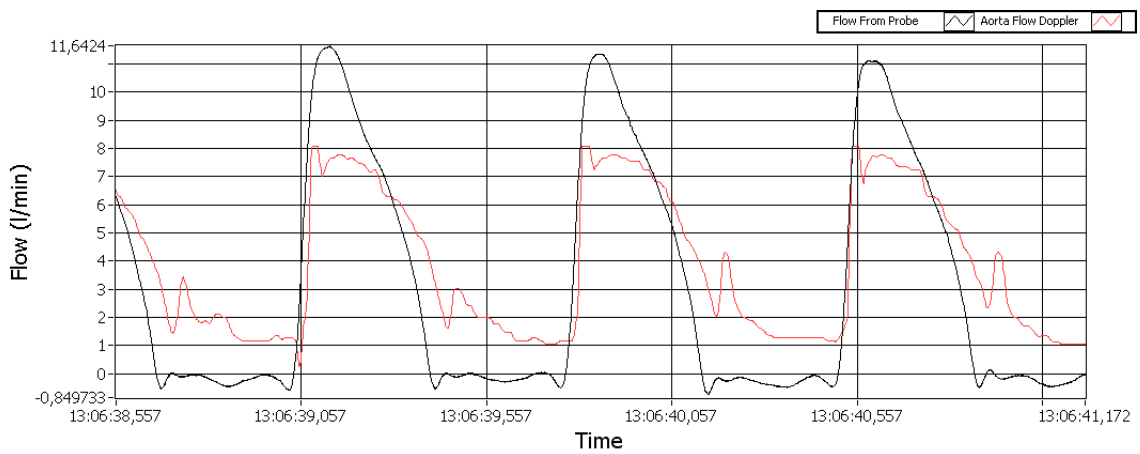


Figure 36: Comparison of the Doppler flow and the flow from the flow probe.

Start Systole detection

Figure 37 illustrates detected heart cycles on the ECG from Leycom Sigma 5DF. In Figure 38 a closer view of the change between cycles is given.

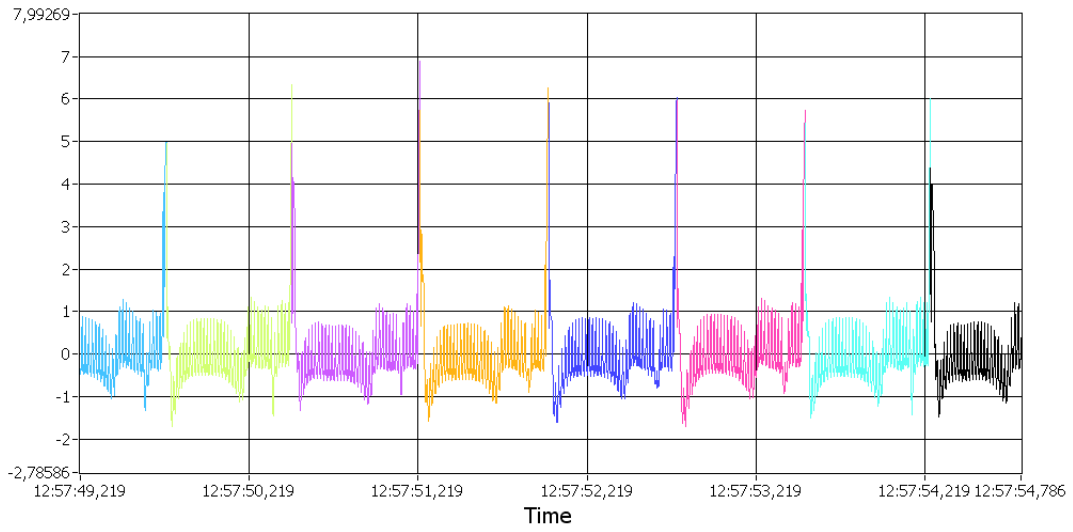


Figure 37: The detected heart cycles is indicated by different colors.

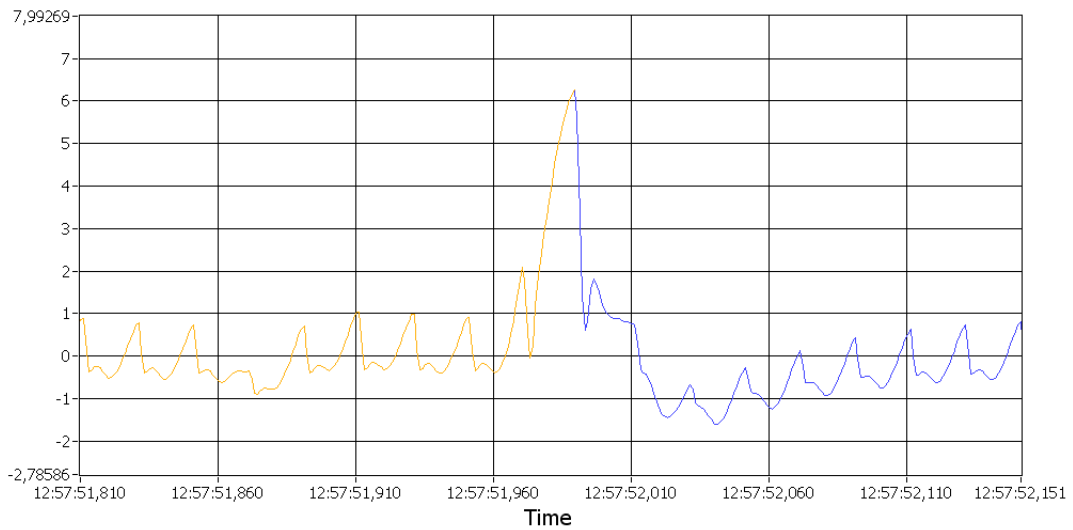


Figure 38: Close view of the change of heart cycles.

End Systole detection

The detected point of end systole is indicated in four PV loops and corresponding plots of aortic- and ventricular pressure. The end of the systole is defined as the closure of the aortic valve. This happens when the pressure in the aorta is higher than the pressure in the ventricle. The current end systole

detection based on the PV loop can therefore be validated against the point where the left ventricular pressure becomes lower than the aortic pressure.

In Figure 39 and 40 standard PV loops are displayed. The detected end systole is very close to the point where the ventricular pressure drops below the aortic pressure.

In Figure 41 and 42 PV loops with altered load are displayed. The detected end systole deviates a little from the point where the ventricular pressure drops below the aortic pressure.

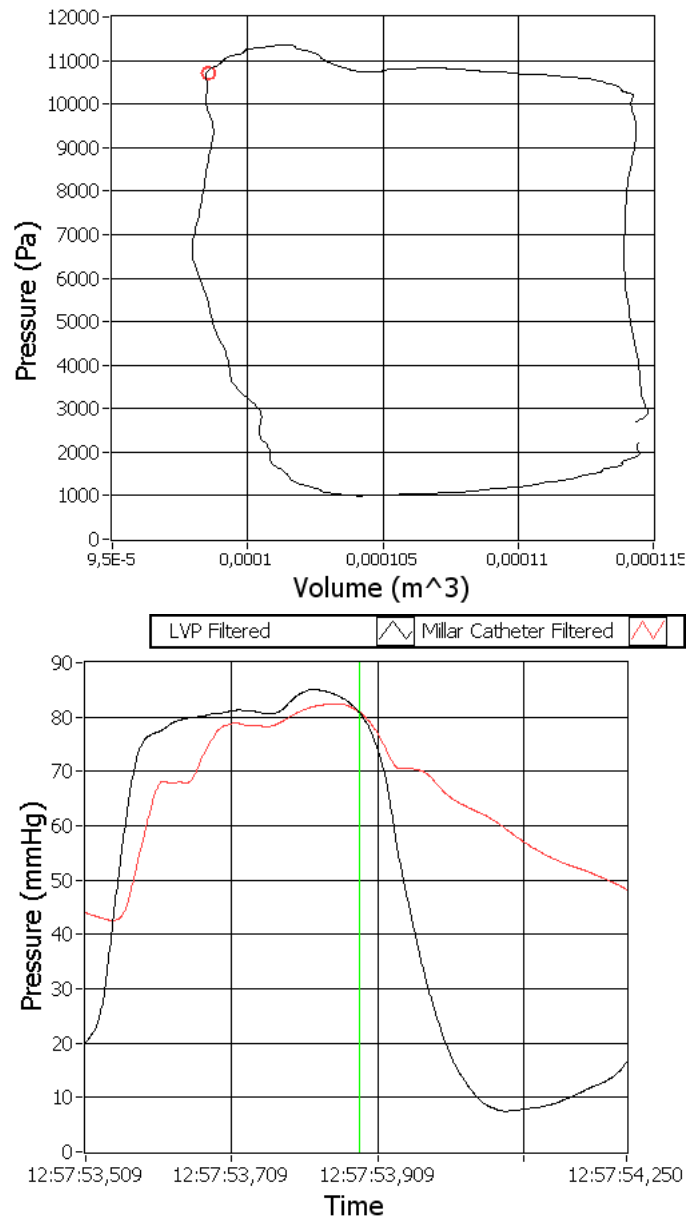


Figure 39: In the top plot is a standard PV loop with the detected end systole indicated in red. In the lower plot is the corresponding left ventricle and aortic pressures, with the detected end systole indicated in green.

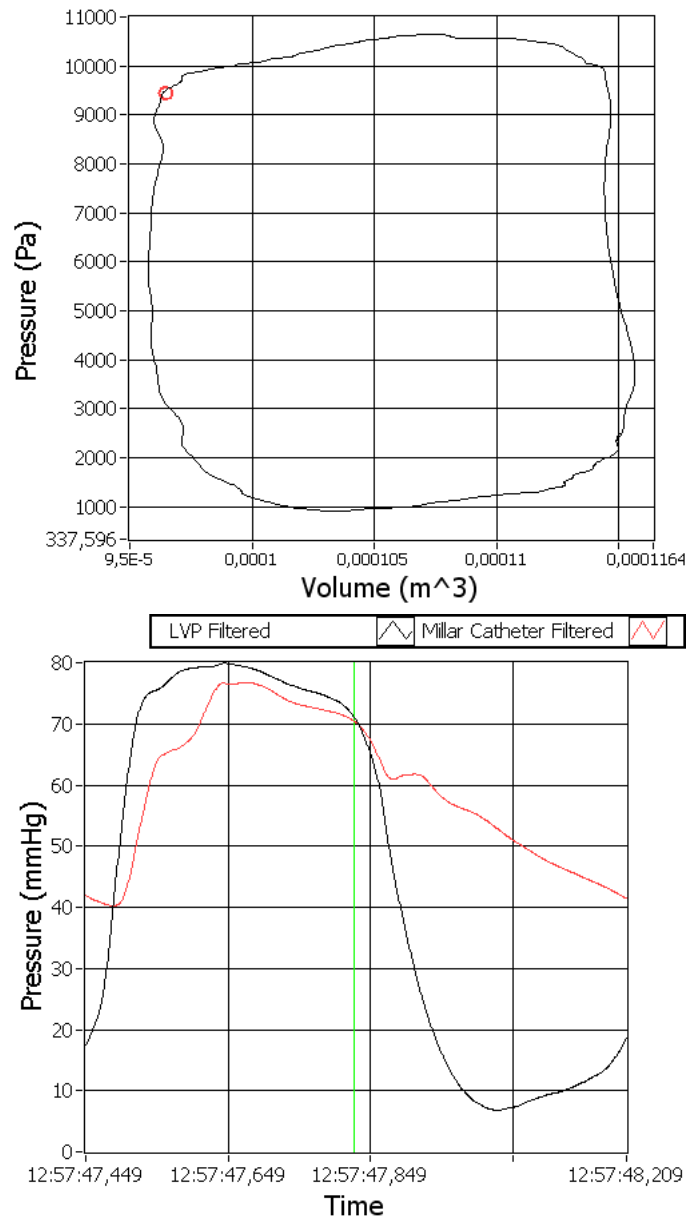


Figure 40: In the top plot is a standard PV loop with the detected end systole indicated in red. In the lower plot is the corresponding left ventricle and aortic pressures, with the detected end systole indicated in green.

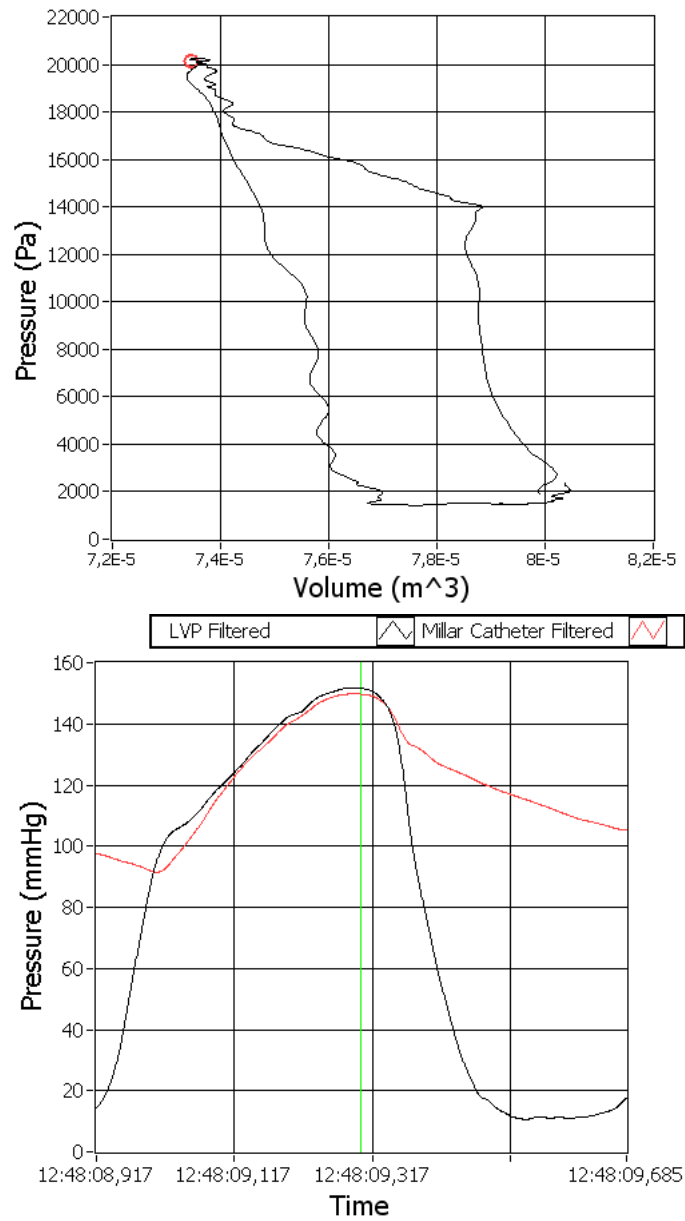


Figure 41: In the top plot is a standard PV loop with increased afterload with the detected end systole indicated in red. In the lower plot is the corresponding left ventricle and aortic pressures, with the detected end systole indicated in green.

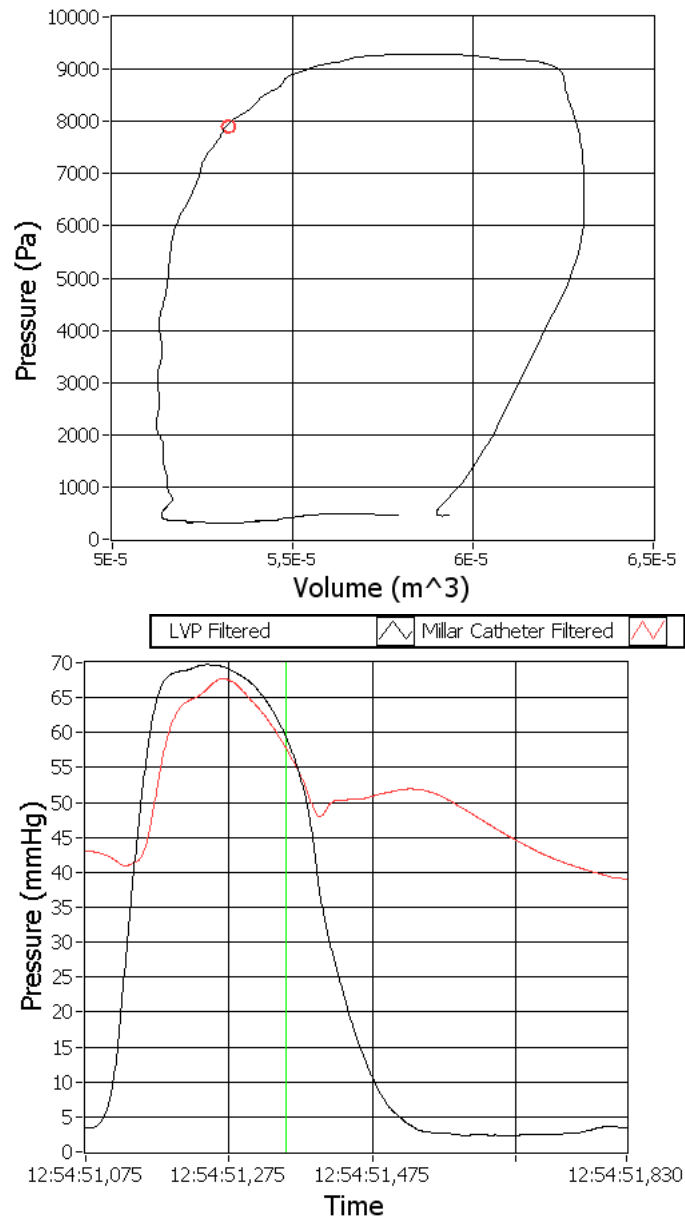


Figure 42: In the top plot is a PV loop with decreased preload with the detected end systole indicated in red. In the lower plot is the corresponding left ventricle and aortic pressures, with the detected end systole indicated in green.

Ea

The Ea is calculated based on the detected end systole. Figure 43 displays the Ea line together with a PV loop.

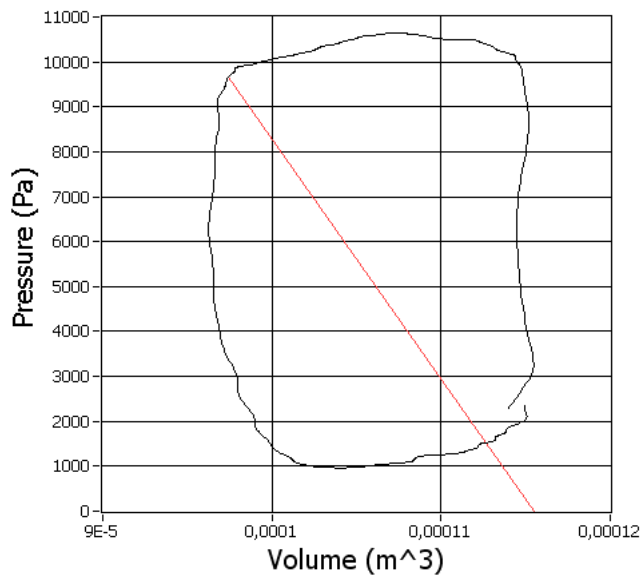


Figure 43: The Ea line illustrated in a PV loop.

Ees

One set with increased afterload and one with decreased preload is used to illustrate Ees. The PV loops and the Ees line for measurements with increased afterload is displayed in Figure 44. Figure 45 displays The PV loops and the Ees line for measurements with decreased preload.

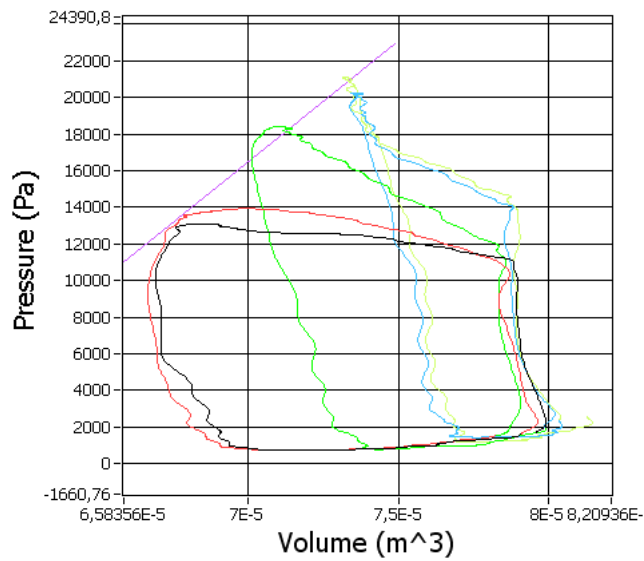


Figure 44: PV loops for increased afterload. The Ees is displayed in purple.

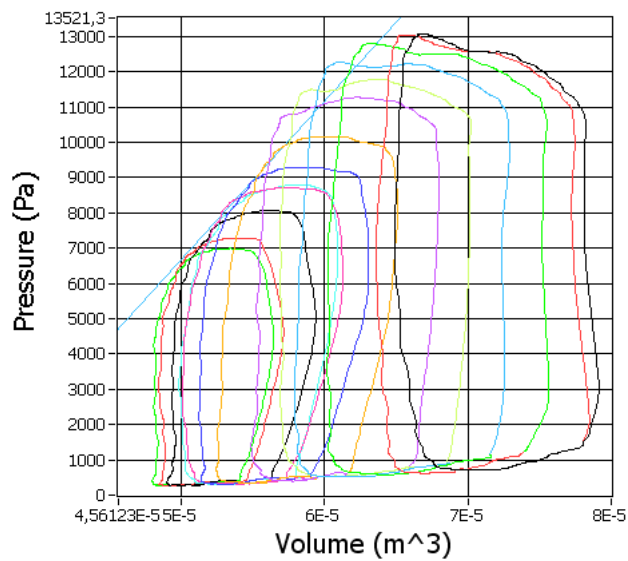


Figure 45: PV loops for decreased preload. The Ees is displayed in blue.

PWR

Four PWRs is calculated. They are the combinations of the two different flow measurements and the pressures measured by the Millar catheter and the fluid filled catheter. Figure 46 displays the PWR curves. The PWR

parameters is found by integrating this curves over the duration of a heart cycle.

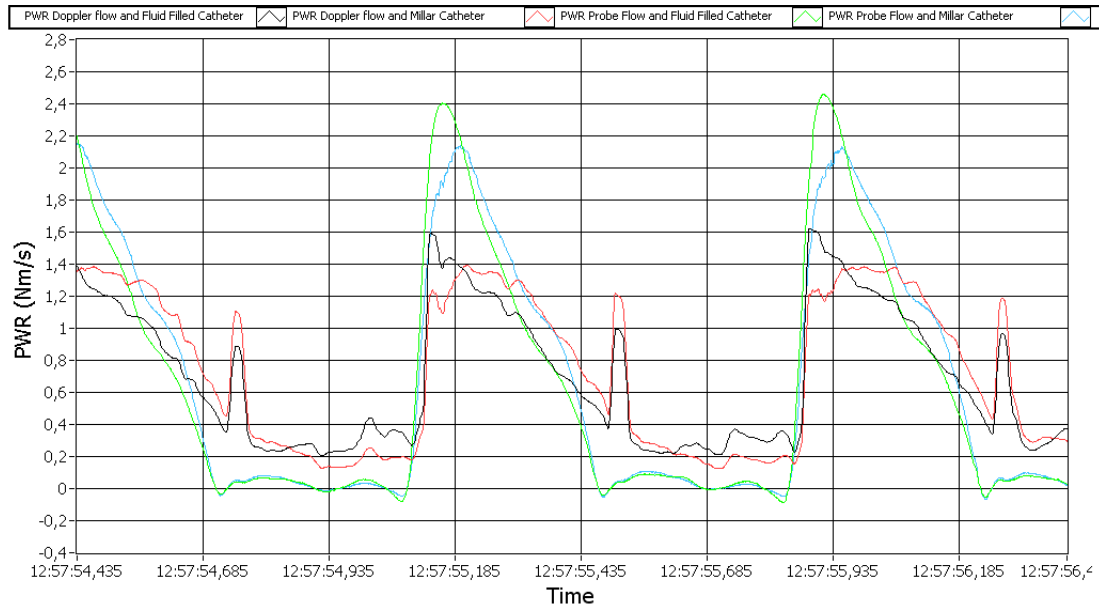


Figure 46: Pressure from the fluid filled catheter and the Millar catheter

Labview Application

Start-up

Figure 47 displays the start-up window. Here the user is required to give the name of a project in the *Project Name* textbox. When the *Create Project* button is pressed, a folder with the given project name is created in the program folder. If a project with the given name already exists, a message giving the user the choice between opening the existing project or cancel is displayed.

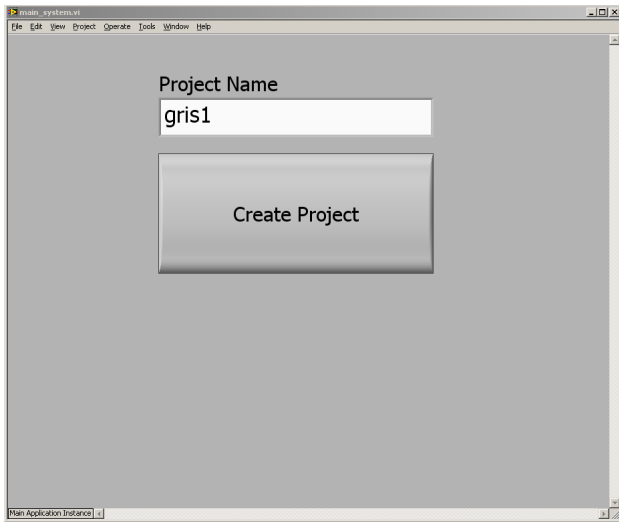


Figure 47: Start-up window

After a project has been opened, the window in Figure 48 is displayed. The name of the current project is displayed in the text field *Name Of Project*. Below is three buttons. The *Acquisition* button starts an acquisition session, where new data can be read and saved. *Analyze* opens an already existing file. *Exit Project* returns to the window in Figure 47.

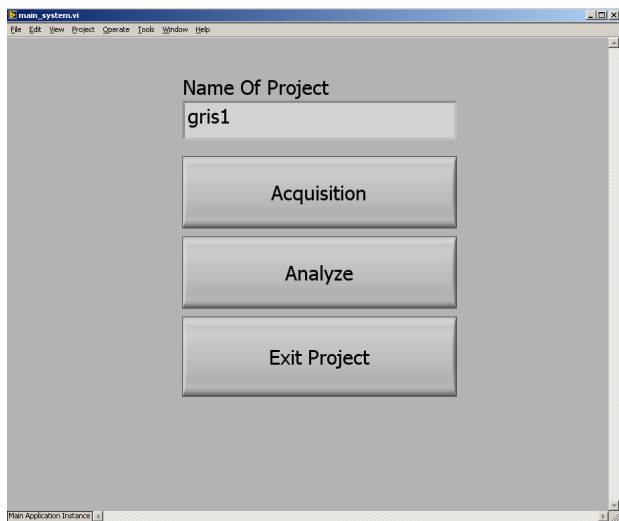


Figure 48: Main menu

Acquisition

When an acquisition session is started, the window in Figure 49 is displayed. To the left a tab with three pages contains the buttons for selecting the desired measurements and parameters. If data from Aisys Datex Ohmeda exceeding the bandwidth limitation on 600 S/s, a message is displayed and the buttons is deselected.

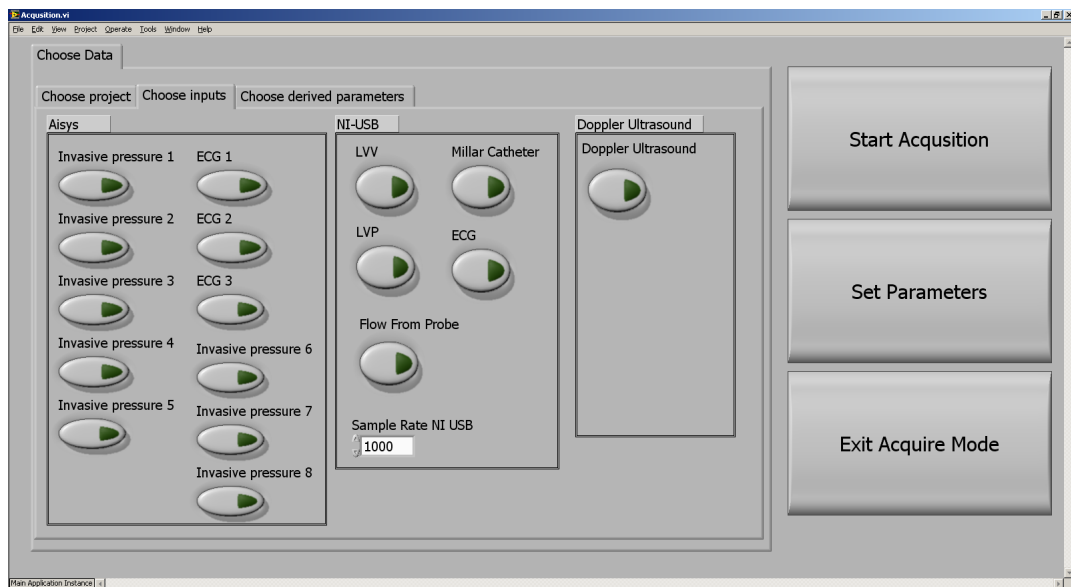


Figure 49: Window for choosing measurements and parameters for a new measurement.

Set Parameters

When the button *Set parameters* is pressed, a tab where the user can calibrate the measurements and set parameters appears. This tab has the pages *Calibration*, *PW Doppler*, *Heart Cycle Detection* and *Synchronize Aisys*.

Calibration When the calibration button for a measurement is pressed, the tab in Figure 50 is displayed. The tab is positioned next to the measurement. When the calibration tab opens, the *Received Value 1* and *Received Value 2* numbers are set to the maximum and minimum of the last 10 seconds of received data. The buttons *Set Value 1* and *Set Value 2* sets the *Received Value 1* and *Received Value 2* to the average of the last second of received data. *Apply Values* sets the scaling and offset values to be the values calculated, while leaving the calibration tab open. *Accept Values* sets the

calibration values and closes the calibration tab, while *Cancel* closes without updating the values.



Figure 50: Calibration

The measurements from Aisys Datex Ohmeda has their names set on the same page as the calibration. Dependent on with measurement that is received from Aisys Datex Ohmeda, data will be present on the different charts, Aisys ECG 1-3 and Aisys Invasive pressure 1-8. The user has to decide which measurement is on which channel and set the name in the text box. The measurement of ECG has to be named *Aisys ECG* and the measurement from the fluid filled catheter has to be named *Fluid Filled Catheter* for the correct recognition in the application. In all experiments performed, the ECG has been on ECG 1 and the fluid filled catheter has been on invasive pressure 1. This is therefore set to be the default values in the application.

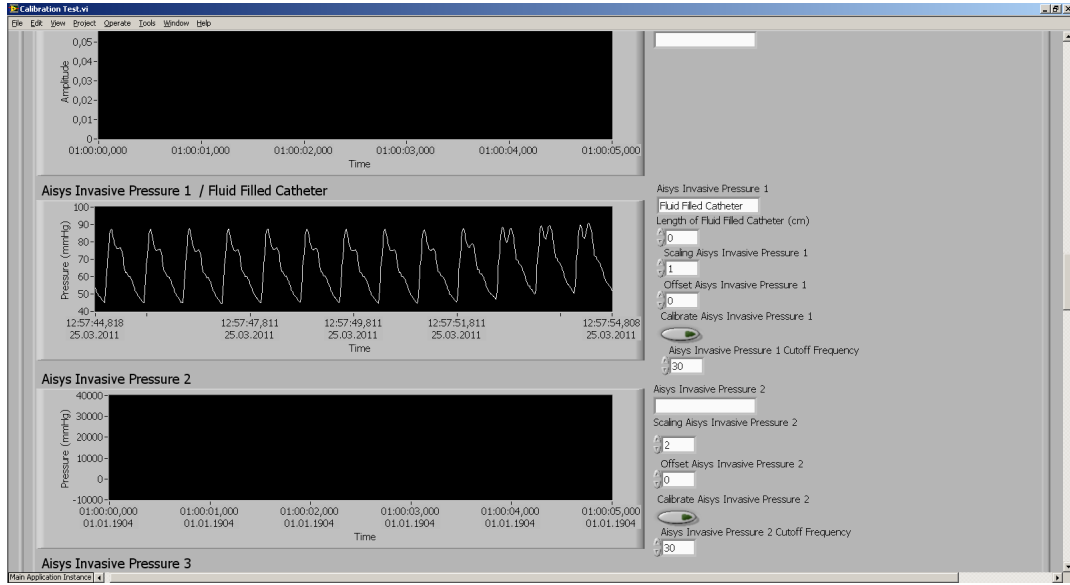


Figure 51: The pressure measurement from the fluid filled catheter is detected on the Aisys Invasive Pressure 1 channel, and the name is set properly.

PW Doppler This page displays the spectrogram and velocity trace from the received IQ-demodulated data, as illustrated in Figure 52. The panel on the right allows the user to set the parameters for calculation of the spectrogram and velocity trace. *Window Size velocity smoothing* is the size of the smoothing filter applied to the velocity trace. *dyn* is the dynamic region. The *Blood Vessel Diameter* needs to be found by B-mode ultrasound. *transmitted frequency* is the frequency of the ultrasound sent into the body. *Percentile* is used for the algorithm for velocity tracing. *theta* is the angle correction. *PRF* is the pulse repetition ratio. *Shift zero* is controlling the adjustment of the baseline. *increment* is the number of samples between each sample used for FFT. *Smoothing* is the horizontal and vertical size of the window used for smoothing of the spectrogram, *FFT Window Size* is the number of samples used for the FFT.

The color of each pixel is set based on the equation:

$$\frac{254}{dyn} \cdot (10 \cdot \log_{10}(G) + gain)$$

Where G is the frequency value from the FFT. The colors is set on a scale from black to white, with the intermediate values in shades of blue.

Increasing the increment, FFT window size or smoothing results in longer processing time and may halt real time performance.

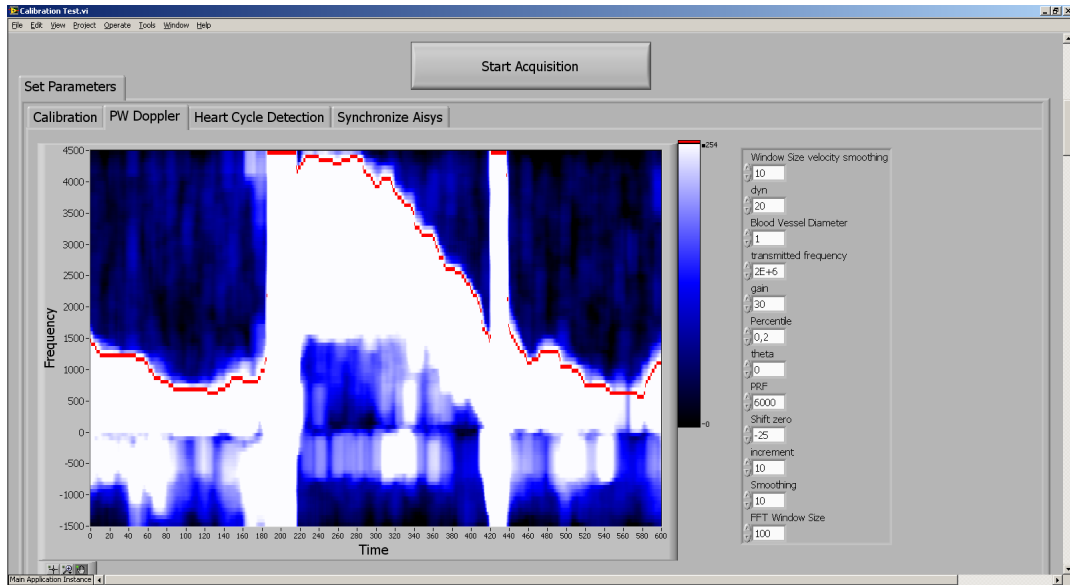


Figure 52: The PW Doppler page

Heart Cycle Detection On this page the detected heart cycles is displayed, as illustrated in Figure 53.

The threshold for the heart cycle detection algorithm is set in the *Threshold heart cycle* field. As heart cycles is detected, the corresponding ECG segments are displayed in different colors in the plot. The 10 latest detected cycles is displayed. Below the plot is also the PV loops displayed.

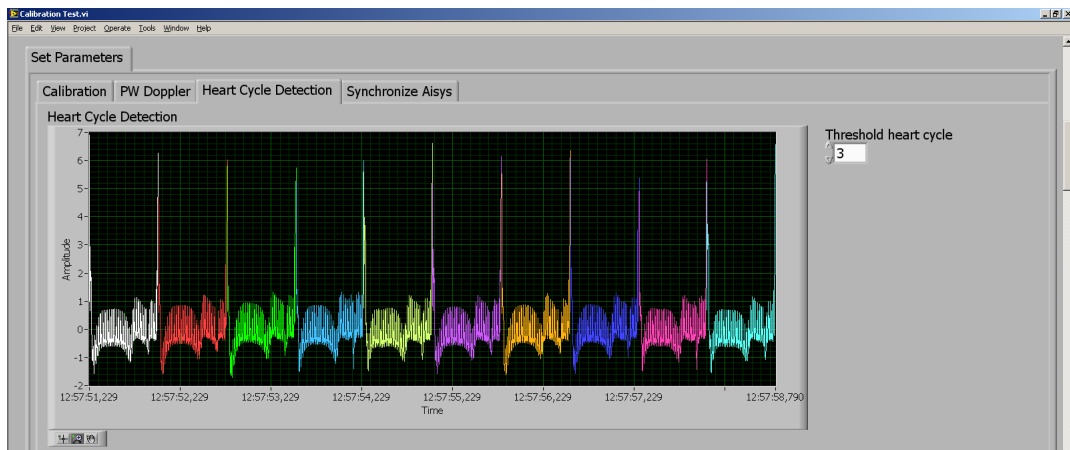


Figure 53: The heart cycle detection page.

Synchronize Aisys On this page the user can set the time adjustment for the measurements from Aisys Datex Ohmeda. In order to synchronize data from different sources manually, a synchronization interface were developed. To synchronize the measurements from Aisys Datex Ohmeda and the data from the NI board, the ECG from the two sources and the aortic pressure is used. The user can adjust the start time for the curves from Aisys Datex Ohmeda. When the user presses the *Receive* button, the two plots is updated with new values. When the *Receive* button is turned off, the data in the graphs is no longer updated, and fine tuning is possible.

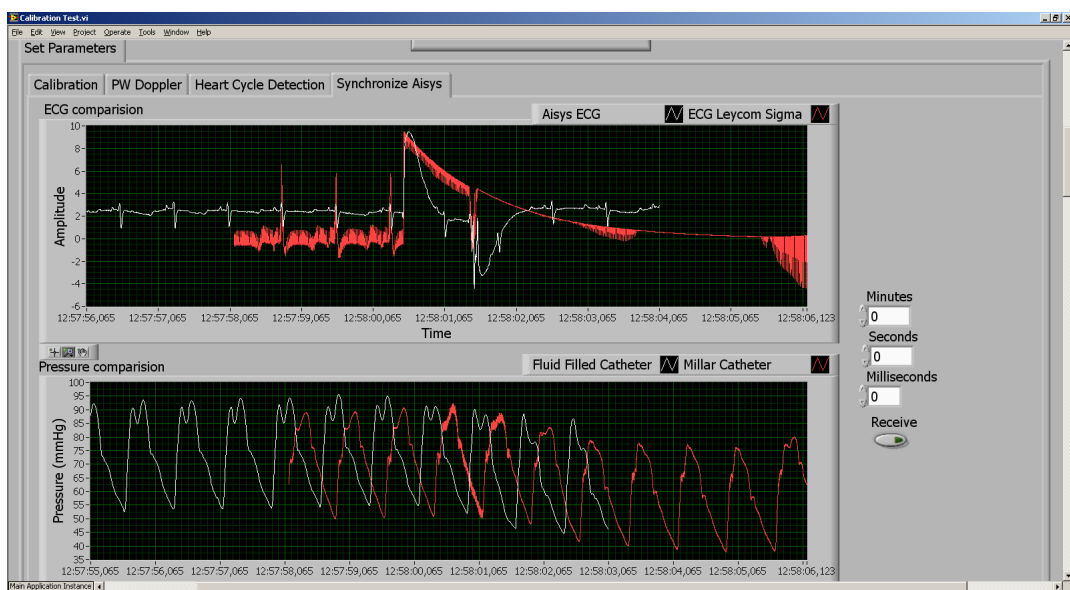


Figure 54: The timestamps of the measurements from Aisys Datex Ohmeda is adjusted by the time given to the right. When the Receive button is pressed new data is added to the plot.

Acquisition When the acquisition state is entered, the acquisition tab is displayed, as illustrated in Figure 55. The selected measurements have their own page with a chart displaying the last 10 seconds of acquired data. ECG from Aisys Datex Ohmeda and Leycom Sigma 5DF is displayed in the same chart. The charts is made large in order to simplify visual validation by the clinical team during operations.

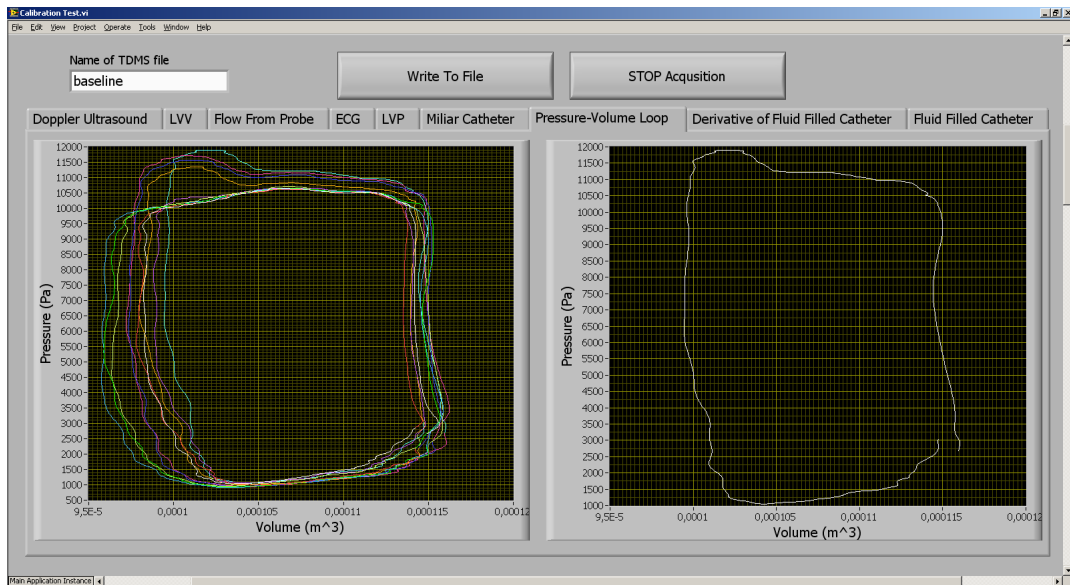


Figure 55: To the right is the last detected PV loop displayed, to the left is the 10 last PV loops.

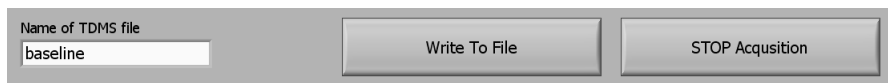


Figure 56: Appearance of the window when the application does not write data to a TDMS file. Writing of data is initiated by pressing the *Write To File* button.

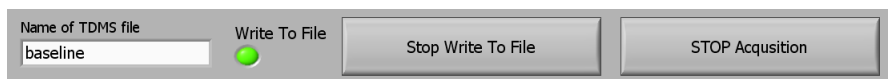


Figure 57: Appearance of the window when the application is writing data to a TDMS file. When *Stop Write To File* is pressed, the application stops writing to the TDMS file. When *STOP Acquisition* is pressed, the application stops writing and exits the acquisition mode.

Analyze

When the analyze state is entered, the last saved file in the project folder is opened and displayed. A tab with pages for the different measurements and calculation options available are displayed to the left. On the right, options for loading and saving is displayed. By pressing the *Load New Data*

Set button, a new TDMS file can be read. In all plots of raw measurements there is a cursor. By pressing the *Update Cursor* button the cursor is set to the same position in all plots. The tab on the left has a dedicated page for all the measurements, except the ECG measurements that are displayed in the *Time Adjustment* page.

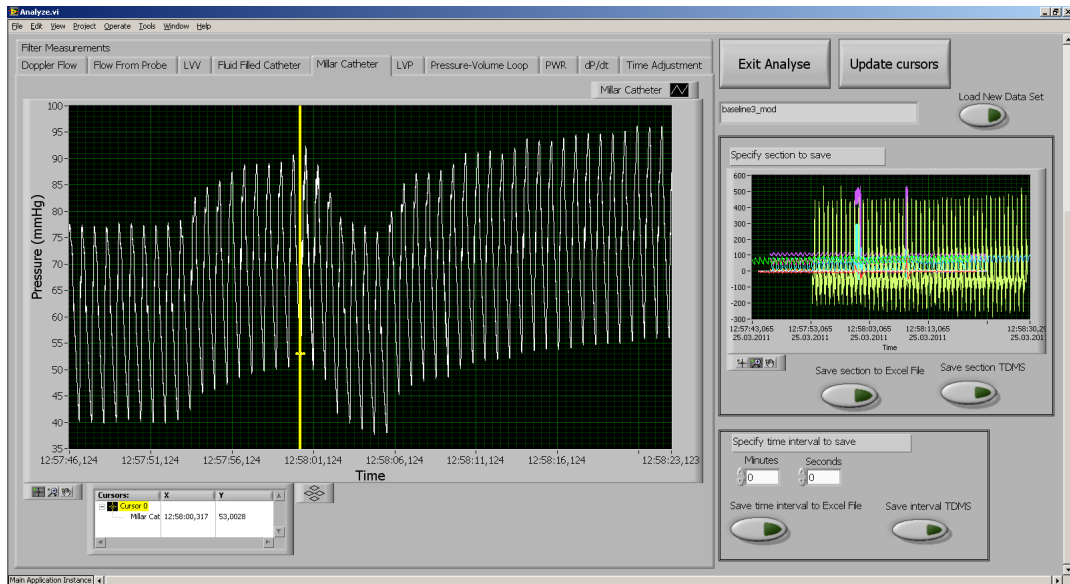


Figure 58: The analyze window.

Time Adjustment On the time adjustment page displayed in Figure 59 the time adjustment of the Aisys Datex Ohmeda clock can be adjusted.

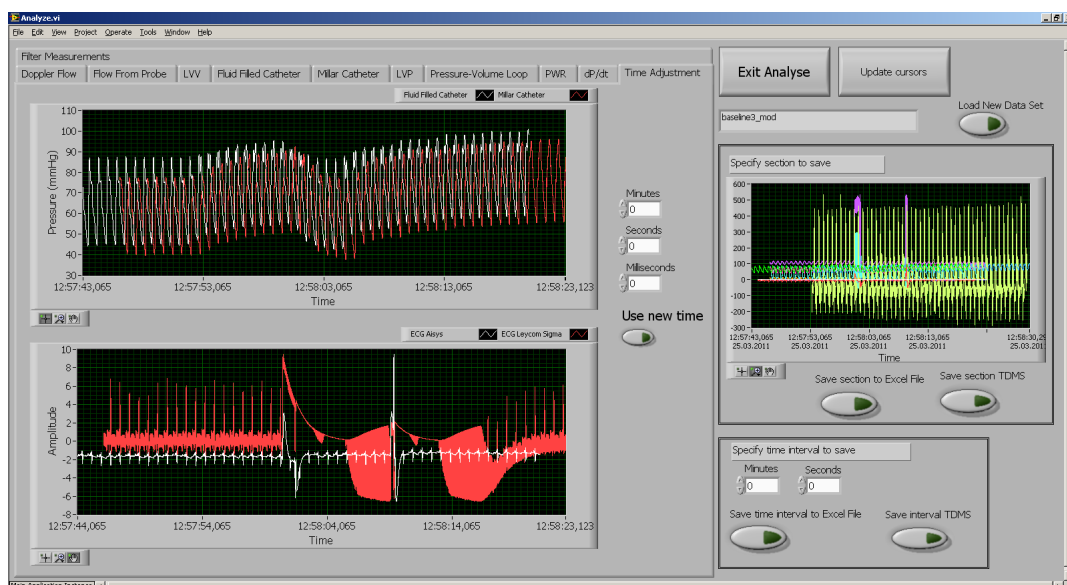


Figure 59: The tab in the analyze window for adjusting the time adjustment for the measurements from Aisys Datex Ohmeda.

Doppler Flow The calculated Doppler flow is displayed on the page *Doppler Flow*, in Figure 60. By pressing the button *Recalculate Blood flow*, the page changes to Figure 61. Here the user can set the parameters for the recalculation of the Doppler flow. When the *Run Calculation* button is pressed, the Doppler flow is recalculated and the spectrogram in Figure 62 is displayed. After the calculation is performed the new Doppler flow is displayed, as can be seen in Figure 63. The user can choose between using the recalculated flow or the old one by pressing the buttons *Use New Flow* or *Cancel*.

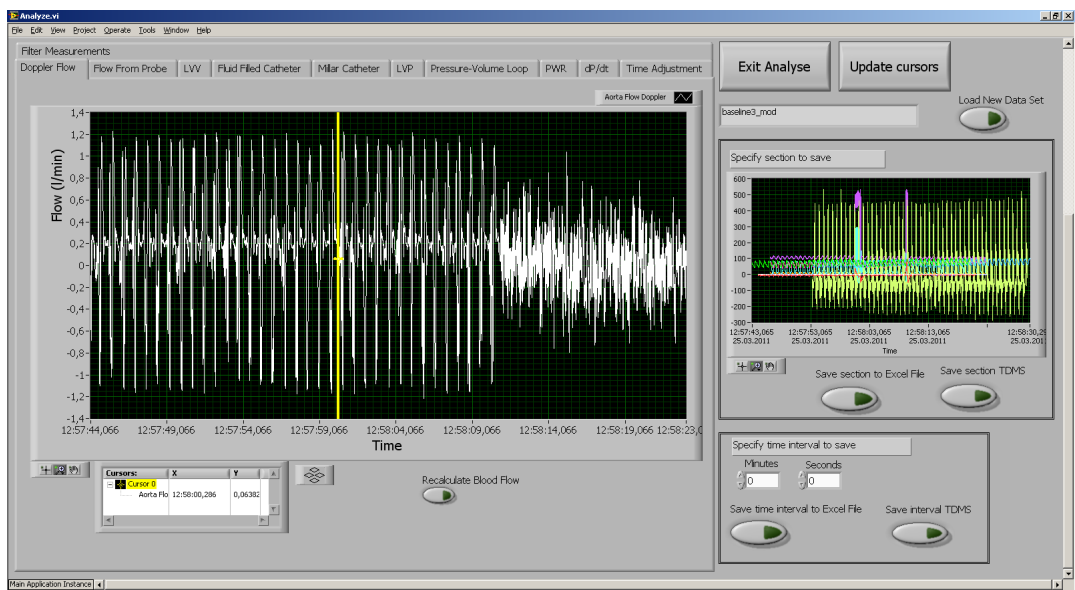


Figure 60: The tab displaying the Doppler flow.

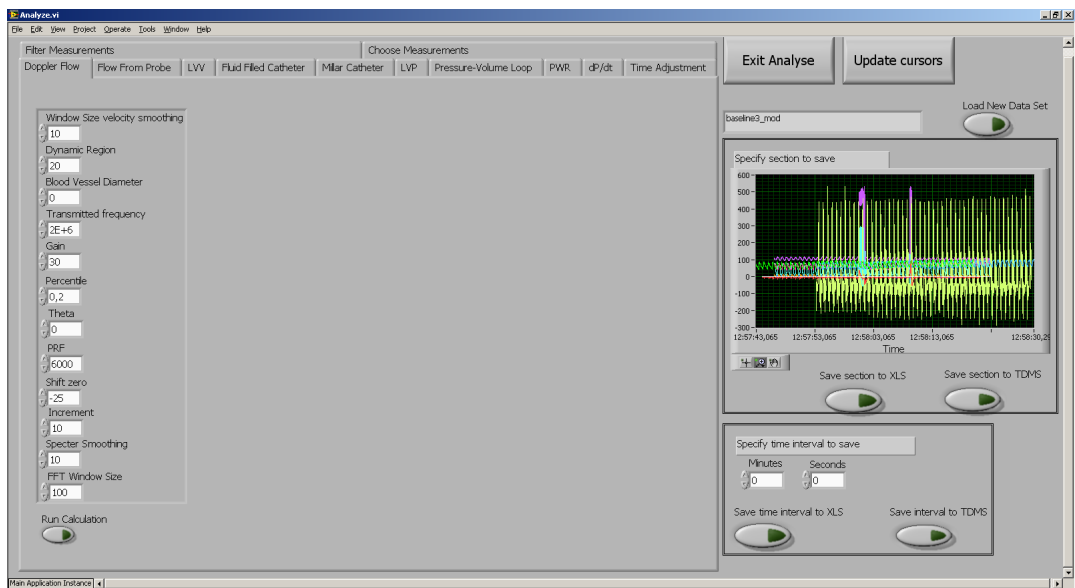


Figure 61: Set parameters for recalculation of Doppler flow.

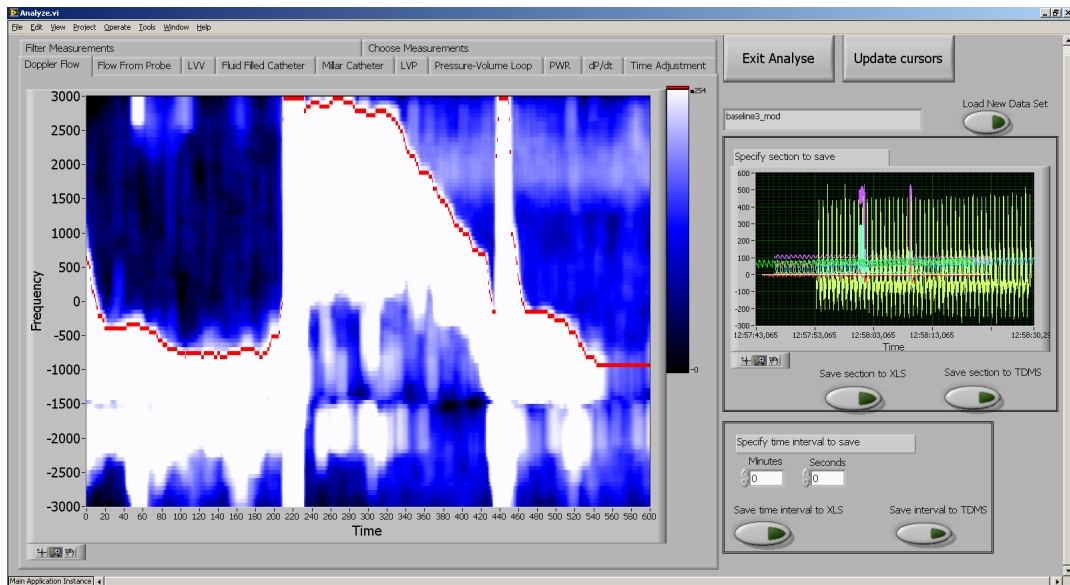


Figure 62: Spectrogram for recalculated Doppler flow

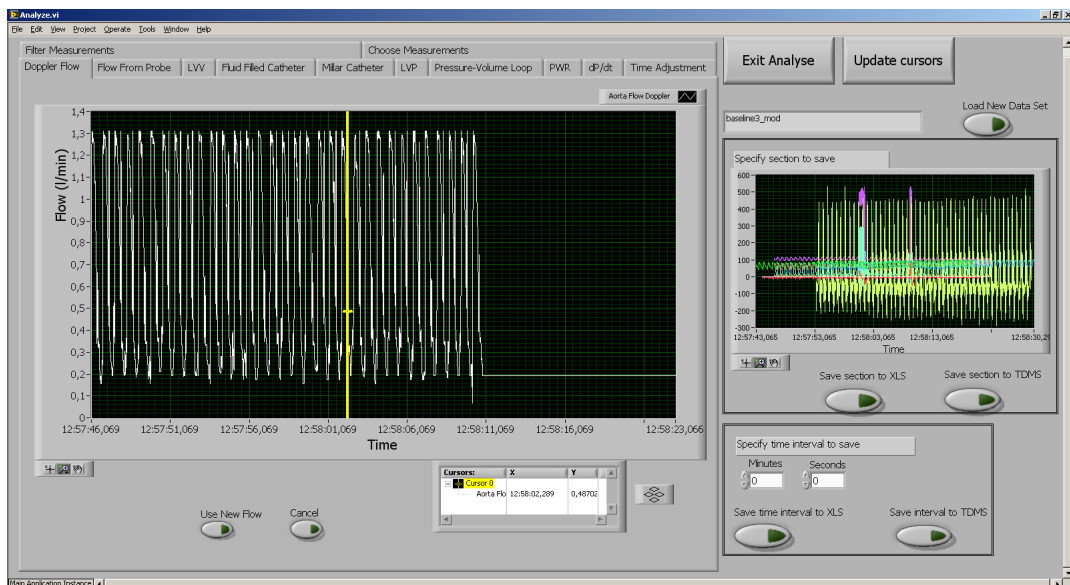


Figure 63: The result of the recalculated Doppler flow. By pressing the button *Use New Flow* the recalculated Doppler flow is used.

Filtering On the page *Filter Measurements* the measurements can be filtered by a low-pass filter, displayed in Figure 64. The user can choose the

measurement to be filtered from the listbox *Available Measurements*. After the filtering is done the filtered measurement is displayed as in Figure 65.

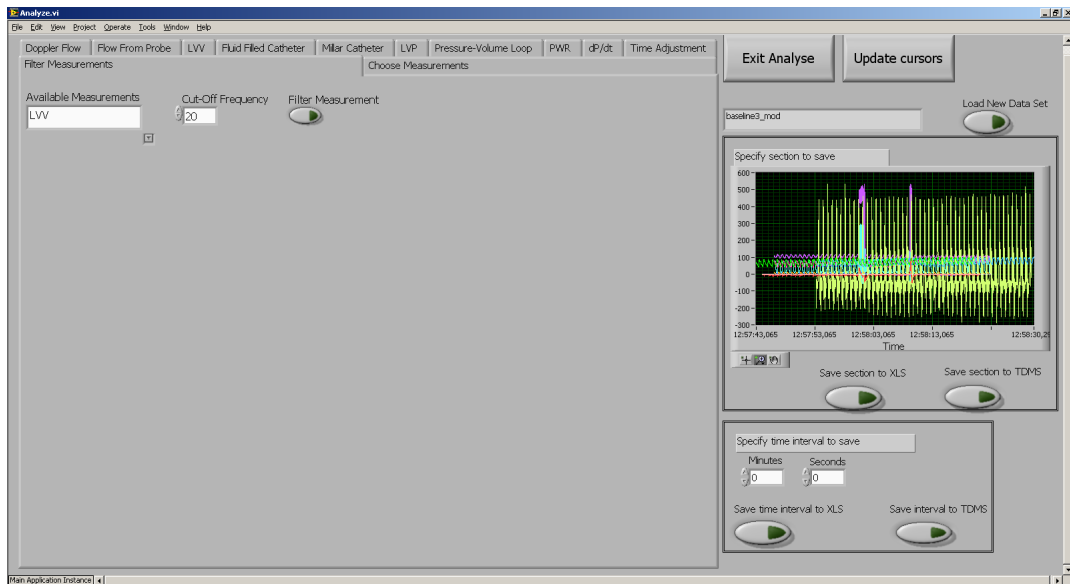


Figure 64: Tab for filtering of the measurements.

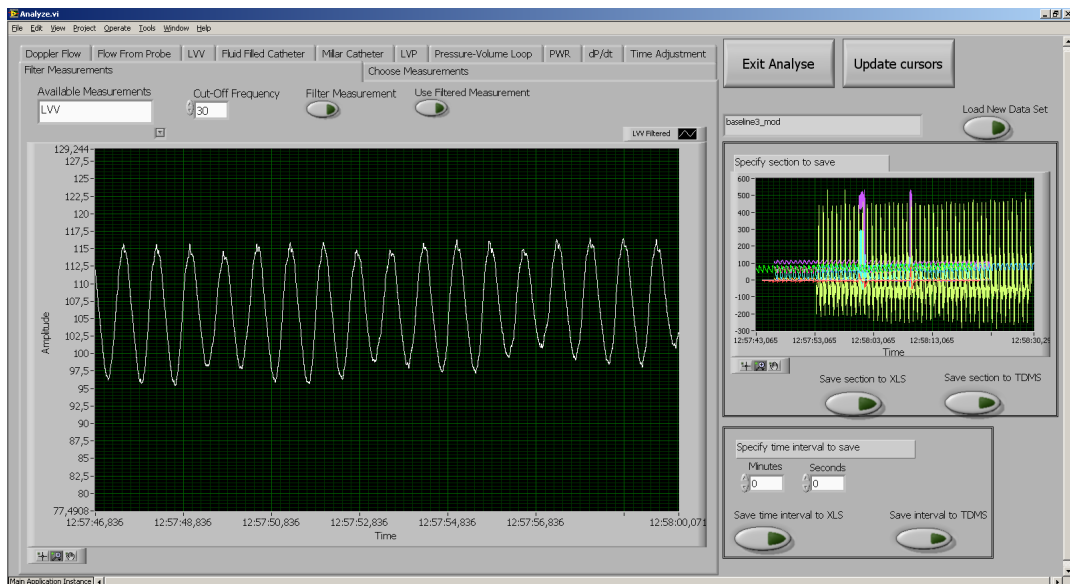


Figure 65: The filtered measurement.

Choose Measurements which parameters to calculate can be set here. The user can also choose whether to use the filtered measurements or the unfiltered measurements for the calculations.

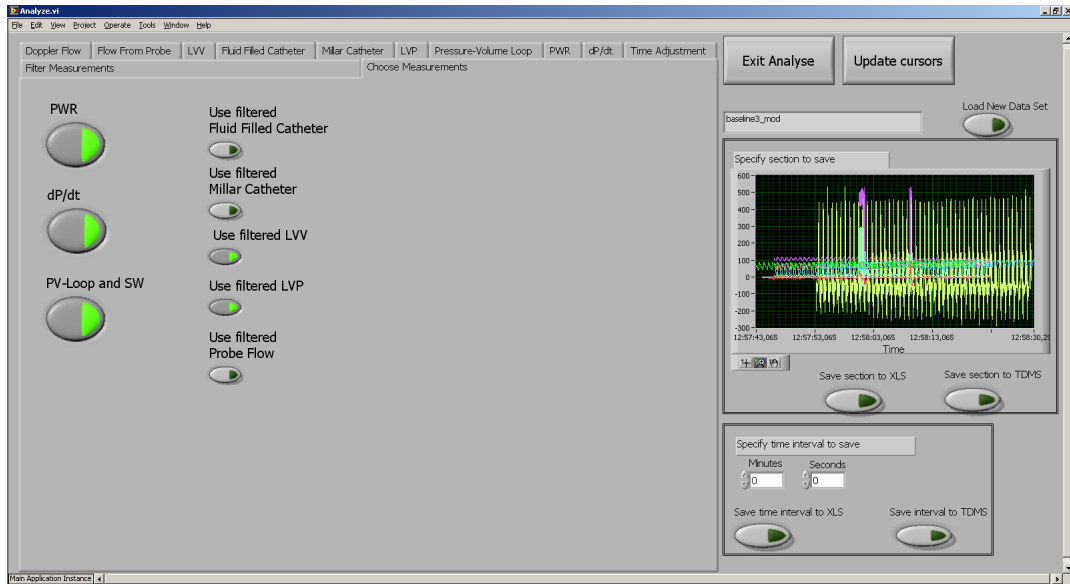


Figure 66: The tab for choosing the measurements.

PV Loops There is also a page for PV loops, as displayed in Figure 67. The cycles to be displayed is chosen by the *Start Cycle* and the *End Cycle* fields. The calculated parameters for each cycle is listed on the right.

The line through the ES points is calculated for every set of cycles selected. When the desired cycles is found, the user can press the button *Use EES*. When this button is pressed the current EES is registered together with the start and stop cycles. When a file is saved, the registered EES is saved.

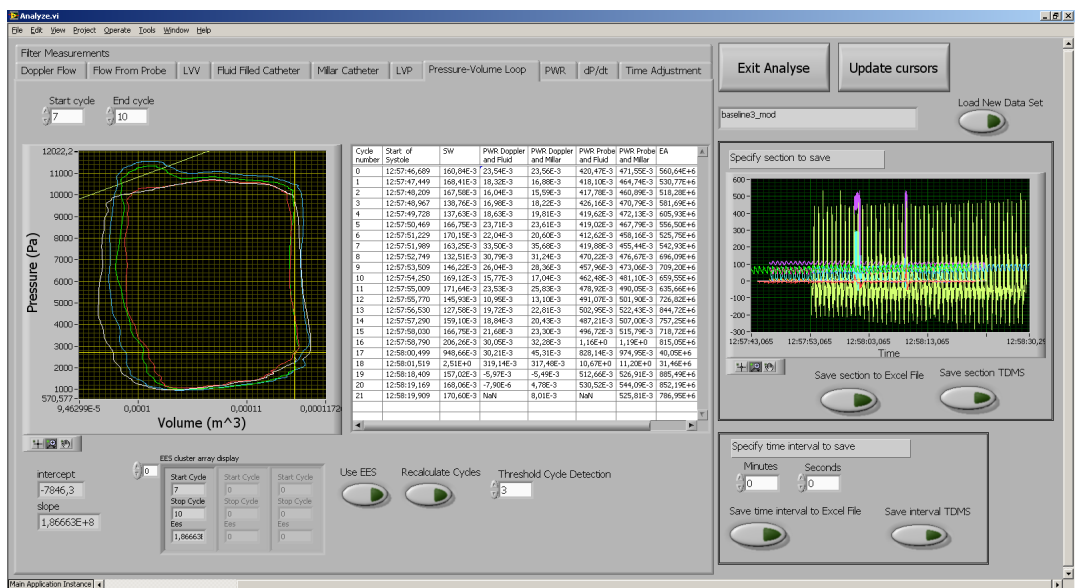


Figure 67: PV loops and parameters

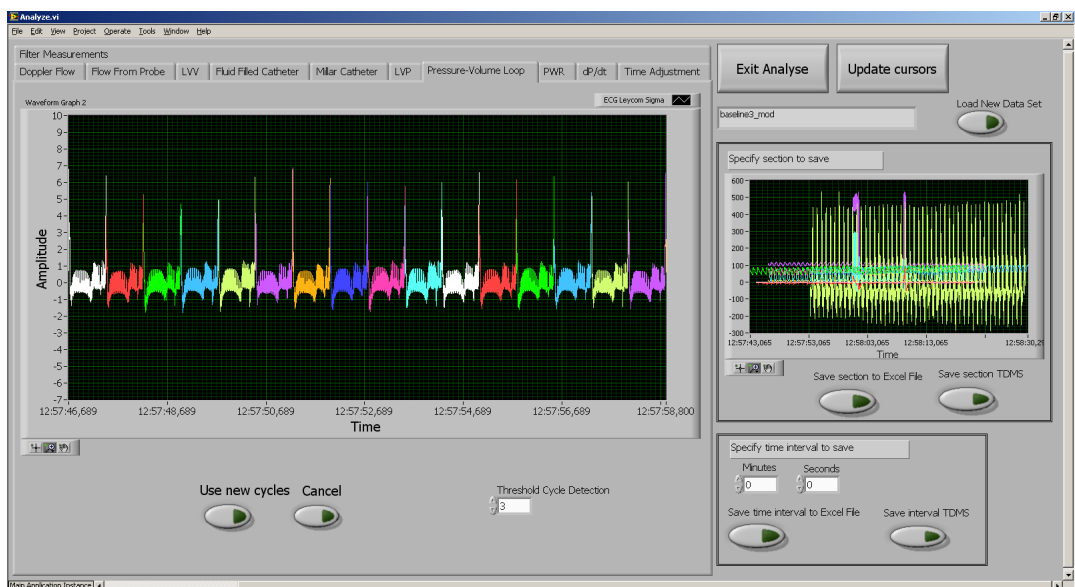


Figure 68: The recalculated heart cycles is displayed, and the user can choose to use them or to use the old ones.

Saving to file The data can be saved to both a TDMS file and a XLS file. By pressing the *Save section to XLS* button or the *Save section to TDMS* button, the interval displayed in the graph beneath the label *Specify section*

to save is saved. If the *TDMS Save time interval to XLS* button or the *Save interval to TDMS* button is pressed, the time from the last timestamp and the time given above is saved.

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Cycle number	Start of systole SW	PWR Doppler and Fluid	PWR Doppler and Millar	PWR Probe and Fluid	PWR Probe and Millar	EA	EES	Start Cycle	Stop Cycle	EES	Measurement Name	Aorta Flow Doppler	Measurement Name			
2	0	57.46,7	1,61E-01	2,36E-02	2,36E-02	4,20E-01	4,72E-01	5,61E+08								600	Samp
3	1	57.47,4	1,68E-01	1,69E-02	1,69E-02	4,18E-01	4,65E-01	5,31E+08								57.44,1	Start
4	2	57.49,2	1,68E-01	1,60E-02	1,56E-02	4,19E-01	4,61E-01	5,18E+08									
5	3	57.49,0	1,39E-01	1,70E-02	1,82E-02	4,26E-01	4,71E-01	5,82E+08									
6	4	57.49,7	1,38E-01	1,86E-02	1,98E-02	4,20E-01	4,72E-01	6,06E+08									
7	5	57.50,5	1,67E-01	2,37E-02	2,36E-02	4,19E-01	4,68E-01	5,57E+08									
8	6	57.51,2	1,70E-01	2,20E-02	2,06E-02	4,13E-01	4,58E-01	5,26E+08									
9	7	57.52,0	1,63E-01	3,36E-02	3,57E-02	4,20E-01	4,55E-01	5,43E+08									
10	8	57.52,7	1,33E-01	3,08E-02	3,12E-02	4,70E-01	4,77E-01	6,36E+08									
11	9	57.53,5	1,46E-01	2,60E-02	2,84E-02	4,58E-01	4,73E-01	7,09E+08									
12	10	57.54,3	1,69E-01	1,58E-02	1,70E-02	4,62E-01	4,81E-01	6,60E+08									
13	11	57.55,0	1,72E-01	2,36E-02	2,58E-02	4,79E-01	4,90E-01	6,36E+08									
14	12	57.55,8	1,46E-01	1,10E-02	1,31E-02	4,91E-01	5,02E-01	7,27E+08									
15	13	57.56,5	1,28E-01	1,97E-02	2,28E-02	5,03E-01	5,22E-01	8,45E+08									
16	14	57.57,3	1,69E-01	1,89E-02	2,04E-02	4,87E-01	5,07E-01	7,57E+08									
17	15	57.58,0	1,67E-01	2,17E-02	2,33E-02	4,97E-01	5,15E-01	7,19E+08									
18	16	57.58,8	2,06E-01	3,01E-02	3,23E-02	1,16E+00	1,19E+00	8,15E+08									
19	17	58.00,5	9,49E-01	3,02E-02	4,53E-02	8,28E-01	9,75E-01	4,01E+07									
20	18	58.01,5	2,51E+00	3,19E-01	3,17E-01	1,07E+01	1,12E+01	3,15E+07									
21	19	58.18,4	1,57E-01	-5,97E-03	-5,49E-03	5,13E-01	5,27E-01	8,85E+08									
22	20	58.19,2	1,88E-01	-7,90E-06	4,78E-03	5,31E-01	5,44E-01	8,52E+08									
23	21	58.19,9	1,71E-01	NaN	8,01E-03	NaN	5,26E-01	7,87E+08									
24																	

Figure 69: Example of XLS file saved from the application.

GcLab Plug-in

GcLab

The GcLab window is organized with a viewer placed in the middle, as displayed in Figure 70. Two panel elements is placed on the left and the right side. On the bottom of the window the available DICOM files in the current folder is listed as small images. In the viewer, an activex component is displayed. This activex component reads the content of the chosen DICOM file, and plots the contents. The activex object has a B-Mode ultrasound image placed on the top. Below is a Doppler spectrum and an ECG plot. On the panels on each side different user interface tools can be displayed. There is a possibility for creating user defined plug-ins, that can be displayed on the panels. In this master work a plug-in named *Physiological* were developed. This plug-in displays two buttons labeled *Open Analyze* and *Set frame*, marked by a red circle in Figure 70. Pressing the button labeled *Physiological* opens the window displayed in Figure 71. Pressing the button labeled *Set Frame* sets the cursors in plotted measurements in the plug-in to the position of the current frame displayed in GcLab.

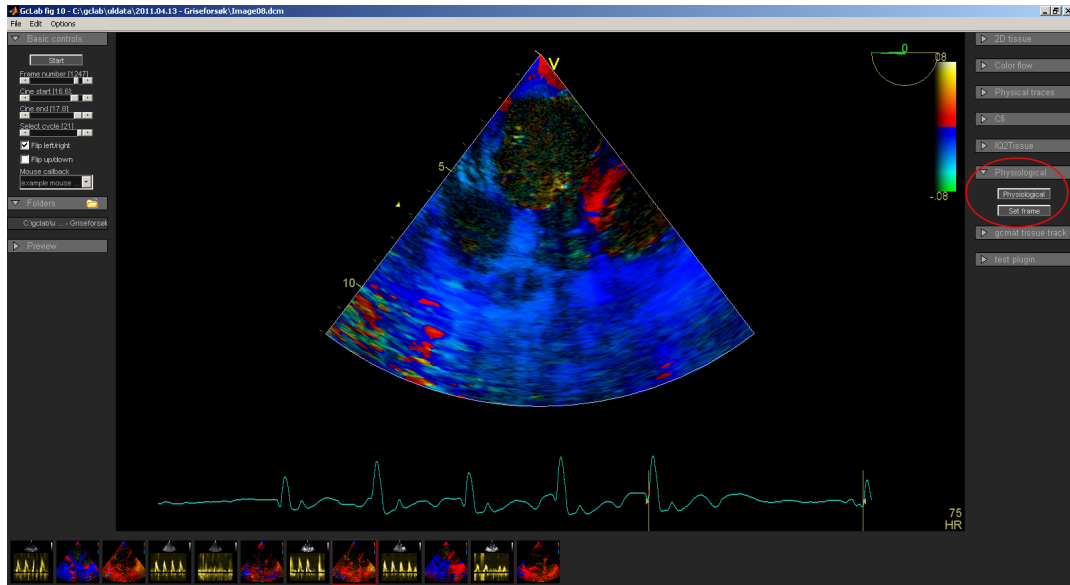


Figure 70: GcLab window. The interface to the developed application is marked by the red circle.

Physiological plug-in

The Analyze window consists of up to four panels. Each panel has a height equal to the height of the Analyze window, and a width depending in the number of panels opened.

To the left is the choose panel. At start-up, this panel consist of two buttons, *Read TDMS* and *Watch TVI Plots*, as displayed in Figure 71. By pressing the *Read TDMS* button, a file dialog allowing the user to choose the desired TDMS file is displayed. When a TDMS file has been read, the menu to the right in Figure 71 is displayed.

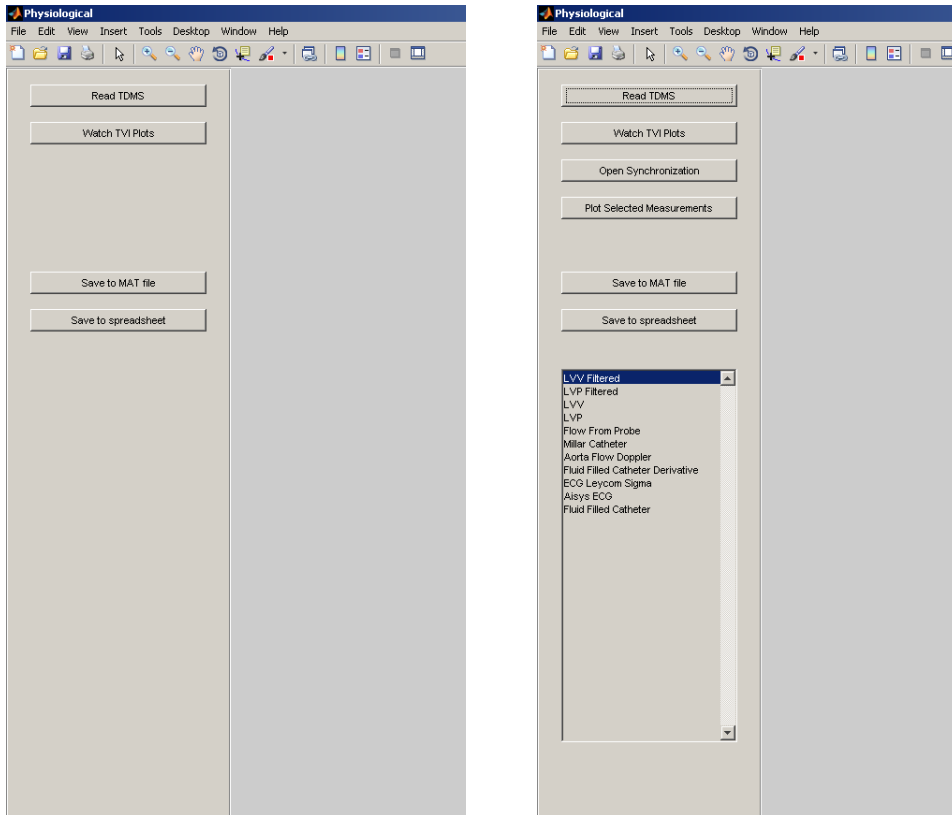


Figure 71: The analyze menu.

When *Read TDMS* is pressed, a open file dialog box is displayed, where the user can choose TDM or TDMS files. When the file is chosen, the data it consists of is read as described in section .

After a TDMS file has been read, and listbox appears with the names of the measurements in the TDMS file. Buttons labeled *Plot Selected Measurements*, *Open Synchronization*, *Save to MAT file* and *Save to spreadsheet* is displayed, as illustrated to the right in Figure .

Synchronize

When the *Open Synchronization* button is pressed, the panel in Figure 72 is opened. This panel allows for synchronization of the measurements from DICOM and TDMS. When this panel is first opened, the measurements are synchronized based on the detected cycles. The threshold used in cycle detection is displayed in the field labeled *Threshold*. The user can set a different threshold and rerun the calculations by pressing the button labeled *Synchronize based on cycles*. If a time adjustment is entered in the field

labeled *Enter Time*, the button *Synchronize based on time* uses the given time for synchronization.

Initially it is the ECG from Leycom Sigma 5DF that is used for synchronization against the ECG from the DICOM file. However, if this measurement is not available, or corrupted with noise, any other measurement from the TDMS file can be used. By pressing the *Use selected measurement plot* button, the first of the selected measurements from the list is used.

Two buttons labeled *Decrease one cycle* and *Increase one cycle* is displayed below the synchronize plot. These buttons offsets the values of the DICOM ECG by one cycle. The plot of the ECG measurement from DICOM is plotted using the time stamps with the calculated time adjustment.

When the user moves the cursor in the measurement plots into an area of overlapping ECG measurements, the corresponding frame in the ultrasound image displayed is set.

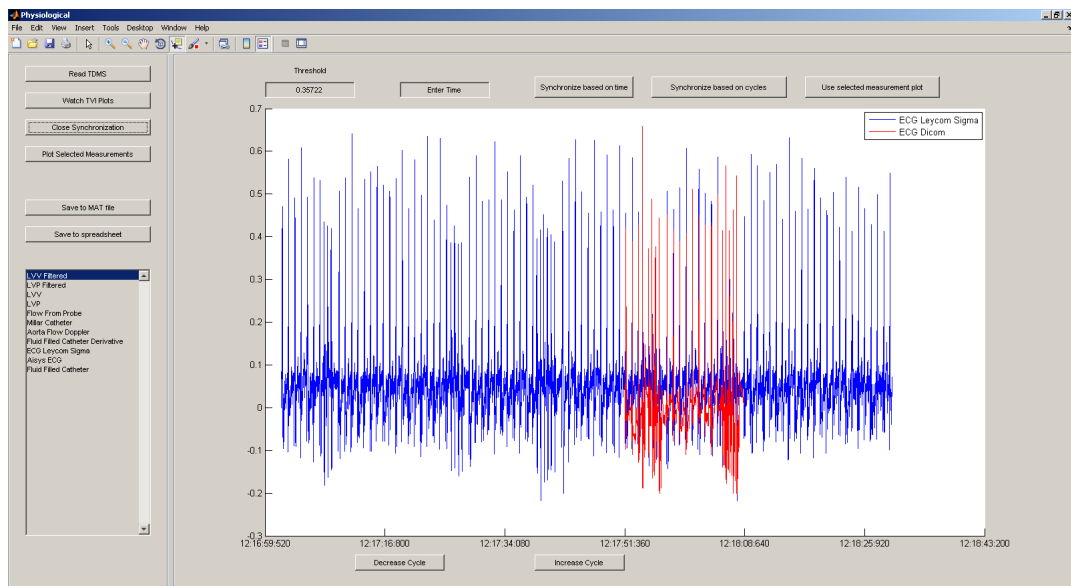


Figure 72: Panel for synchronization of measurements from TDMS and DICOM.

Measurement Plots

A list of the names of all the measurements in the TDMS file is displayed. The user can choose the desired measurements and display them by pressing the *Plot Selected Measurements* button. Figure 73 displays the appearance of three measurements. The size of the plots is automatically adjusted based on the number of selected measurements. The measurements values displayed

is the values overlapping from the DICOM file.

When the cursor is moved in one plot, the cursors in all the other plots moves simultaneously. The frame displayed in the GcLab viewer is also updated. When the *Set Frame* button in GcLab is pressed, the cursors are set to the position of the current frame displayed.

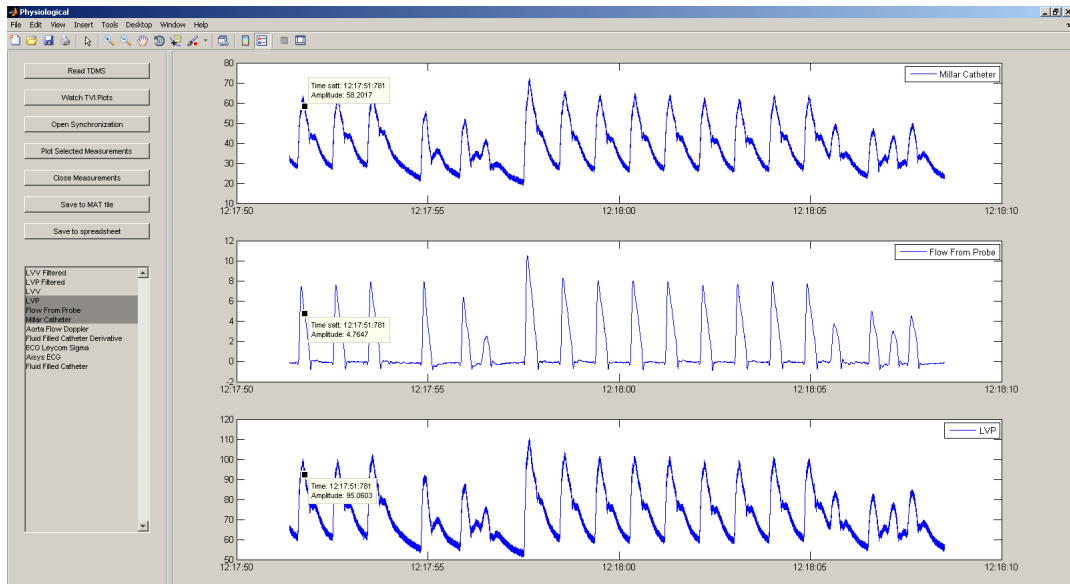


Figure 73: Selected measurements panel.

TVI Plots

If the *Watch TVI Plots* button is pressed, a panel for viewing TVI plots extracted from the DICOM file is displayed. A plot is generated every time the user presses the button inside the ultrasound image. A button next to the plot allows for deleting of the plot. The height of the plots is adjusted automatically when the number of plots changes.

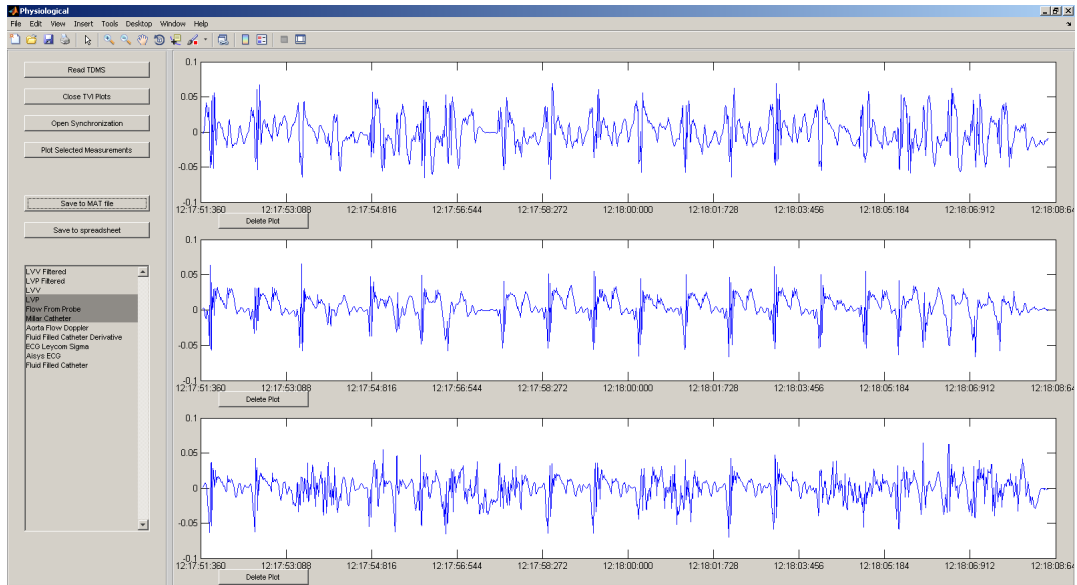


Figure 74: The panel for TVI curves.

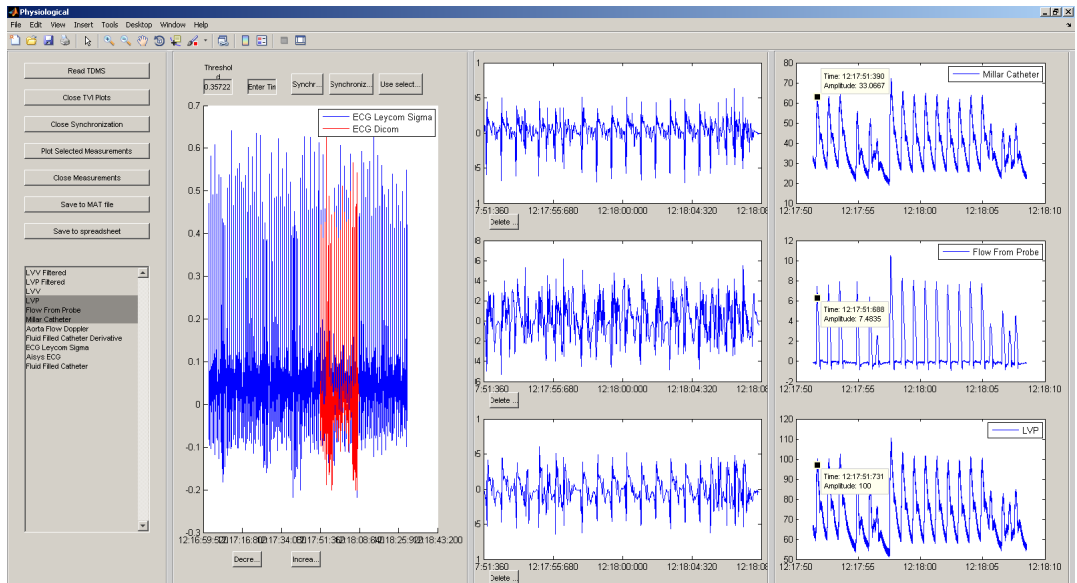


Figure 75: All panels open on the same time.

Discussion

Inputs and instruments

The data acquired through the NI USB-6251 BNC and the Aisys Datex Ohmeda appears to be reasonable. However, some measurements had high frequency noise present. This may be due both to the instruments and the NI USB-6251 BNC. A possibility for low-pass filtering of the measurements was implemented to remove the noise.

The sound card had a deviation between the given sampling rate and the actual sampling rate. This caused an error in the timestamps of the Doppler flow measurements. The deviation was reduced by sampling at a higher frequency, and then resampling the signal. If the inaccuracy in the sampling rate is still deemed to high, a solution might be to buy an external sound card. The sound card used in this project is the one included when the laptop was bought, and more accurate alternatives is probably available.

Calibration

Correct calibration of the sensors connected to the animal is assumed. The developed system includes the possibility for calibrating the connection between the instruments and the laptop.

Calibration of the instruments with the possibility for producing reference values is assumed to be accurate. This includes all instruments except Aisys Datex Ohmeda. Aisys Datex Ohmeda displays the maximum and minimum values of the pressure measurements on the screen. When the maximum and minimum values is calculated for the incoming measurements at the laptop, an accurate calibration is achieved if the pressure is stable.

The data from Aisys Datex Ohmeda is sent to the laptop through a RS-232 connection, which is a digital communication protocol. It is therefore reasonable to assume that the scaling and offset will be constant, but no information on this is included in the documentation.

Synchronization

Three different clocks needs to be synchronized in the system. This assumption is based on all the instruments connected to NI USB-6251 BNC having negligible delays. An indicator that this assumption is correct is given by the plot of all the measurements collected by NI USB-6251 BNC.

Diathermy

The diathermy enabled synchronization of all sources. However, the electrical noise may become a problem for instruments with different degrees of electrical insulation. In the measurements acquired in the operations the the ECG measured by Leycom Sigma 5DF was disturbed seconds after the spike occurred. This makes cycle detection based on the ECG impossible in this period. Synchronization based on diathermy is therefore not well suited for applications requiring heart cycle detection.

Pacemaker

Synchronization based on pacemaker enabled synchronization of all three clocks in the system. This is dependent on the pacemaker being able to create an interval of significant altered heart rate. When this is the case all ECG measurements is affected, and synchronization of all clocks in the system is possible. An increased heart rate is easier to detect automatically than a diathermy spike. Therefore synchronization by pacemaker is better suited for automatically synchronization.

Load change

If neither a pacemaker nor diathermy is present, the laptop clock and Aisys Datex Ohmeda can be synchronized based on the aortic pressure and ECG measurements. The DICOM files can not be synchronized in this manner.

Calculation of parameters

Doppler flow

The Doppler flow is found from the spectrogram. The trace found is reasonable from the spectrogram. The Doppler flow is the most uncertain measurement in the system. It is dependent on proper placement of the ultrasound probe and the correction angle. It also depends on correct tracing in the specter and a good estimate for aortic diameter. The algorithm used finds the maximum frequency in the spectrum. This is correct for near-plug flow, which is an reasonable assumption in aorta.

Comparison of the Doppler flow and the flow measured by the ultrasound probe gives a reasonable result.

Start- and end Systole detection

The start of the systole is set to be the peak of the R-wave in the ECG measurement in this system. Other definitions of the start systole exists, but it was decided together with the clinical team to use the R-wave. As long as there is no strong disturbance on the ECG measurement, the start systole is detected correctly.

The end systole is identified from an algorithm that detects the upper left corner in the PV loop. Other end systole point might have been found from other definitions, like the point where the ventricular pressure drops below the aortic pressure. However, the clinical team expressed a wish for end systole based on the upper left corner of the PV loop.

The parameters PWR and SW depends on correct detection of start systole. For the Ea and the Ees both start- and end systole must be correct.

If it can be assumed that start- and end systole and the calibration is correct, the mentioned parameters will also be calculated correctly..

Developed Applications

Two applications were developed providing an interface for the acquisition and analysis of the measurements and parameters. The applications is designed to be used both in the projects described and in other projects requiring some or all the same measurements and parameters. From the Labview application the data can be saved as TDMS and XLS files. From the GcLab plug-in the data can be saved as MAT and XLS files.

Conclusion

The developed applications meets the demands for the clinical projects described in the introduction, and is ready to be used. The Labview application collects the invasive measurements, ECG and PW Doppler. The GcLab plug-in enables synchronization between the measurements collected by the Labview application and B-mode ultrasound images and TVI curves.

The NI USB-6251 BNC board functioned properly, despite not being intended for medical environments. A possibility for low-pass filtering of the collected measurements was included to compensate for noise observed in the measurements.

Of the measurements the Doppler flow is the most uncertain. It depends on a correct angle correction and measurement of aortic diameter.

The sampling rate delivered by the sound card input deviated from the given sampling rate. The deviation were smaller for higher frequencies, so the solution became to sample at a high frequency and then resample the measurement. If it is decided that the sampling rate is not accurate enough, a solution might be to by an external sound card.

Appropriate calibration procedures were found for all instruments. An interface calculating the calibration parameters based on the incoming data and reference values from the instruments is implemented.

The pacemaker gave the most efficient synchronization and is most suitable for automatically synchronization. However, it depends on attaching the pacemaker to the heart. Diathermy is less complicated, and also gave synchronization for all clocks. Still, the diathermy spikes is difficult to identify automatically, and the electrical noise generated disturbs other equipment. Synchronization based on load changes only synchronizes Aisys and NI DAQ, but does not depend on external devices.

Good estimates for start- and end systole is found. Together with correctly calibrated and synchronized measurement the start- and end systole is used for calculating several parameters related to cardiac function.

Appendix A: Handling of Packages from Aisys Datex Ohmeda

Package creation

The buffer is read by the *VISA Read Block* in Labview. The data is received as a string of bytes. The program gives an error message and stops the application if the buffer overflows and received data is lost. It is therefore assumed that all bytes are received and belongs to a packet.

The record starts and ends with the character 0x7E. The package handling algorithm detects the start and end of the records based on this character. The characters before the first instance of 0x7E is saved and appended to the characters after the last instance of 0x7E from the preceding buffer read. The characters after the last instance of 0x7E is saved and used next time the buffer is read. Special care is taken to handle situations where the characters read from the buffer starts or ends with 0x7E or 0x7E 0x7E. If the read characters start with 0x7E 0x7E this means that the end of the last buffer read was the end of the last package. If the read characters starts with 0x7E this means that the last characters read ended with 0x7E. In the case of 0x7E 0x7E the first character is removed. In the next step the bytes before 0x7E, in this case none, is appended to the rest of the string from the last time, and appended to the array of packets. This will give the correct result because the last 0x7E is removed from the rest string before it is saved. The algorithm gives an array of packets in the correct order as its output. A flow chart representation of the package generation algorithm is shown in Figure 76.

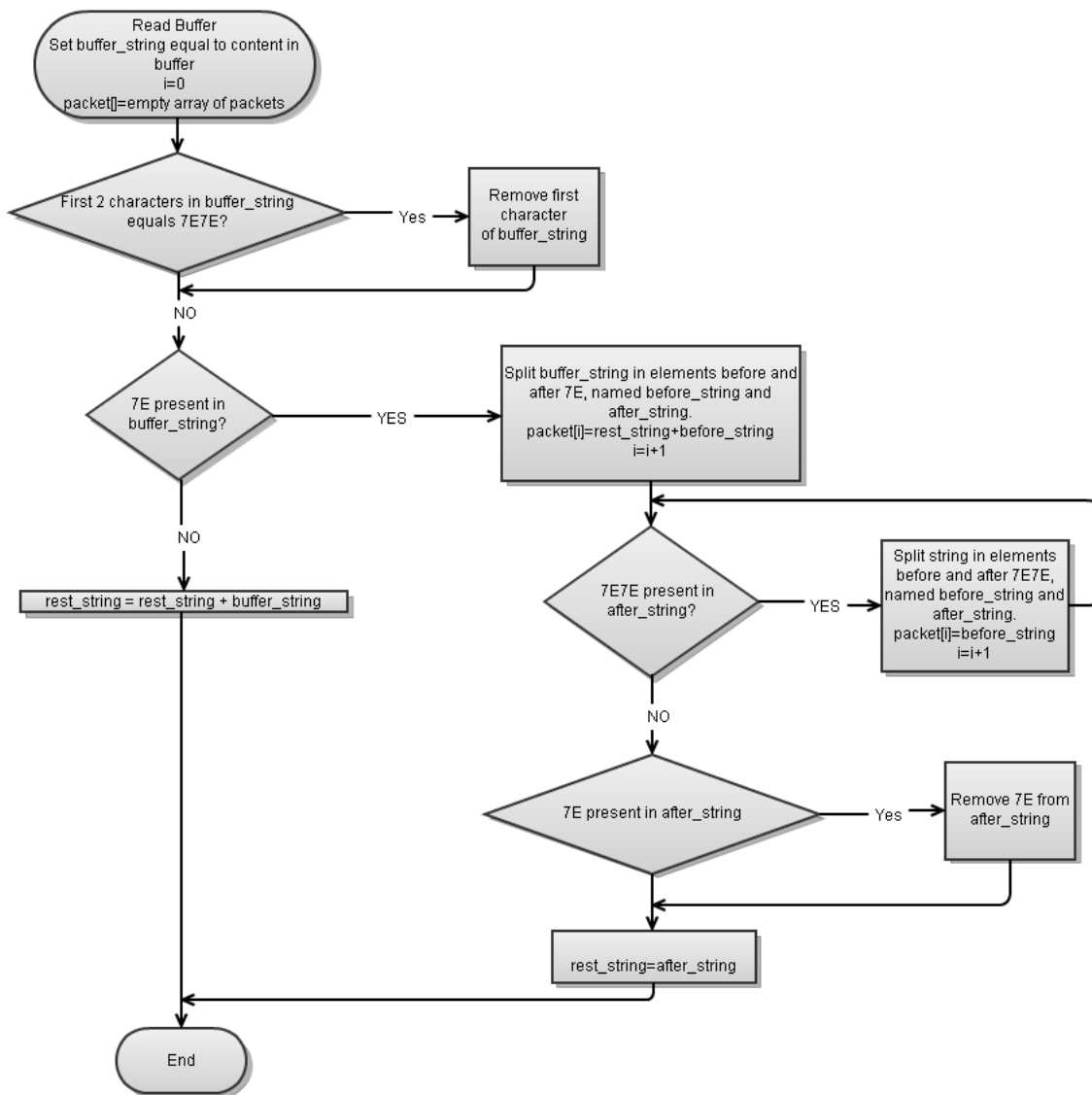


Figure 76: Flow chart of the package generation algorithm

Package handling

The first step of the package handling is to detect all instances of the control byte 0x7D in the incoming packages. If the byte following the control character is 0x5D, the two bytes are replaced by the single byte 0x7D. If the following byte is 0x5E, the two bytes are replaced by 0x7E.

After this transformation the next step is to decode the package header.

Only packages of the waveform type are accepted, as this is the only type of interest in this project. The array describing the subrecords is iterated over, and information of type, offset and length of all waveforms included in the package is obtained. An empty array of waveforms, with room for all possible waveform types, is created for each package that is received. A Labview waveform is created for each of the waveforms included in the package, and inserted in the appropriate place in the waveform array. The first time a waveform of a given type is received, the starting time of that waveform is set to the timestamp included in the package. When data of the same type is received in subsequent packages, the timestamp is updated by adding the number of samples received multiplied with the sampling ratio.

The transmit time of the records is only given in a resolution of whole seconds and the clock of the Datex Ohmeda and the computer is not synchronized. This leads to a need for time synchronizing in the application.

Appendix B: Detection of Heart Cycles

Detection of heart cycles

An algorithm for both real time and offline identification of heart cycles was developed. The ECG signal is used for identification of the end of diastole and start of systole. This event is defined as the peak of the R wave for this application. An array of timestamps representing the start of each cycle is generated by the Matlab function `detect cycle`. This function is run for each new arriving set of ECG data. The Matlab function is called by the Labview block Matlab script node. This function takes the arriving ECG signal, sampling rate, and the start time of the ECG signal, a threshold value and the remainder ECG signal from the last iteration as input parameters. The remainder ECG signal is the ECG values after the last detected end diastole time from the last iteration.

The average value of the ECG signal is calculated. A threshold is calculated by addition of the input threshold and the average value of the ECG signal. The ECG values that exceeds this threshold is identified, and their timestamps is included in an array. The values after first value in the last continuous interval of values exceeding the threshold are saved for the next iteration. This is necessary in order to avoid ambiguity when the last received sample is at, or close to, the peak. This values is then removed from the timestamp array. In the next step the highest ECG value in each continuous interval of timestamps is found. The other timestamps are then deleted, and the array of timestamps is returned.

Creation of intervals The cycle detection algorithms returns an array of timestamps, witch is appended to an array of timestamps. To correctly segment the incoming data into heart cycles it is necessary to implement a function that stores incoming data and checks whether the data matches a detected interval. In order to avoid to much data being saved in case no heart cycles is detected, no waveforms can grow longer than 10 seconds.

Whenever there is more than one timestamp in the array of timestamps, a check of whether the two timestamps is included in all of the saved data is performed. If this is true, the data between the timestamps is returned. Samples before the first timestamp are deleted. The first timestamp is then deleted from the timestamp array.

If the first timestamp is not included in all of the saved data, but the

```

ECG = ECG_in appended to the end of ECG_last
threshold=mean(ECG)+threshold
initialize empty array timestamps

for elements in ECG
    if element>threshold
        append the timestamp corresponding
        to the ECG element to the timestamp
        array

delete last continuous interval of timestamps in
timestamp array

ECG_last = ECG values from last element in timestamp to
the end of ECG

for continuous intervals of timestamps in timestamps
    append the timestamp corresponding
    to the highest ECG value to timestamps_out

return timestamps_out and ECG_last

```

second is, then the first timestamp is deleted from the array. If the first timestamp is included in some or all of the data, but the second timestamp is not, then nothing is returned.

Appendix C: Connection of cables

Connection to Aisys Ohmeda

Aisys Ohmeda to the laptop is connected to the laptop through a serial cable. The serial cable is to be inserted into the port on the backside of Aisys as marked in red in figure 77. This port can be found by removing the cover on the back side of Aisys. The serial cable is to be inserted into the laptops docking station, as marked in red in figure 78.

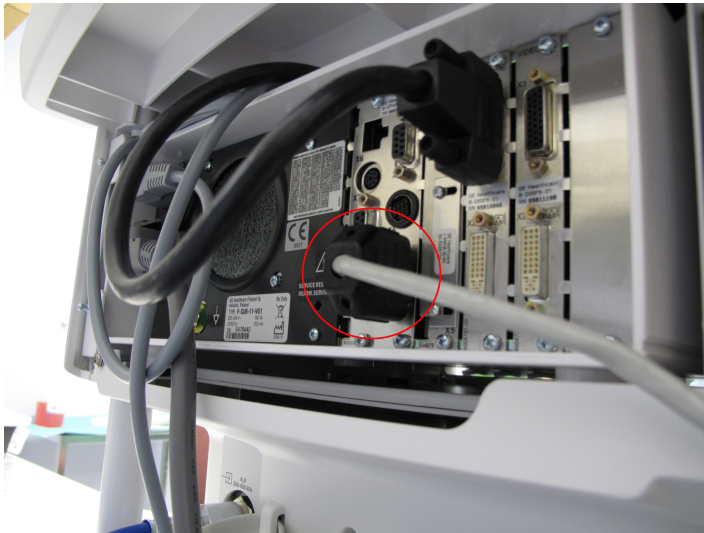


Figure 77: Connection of cable to Aisys Datex Ohmeda

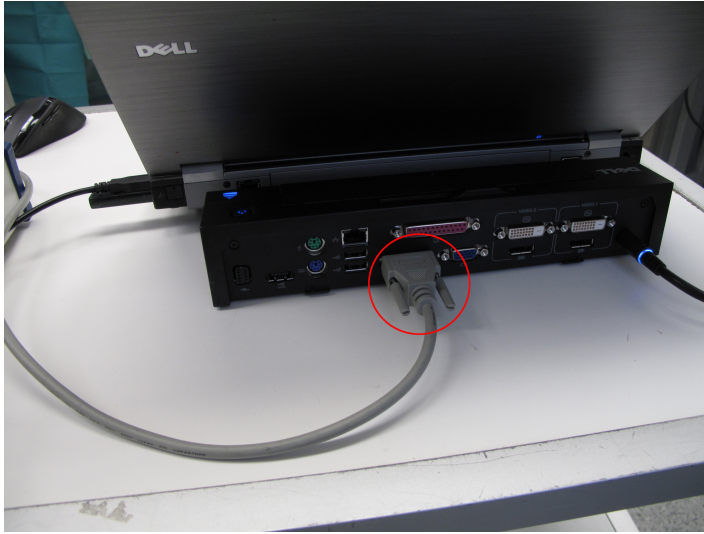


Figure 78: Connection of the cable to the laptops docking station

NI USB-6251 BNC

The analog inputs is connected to the NI USB-6251 BNC through Coax Cables.

The different inputs shall come as displayed in Table 3.

Name	Channel
LVV	AI 0
CardioMed CM-4000 Flowmeter	AI 1
ECG Leycom Sigma 5DF	AI 2
Millar Catheter	AI 3
LVP	AI 4

Table 3: Connection to NI USB-6251 BNC

Of special importance is the cable from the Millar catheter. This cable needs to be grounded to AI GND on the NI board. One of the coax cables has a red wire connected to its ground, and is intended to be used for the Millar catheter.

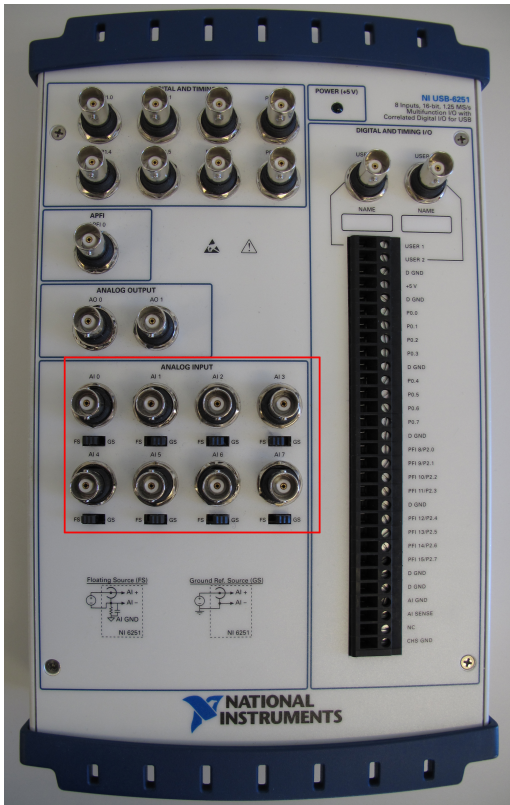


Figure 79: NI USB-6251 BNC. Analog inputs is marked in red.

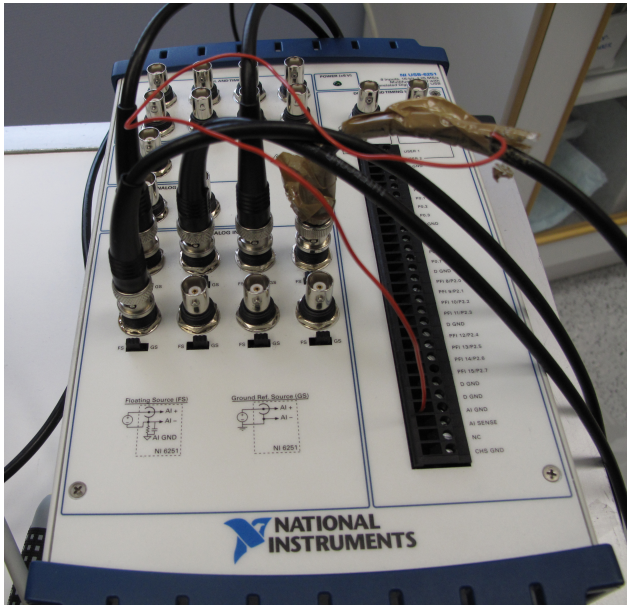


Figure 80: NI USB-6251 BNC with cables connected

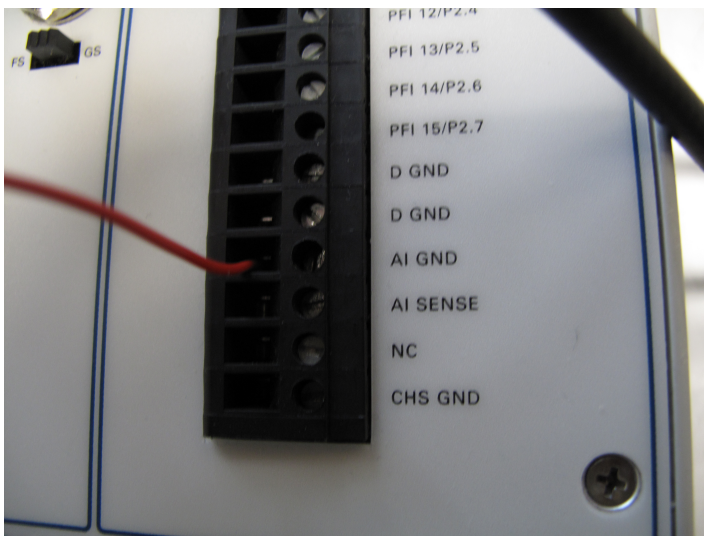


Figure 81: Grounding of Millar catheter

CardioMed CM-4000 Flowmeter

Figure 82 displays the placement of the coax cable into the Flowmeter in red. It is also important to disable the option *delayed analog readout* on the CardioMed CM-4000 system.

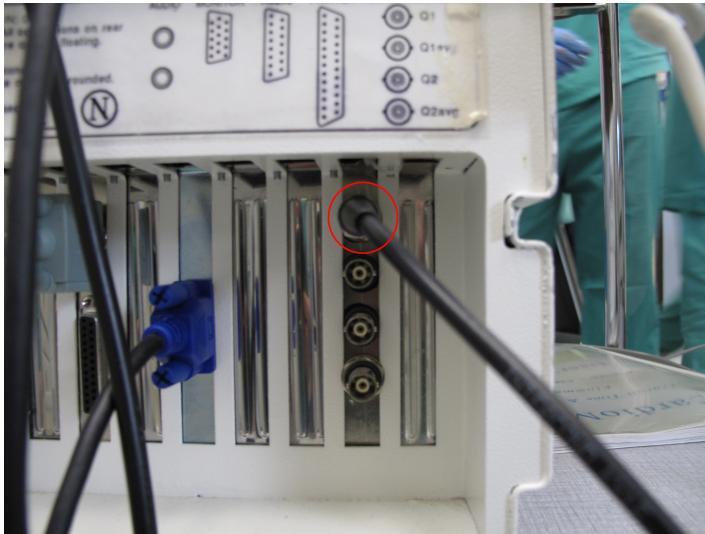


Figure 82: CardioMed CM-4000 Flowmeter connection

Leycom

From Sentron Pressure Measurement System a T-Joint is providing the pressure measurement to both the NI Board and the Leycom Sigma 5DF, displayed in Figure 83.

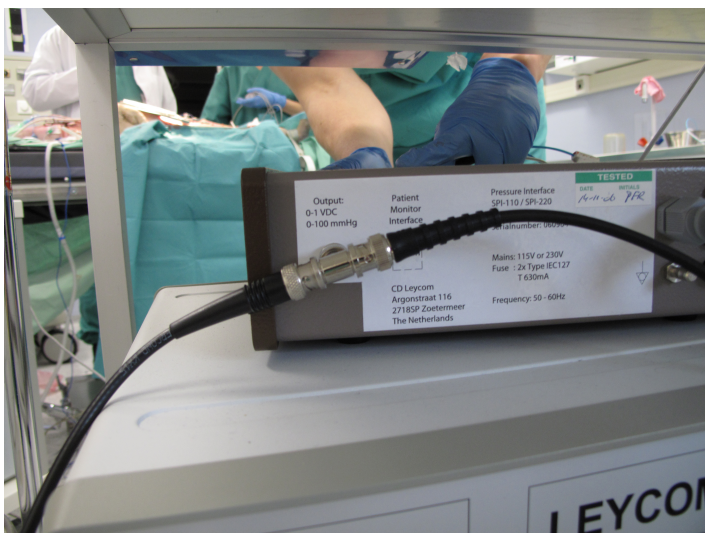


Figure 83: Connection to the Sentron pressure interface

The connections to Leycom Sigma 5DF is displayed in Figure 84. The pressure from the Sentron Pressure Measurement System is connected to the

input marked *Pressure*. The output from *Vtot* is the Left Ventricle Volume. The output from *ECG* is the Leycom Sigma 5DF ECG.

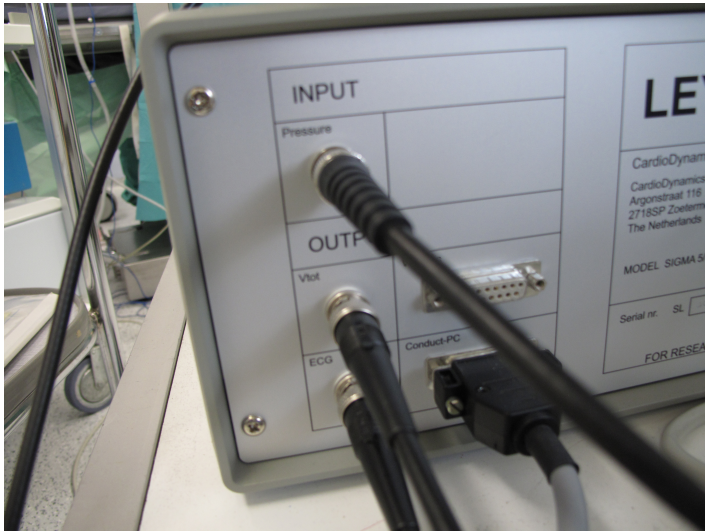


Figure 84: Connection to the Leycom Sigma 5DF

Sound Card Input

The cable from GE Vingmed Vivid7 is connected as displayed in Figure 85. It is important to select the option *Linjeinngang* in the dialog box that is displayed when the cable is connected, as illustrated by Figure 86.

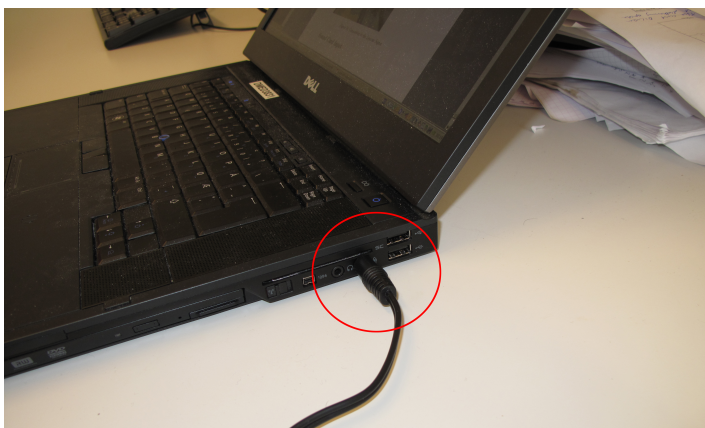


Figure 85: The sound card input.

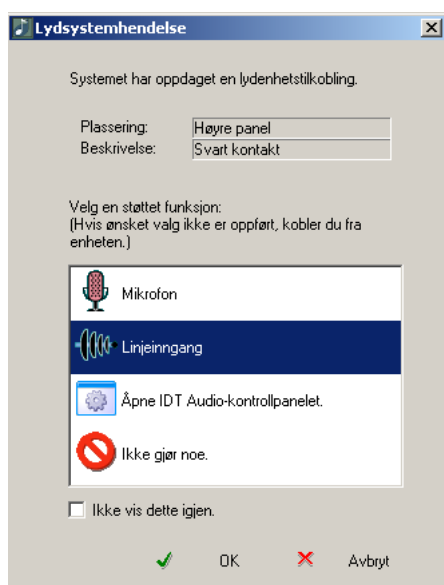


Figure 86: This dialog box is displayed when the cable is inserted to the sound card input. It is important to choose the option *Linjeinngang*.

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