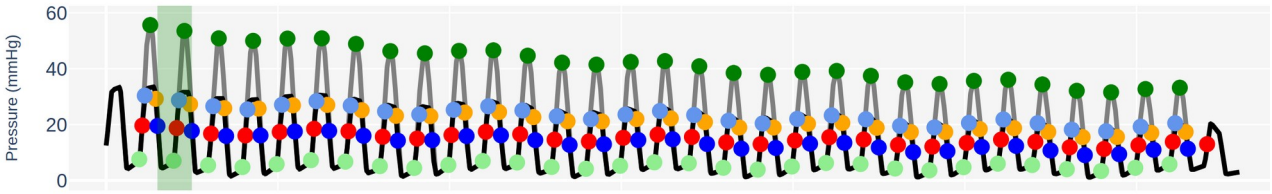
Instructions For Use

Software Name: Single-Beat Analyzer
IFU Revision: 04



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0. Glossary

This section defines key terms and abbreviations used throughout this document to ensure clarity and consistency.

Term	Abbr.	Definition
Instructions for Use	IFU	A manual describing the functions, operation, and intended use of the software.
Single-Beat Analyzer	SBA	A software tool designed for analyzing ventricular pressure waveforms, including beat detection, pressure-volume loop analysis, and hemodynamic parameter estimation.
Hemodynamix	HDX	The platform hosting the Single-Beat Analyzer, accessible at www.hemodynamix.com.
End-Diastolic Pressure	EDP	The pressure measured at the end of the diastolic phase, just before ventricular contraction begins.
Pressure at Maximum of First Derivative	pdpdtmax	The pressure at the time point where the first derivative of the pressure signal (dpdt) reaches its maximum, indicating the peak rate of pressure rise during systole.
Maximum First Derivative of Pressure	dpdtmax	The highest value of dpdt, representing the maximum rate of pressure increase during ventricular contraction. It is used as an indicator of systolic function.
Beginning-Systolic Pressure	BSP	The pressure at the start of the systolic phase, before the arrival of reflected pressure waves.
End-Systolic Pressure	ESP	The pressure at the end of systole, typically measured when ventricular contraction is complete and before relaxation begins.
Pressure at Minimum of First Derivative	pdpdtmin	The pressure at the time point where the first derivative of the pressure signal (dpdt) reaches its minimum, indicating the peak rate of pressure decline during diastole.
Minimum First Derivative of Pressure	dpdtmin	The lowest value of dpdt, representing the maximum rate of pressure decrease during ventricular relaxation. It is used as an indicator of diastolic function.
Isovolumic Pressure	Pmax or Piso	The theoretical maximum pressure the ventricle would reach if the outgoing valve remained closed, meaning the ventricle contracts against a constant end-diastolic volume.
Right Ventricular Pressure	RVP	The pressure inside the right ventricle, typically measured to assess right ventricular function and pulmonary circulation.
Left Ventricular Pressure	LVP	The pressure inside the left ventricle, a key parameter in evaluating left ventricular function and systemic circulation.
General Data Protection Regulation	GDPR	A European Union regulation governing data protection and privacy, ensuring that personal data is handled securely and transparently.
Health Insurance Portability and Accountability Act	HIPAA	A U.S. law that establishes standards for the protection of sensitive patient health information.
Structured Query Language	SQL	A standard programming language used for managing and querying relational databases.
Revision	REV	A version identifier used to track changes and updates to software, documents, or datasets.

Table 0.1: Glossary.

1. Introduction

1.1 Overview

The Single-Beat Analyzer (SBA) is a Python-based software application hosted on a secure server and publicly accessible via www.hemodynamix.com.

The SBA is designed for the analysis of right and left ventricular pressure waveforms, facilitating detailed waveform assessment and the extraction of key hemodynamic parameters. It is intended to support cardiovascular research, academic studies, and scientific publications by providing advanced computational analysis of existing invasive pressure data.

1.2. Intended Use

The SBA is strictly for research purposes and is not intended for clinical diagnostics, patient management, or any medical applications. It must not be used as a substitute for professional medical evaluation, diagnosis, or treatment. The results generated by the SBA are for informational and research purposes only and must not be used to guide clinical decision-making. The SBA is not a medical device and does not meet the criteria for medical device software.

1.3. User Responsibilities

Users are responsible for ensuring compliance with applicable regulatory, ethical, and institutional guidelines when utilizing data derived from the SBA. Any application of the results must align with the intended use of the software.

1.4. Data Handling and Privacy

The SBA does not store or retain uploaded data; all data is processed solely for analysis and is not saved.Users must only upload anonymized data that does not fall under HIPAA, GDPR, or other data protection regulations to ensure compliance with privacy standards.

2 Quick Guide



Figure 2.1: Basic functions of the analyzer.

A. **Select** a suitable file from your PC using the UPLOAD/EXPORT button
B. **Adjust** the sample rate and beat detection to correctly identify your data
C. **Calibrate** your data using reference signals or reference values
D. **Update** after each change to refresh your analysis
E. **Analyze** your data using the signal and pressure-volume graphs
F. **Export** your data for further analysis and documentation

3. User Interface

This section provides an overview of the user interface elements of the Single-Beat Analyzer (SBA), detailing their functions and interactions within the software.

3.1 General

The user interface consists of six main elements:

1. **Upload/Export** – Enables users to upload data for analysis and export results.
2. **Tabs** – Organizes different functionalities and views within the interface.
3. **Update** – Refreshes settings and redraws the graphs.
4. **Signal Graph** – Displays time-domain signals like pressure and volume.
5. **Loop Graph** – Visualizes pressure-volume relationships.
6. **Quick Settings** – Activate and view preselected analysis settings.



Figure 3.1: User interface of the Single-Beat Analyzer (SBA) highlighting its six main elements. The Upload Data side tab opens when the Upload/Export button is pressed.

Changes that are made in the settings of the analyzer are not updated until the green Update button is pressed.

3.2 Upload/Export

The Upload/Export side tab can be opened by pressing the UPLOAD/EXPORT button. Within this tab, users can select files from their PC for upload. Once a file is selected, the upload process starts when the cloud icon is pressed. Upon successful upload, the analysis is displayed using the current settings. The upload is restricted to files up to 100 MB, and in the current version of the SBA, only the first 100,000 rows will be loaded.

The analyzer features automatic detection of several common file formats. If the uploaded file contains a header, the following keywords are recognized: RVP, RVV, LVP, LVV, SV, CO, PAQ, AOQ, PRESSURE, Pressure. If no header is present, users can manually select the column containing the pressure values.

In the Export section, users can export data in CSV format. The available options are:

- **EXPORT DATA** – Exports the full dataset.
- **EXPORT LOOP** – Exports only the averaged loop data.

At the bottom of the Upload/Export side tab, users can log in to the Hemodynamix database to save and load signals. Prior registration is required for login. Data is stored in the database using encryption, with encryption keys derived from the user's password. If the password is lost, access to the data is permanently lost, and recovery is not possible.

3.3 Tabs



Figure 3.2: Tab menu of the single-beat analyzer.

The tab menu contains all settings of the Single-Beat Analyzer (SBA), categorized as follows:

- **Input** – Configures the sample rate, decimal format, signal selection, and column selection.
- **Beat Detection** – Adjusts parameters for beat detection, including low-pass filtering, minimum height and width for beat identification, and the interquartile range (IQR) filter.
- **Calibration** – Defines calibration settings for flow, volume, and ejection fraction algorithms.
- **Qmax** – Provides methods for estimating Pmax, ESP, and Qmax.

- **Elastance** – Enables or disables multi-beat and single-beat methods for estimating pressure-volume relationships.
- **Graph 1** – Controls settings for time-domain signal visualization.
- **Graph 2** – Adjusts settings for the pressure-volume graph.
- **Log** – Maintains an automatic log of all actions, with options to export or clear the log.
- **Generate** – A simple ventricular pressure waveform generator
- **Calc** – Displays key variables for easy visual access
- **Expert** – Automatic waveform evaluation – Experimental
- **Label** – Labeling of waveforms including PCA coefficients and key variables
- **Combine** – Can be used to upload external volumes for example from 3D-Echocardiography
- **Info** – Displays details about the Single-Beat Analyzer, including the software version.

3.4 Update

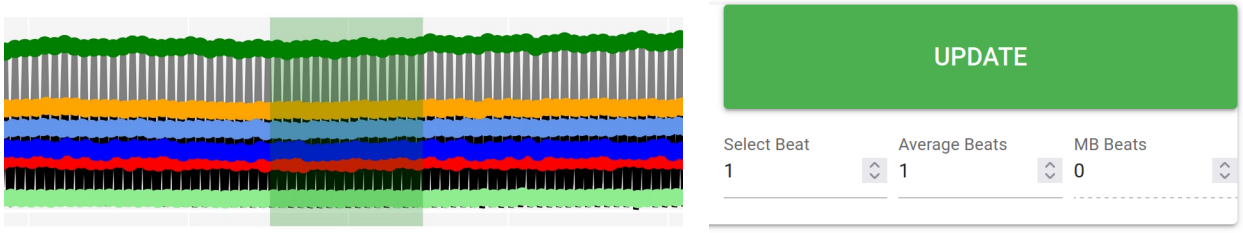

Figure 3.3: UPDATE button and beat selection elements.

The UPDATE button refreshes the graphs using the current settings. Below the UPDATE button, users can specify the starting beat and the number of beats used to calculate the average pressure and volume for the pressure-volume graph. Alternatively, beats can be selected directly in the signal graph using the select box tool. Additionally the number of selected multi-beats are displayed when the „Clear Plot“ option in tab „Graph 2“ is deactivated.

3.5 Signal graph

The signal graph displays the following data from top to bottom:

- Pressure
- Pressure-derived volume and reference volume (if available)
- Estimated cardiac output and reference cardiac output (if available)
- Ventricular-arterial coupling and afterload index
- Pressure-derived flow and reference flow (if available)

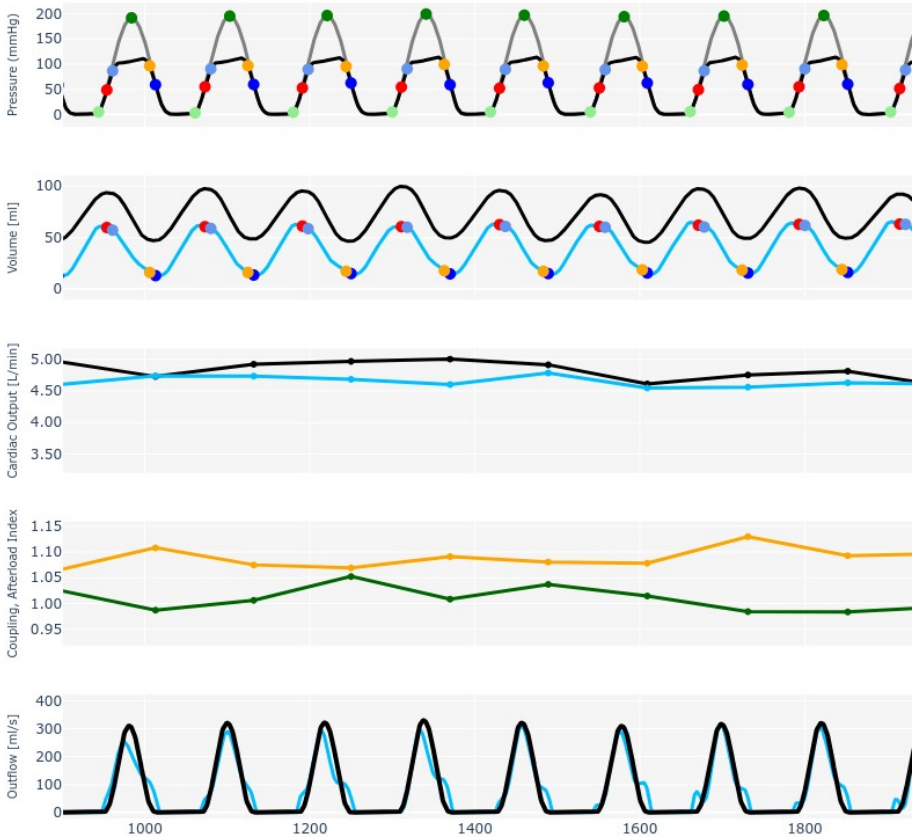

Figure 3.4: Signal graph with the signals pressure, volume, cardiac output, coupling+afterload index and flow.

The time points of the detected pressure peaks are also displayed in the same colors within the reference volume.

The graph includes a set of tools located at the top right, including zoom and selection tools. The selection tools allow users to choose specific beats for averaging, which are then displayed in the pressure-volume graph.

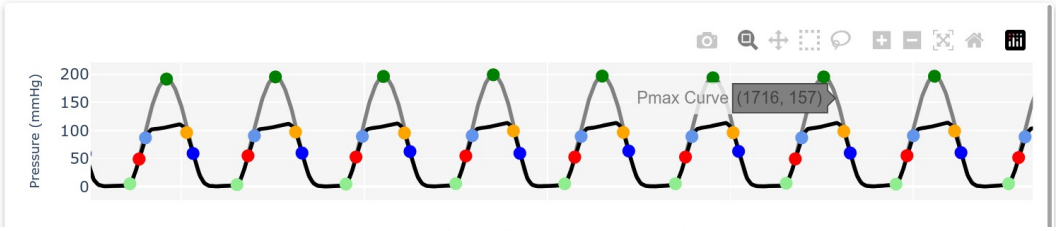

Figure 3.5: Graph tools in the top right corner.

The legend for the signal graph can be activated in the GRAPH 1 menu tab.

3.5 Pressure-volume graph

The pressure-volume graph displays the selected pressure-volume loop derived from pressure signals, as well as from the reference signal if available. SV, EDV and EF are calculated from the minimum and maximum values of the averaged volume signal and reference signal, if available. The end-systolic pressure is calculated from the elastance of the averaged pressure and volume signals.

The graph always reflects the data selected in the signal graph (highlighted in the green area). If multiple beats are selected, an averaging algorithm is applied to compute the representative pressure-volume loop.

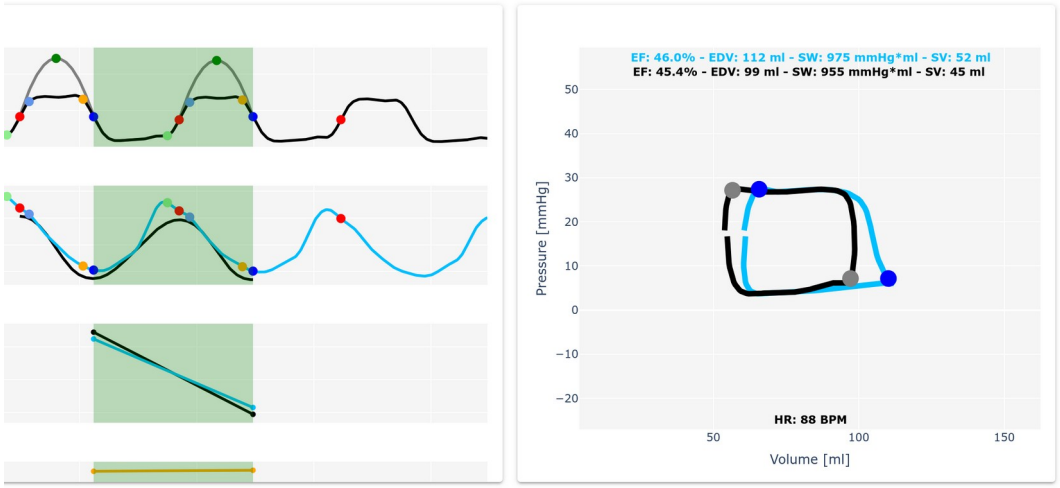

Figure 3.6: The pressure-volume graph (right) and a portion of the signal graph (left), with the selected beats highlighted in green.

At the top of the pressure-volume graph, calculated values from the selected beats are displayed. Values derived using the reference volume are shown in blue, while values derived from pressure-derived volume are shown in black.At the bottom of the graph, the heart rate is displayed, which remains the same for all signals.

4. Loading Data

This section explains how to load ventricular pressure data and associated reference signals.

4.1 Selecting a file

To upload a file for analysis, follow these steps:

1. Press the UPLOAD/EXPORT button to open the side tab for uploading and exporting data.
2. Click the PLUS symbol to open a dialog for selecting a file from your PC.
3. Choose a file in CSV or TXT format for upload.
4. Once selected, the file will be displayed in the upload element.
5. Click the CLOUD symbol to upload the file to the server for analysis.
6. After a successful upload, the initial analysis will be automatically displayed using the previously selected settings.

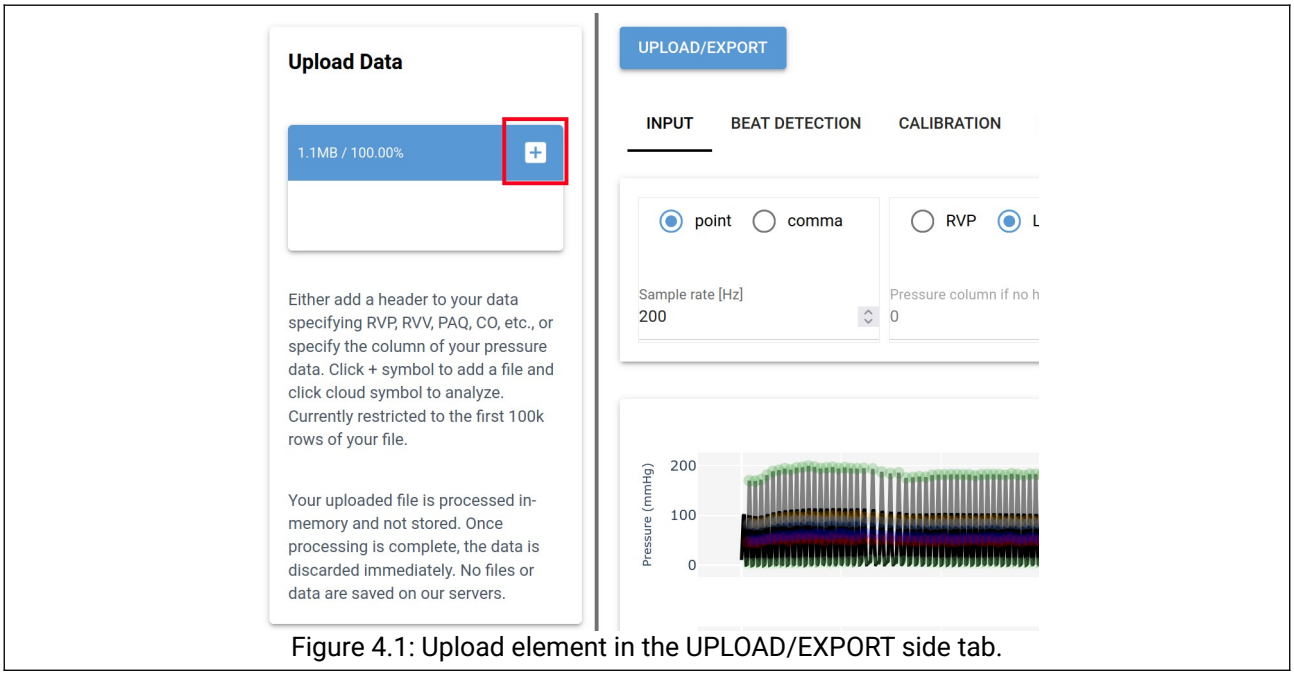

Figure 4.1: Upload element in the UPLOAD/EXPORT side tab.

4.2 Files with header

The analyzer automatically detects specific keywords in the file header. Based on these keywords, the corresponding signals are extracted from the respective columns for analysis.

Recognized header keywords:

Header Keyword	Signal	Derived signals	Used for
Volume	Volume	Flow, SV, CO	RVP, LVP, Pressure
volume	Volume	Flow, SV, CO	RVP, LVP, Pressure
VOLUME	Volume	Flow, SV, CO	RVP, LVP, Pressure
+VOL	Volume	Flow, SV, CO	RVP, LVP, Pressure
CO	Cardiac output	CO	RVP, LVP, Pressure
SV	Stroke volume	CO	RVP, LVP, Pressure
RVP	Ventricular pressure	Flow, CO, Volume, Coupling, Afterload index	RVP
LVP	Ventricular pressure	Flow, CO, Volume, Coupling, Afterload index	LVP
Druck	Ventricular pressure	Flow, CO, Volume, Coupling, Afterload index	Pressure
PRESSURE	Ventricular pressure	Flow, CO, Volume, Coupling, Afterload index	Pressure
Pressure	Ventricular pressure	Flow, CO, Volume, Coupling, Afterload index	Pressure
RVV	Volume	Volume, Flow, CO	RVP
PAQ	Flow	Flow, CO	RVP
PaQ	Flow	Flow, CO	RVP
LVV	Volume	Volume, Flow, CO	LVP
AOQ	Flow	Flow, CO	LVP
AoQ	Flow	Flow, CO	LVP

Table 4.1: Recognized header key words.

4.3 Files without a header

If the file to be analyzed does not contain a header, you can either add one before uploading or proceed without a header and manually select the column containing the ventricular pressure data after upload. However, reference signals cannot be used if the file does not contain a header.

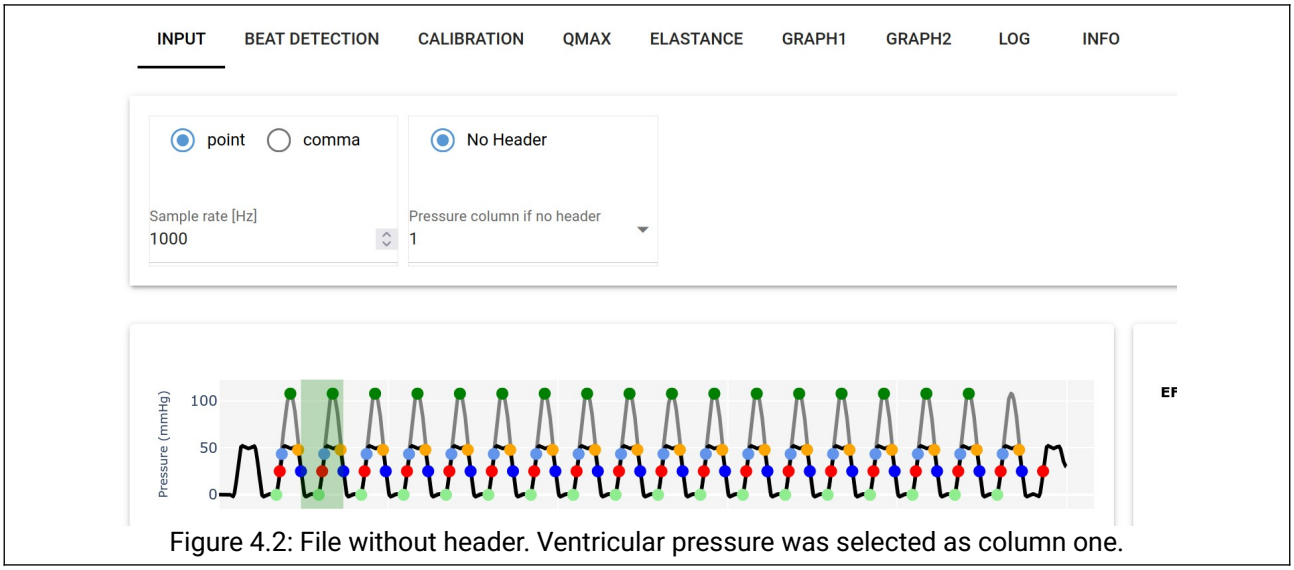

Figure 4.2: File without header. Ventricular pressure was selected as column one.

5. Perfoming analysis

This section describes how to perform data analysis on ventricular pressure waveforms using the Single-Beat Analyzer (SBA).

5.1 General analysis

To perform an analysis select a file from your PC and upload it. After you see the resulting analysis first make sure the correct sample rate is selected. If not enter the samplerate that fits the data you uploaded.

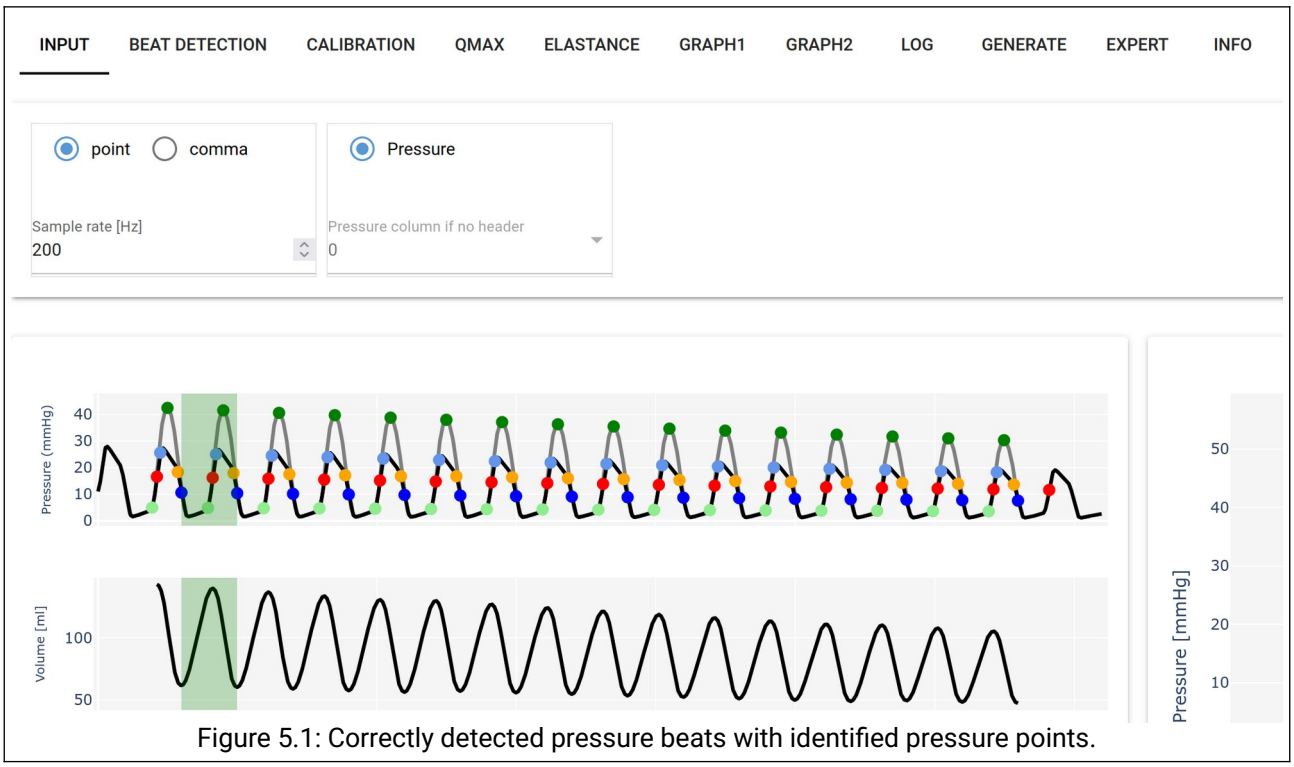

Figure 5.1: Correctly detected pressure beats with identified pressure points.

Next take a look at the ventricular pressure waveforms and ensure that the pressure points are detected correctly and the Pmax curve is correctly displayed.



Figure 5.2: Misdetected beats in the diastolic phase caused by incorrect beat detection settings.

If misdetections occur in your analysis, adjust the beat detection settings by first modifying the minimum beat width and height and also minimum ejection time, followed by the low-pass filter settings. Additionally, ensure that the correct sample rate is selected for your signal. If the point of dpdtmax is found too late you can adjust the parameter dpdtmax distance to increase the distance to the systolic peak.

Next calibration of the flow-derived signals can be performed. Calibration can be done in the CALIBRATION tab.

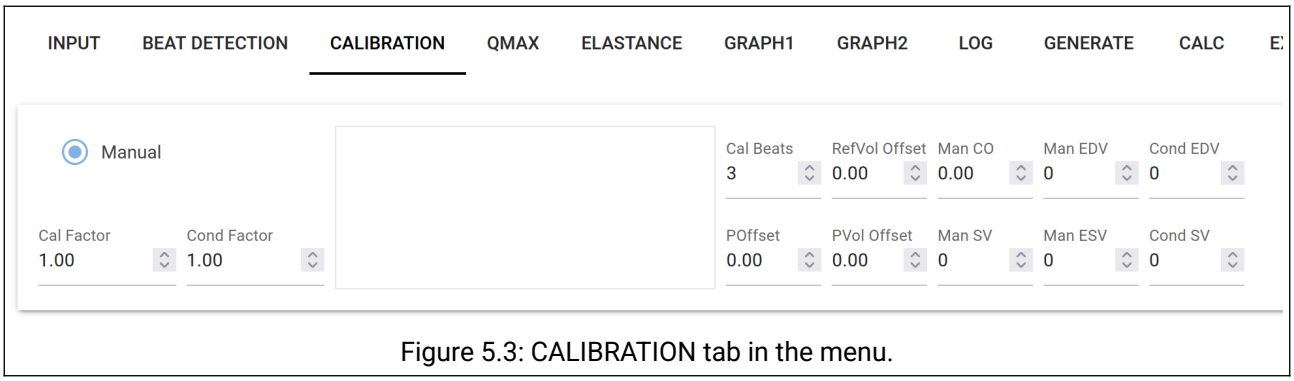

Figure 5.3: CALIBRATION tab in the menu.

If a reference signal is present in the analysis, automatic calibration is selected by default. Calibration is performed using the first N beats of the data, where N is set to 3 by default but can be adjusted. If multiple reference signals are available in the data, the desired reference signal can be selected. Reference signals for volume calibration may include volume, flow, cardiac output (CO), or stroke volume (SV) data.

If no reference signal is present, only manual calibration can be performed. In this case, a calibration factor must be entered in the CALIBRATION tab or a static SV or (EDV and SV) or (EDV and ESV) or CO value can be entered and the selected pressure range (green area) will be calibrated after pressing UPDATE.

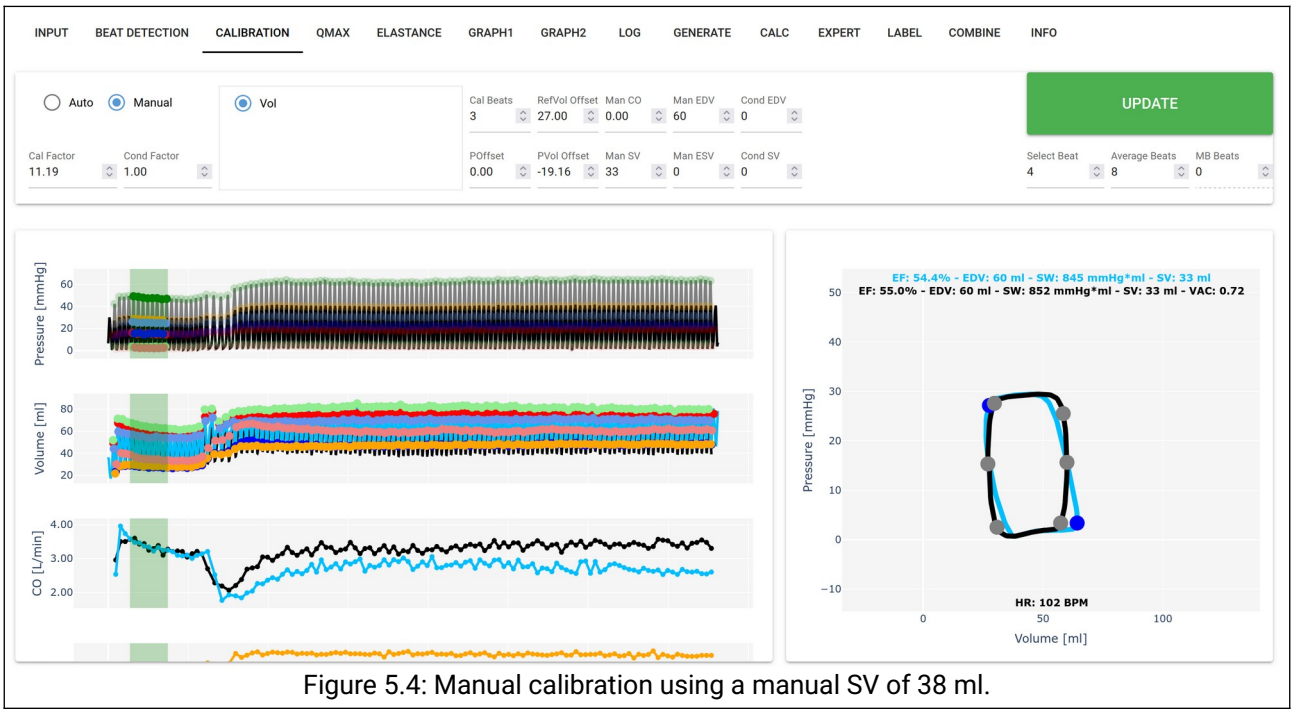

Figure 5.4: Manual calibration using a manual SV of 38 ml.

The calculated ejection fraction does not require calibration. However, if additional adjustment is desired the baseline of the generated volume signal (Pvol Offset) and also the reference volume signal (RefVol Offset) can be shifted. The pressure signal itself can also be baseline shifted using the POffset setting.

In the menu tab QMAX the estimation methods for Pmax, ESP and Qmax can be selected.

Reference volume signals for example from conductance catheters can be also calibrated by entering Cond EDV and Cond SV.

Make sure to reset the calibration settings when starting a new analysis.

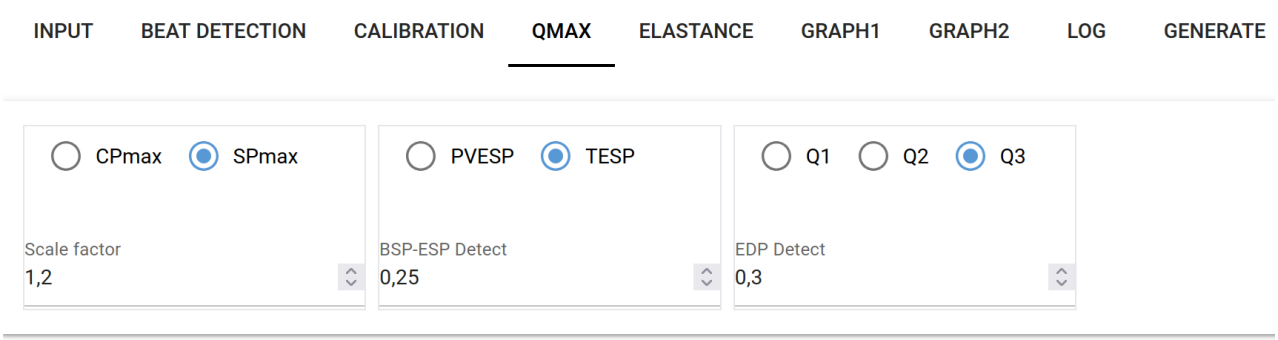

Figure 5.5: QMAX tab in the menu for selecting the Pmax, ESP, and Qmax estimation methods.

Methods available for estimating the isovolumic pressure (Pmax):

1. Tangent Intersection Method (CPmax) – This method calculates Pmax by determining the intersection of two tangents as described in [1], [2], and [3].
2. Spline Interpolation Method (SPmax) – This method constructs a spline to estimate Pmax [5].

The calculated Pmax value can be adjusted using the "Scale Factor", which is set to 1.2 by default. This factor is applied to both dpdtmax and dpdtmin, scaling their values to compensate for smoothing effects in the pressure signal.

By modifying the Scale Factor, users can fine-tune the Pmax estimation based on the characteristics of their dataset.

Methods available for estimating end-systolic pressure (ESP):

1. PVESP - Time-Varying Elastance Method – This method calculates the time-varying elastance. ESP is identified as the point where elastance reaches its maximum. See also [4] and [5].
2. TESP - Tangent Intersection Method – This method constructs a tangent at dpdtmin and determines the distance to the pressure curve.

Methods available for estimating the maximum right ventricular outflow (Qmax):

1. Q1 - Difference Curve Method: This method calculates the difference between the isovolumic and the ventricular pressure curve.
2. Q2 - BSP and Ventricular-Arterial Coupling Method: In this method, Qmax is calculated using the beginning-systolic pressure and the ventricular-arterial coupling.
3. Q3 - Adjusted Difference Curve Method.

In both methods, the estimated Qmax value is subsequently used to scale the difference curve (Pm(t) – Pv(t)).

For more detailed information, refer to the chapter on Algorithms.

We recommend adjusting the analysis settings to match the reference values of your experimental configuration. Once these settings are configured, use them consistently for analyzing pressure-only signals from the same configuration.

5.3 Single-beat relations

In the ELASTANCE menu tab, you can activate or deactivate the single-beat and multi-beat methods for estimating the end-systolic pressure-volume relationship (ESPVR) and end-diastolic pressure-volume relationship (EDPVR). The single-beat method requires only one pressure-volume loop for estimation.

- The ESPVR is calculated as:

  $p(V)=V0+SV(Pmax-ESP)\cdot V$

  A straight line is generated through the two points: (Pmax, EDV) and (ESP, ESV).

- The EDPVR is calculated as:

  $p(V)=A\cdot[\exp(B\cdot(V-V0))-1]$

  The exponential function is fitted through the three points: (V0, 0), (EDV, EDP), and (V15, 15). V15 is calculated using the Klotz single-beat method [6].

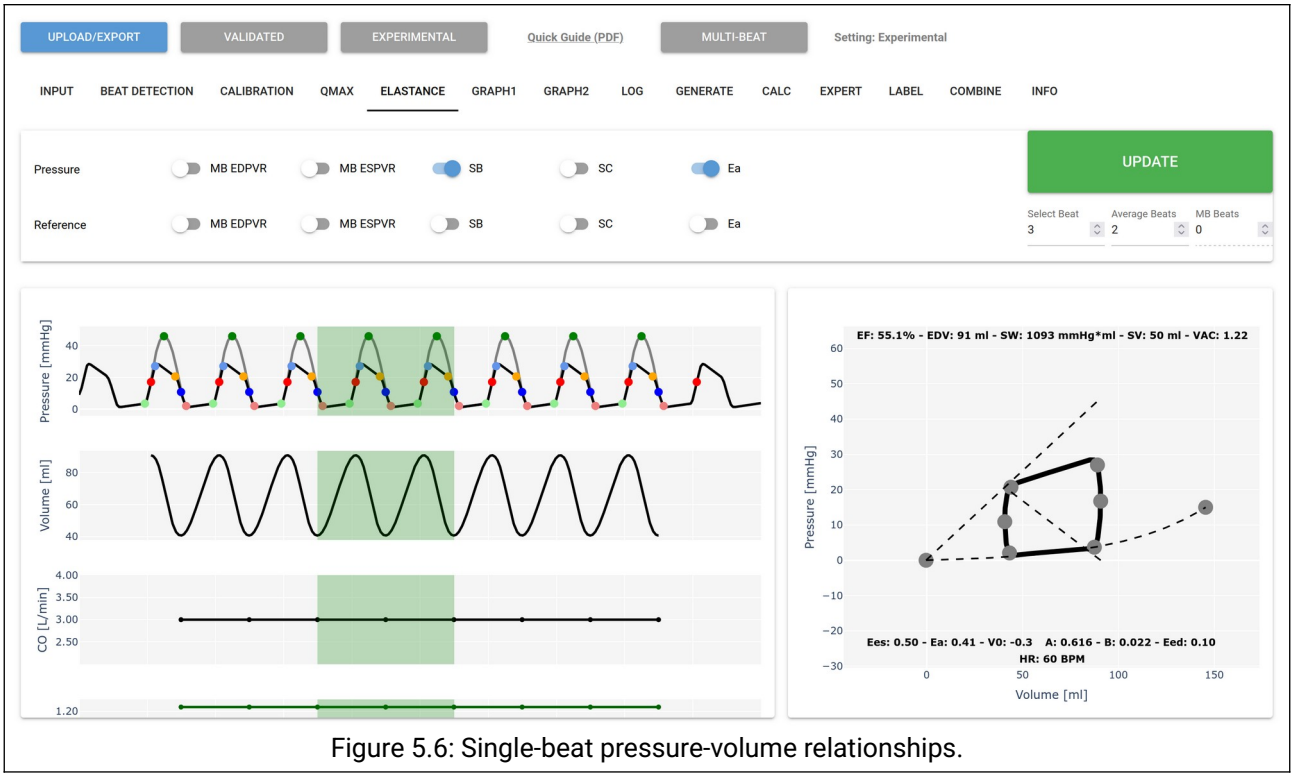

Figure 5.6: Single-beat pressure-volume relationships.

Additionally, a Senzaki-Chen-based (SC) method [9] can be selected. This method calculates V0 and Pmax using a combination of pressure and volume measurements. The implementation is still experimental and may be subject to future modifications. The calculated values are written in to the analysis log. For pressure dervied volumes the SC based ESPVR will be displayed in gold and for reference volumes in purple.

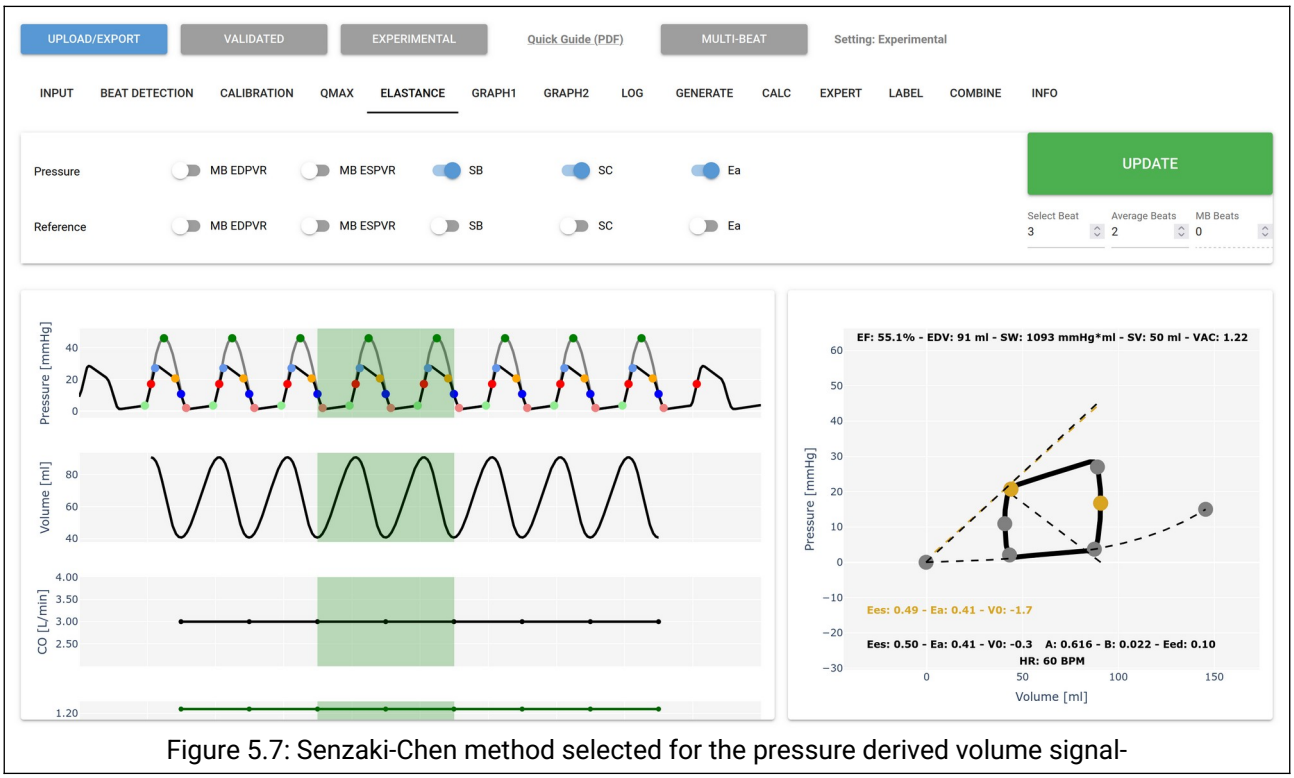

Figure 5.7: Senzaki-Chen method selected for the pressure derived volume signal-

5.4 Multi-beat relations

The ESPVR and EDPVR can also be estimated using multiple pressure-volume loops. The GRAPH2 menu tab includes a selection option called "Clear plot". When this option is deactivated, the pressure-volume graph is not cleared upon pressing UPDATE. Each time a new loop is added, the points (ESP, ESV) and (EDP, EDV) are appended to an array. Once enough points are collected, the ESPVR is generated using linear regression, and the EDPVR is generated using non-linear regression with the function:

$$p(V)=A\cdot[\exp(B\cdot(V-V0))-1]$$

The ESPVR requires at least two points, while the EDPVR requires at least three points. By activating the "Clear plot" option, both the graph and the array are cleared. We recommend to use the MULT-BEAT setting when performing multi-beat analysis.

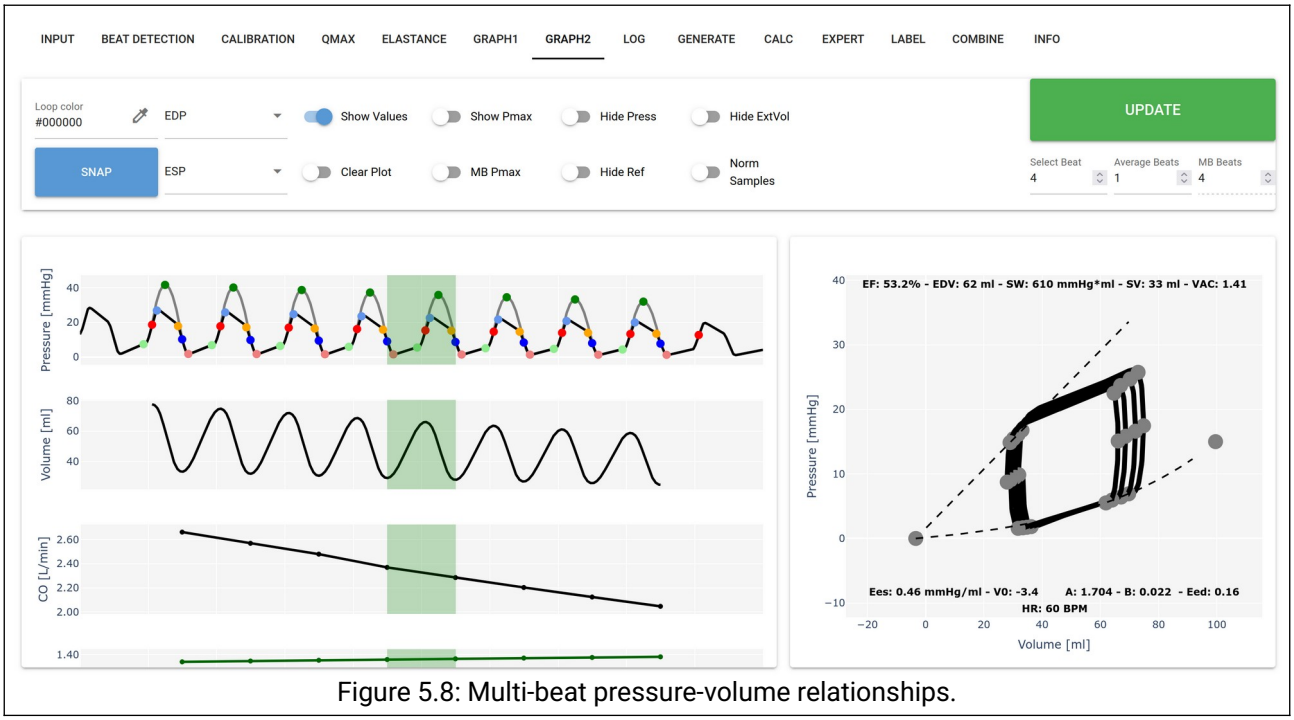

Figure 5.8: Multi-beat pressure-volume relationships.

5.5 Graph settings

The following settings can be adjusted in the GRAPH1 tab:

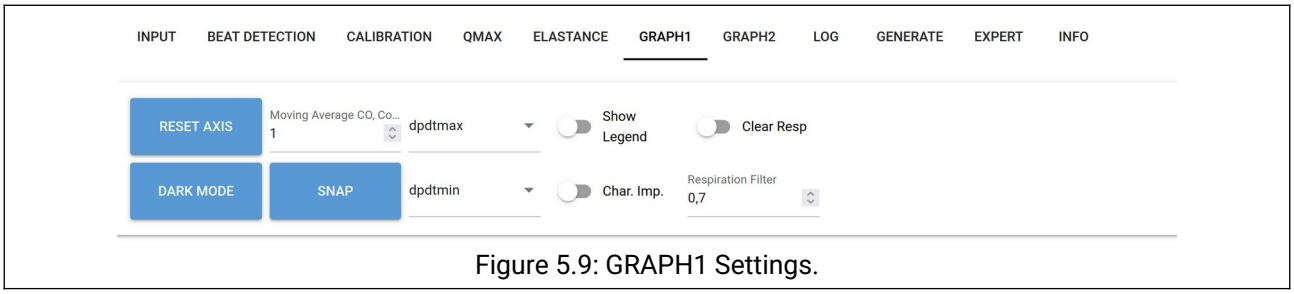

Figure 5.9: GRAPH1 Settings.

Element	Function
RESET AXIS	Resets both x and y-axis for the signal graph.
DARK MODE	Switches between dark mode and light mode.
Moving Average	Number of points for moving average calculation of derived signals in GRAPH1
SNAP	Generates high quality screenshot of GRAPH1
Point of EDV	Selects point of EDV for the reference volume signal
Point of ESV	Selects point of ESV for the reference volume signal
Show Legend	Shows signal legend for GRAPH1

Char. Imp	Displays/Hides characteristic impedance
Clear Resp.	Activates high-pass filter to remove respiration effect in the pressure signal
Respiration Filter	Adjustes frequency of the high-pass filter

The following settings can be adjusted in the GRAPH2 tab:

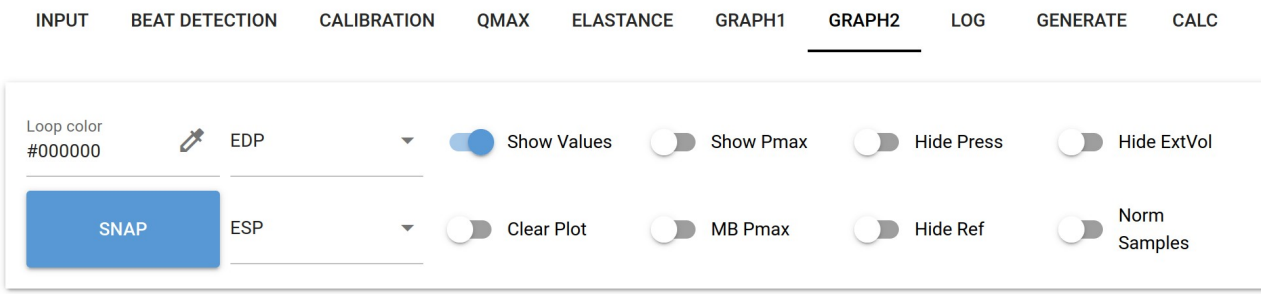

Figure 5.10: GRAPH2 Settings.

Element	**Function**
Loop color	Selects color for the pressure derived PV Loop
SNAP	Generates high quality screenshot of GRAPH2
Point of EDV	Selects point of EDV for the PV Loops
Point of ESV	Selects point of ESV for the PV Loops
Show Values	Displays/Hides parameters in the PV Loop Graph
Clear Plot	If Clear Plot is deactivated the PV Loop Graph is not cleared with each Update and each generated Loop is used for multi-beat (MB) calculations. Reactivating Clear Plot clears the lists and the graph.
Show Pmax	Displays/Hides Pmax in the PV Loop Graph
MB Pmax	If activated Pmax is used instead of ESP for MB calculations
Hide Press	Hides the presure-volume loop generated from pressure (black)
Hide Ref	Hides the reference loop generated from pressure and reference volume (blue)
Hide ExtVol	Hides the external volume loop generated from pressure and external volume (red)
Norm Samples	Exported loop is set to 500 samples instead of average samples of the selected beats

6. Exporting data

This section explains how to export the generated analysis, including the full signals, loops, and the analysis log.

6.1 Exporting analysis

The full signals including pressure, volume, identified pressure points and cardiac output can be exported by clicking on the EXPORT DATA button in the UPLOAD/EXPORT side tab. The data will be available for download in the browser.

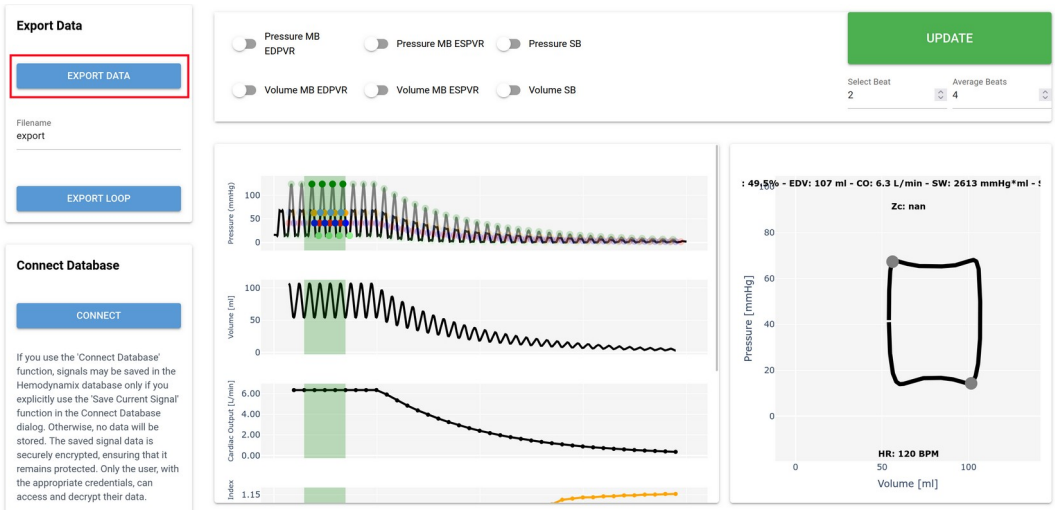

Figure 6.1: Exporting data by clicking on the EXPOR DATA button.

Header of the exported CSV file:

Index	Time	PressVolume	PmCurve	RawPressure	Pressure	Pmax	ESP	EDP	BSP	HR	PressSV	Press CO	Press VAC	AIndex	Int1	Int2	RawRefVolume	RefVolume	RefCO

Table 6.1: EXPORT DATA header of CSV file.

6.2 Exporting loops

Apart from the full signals only the pressure-volume loops can also be exported. This is done by clicking on the EXPORT LOOP button. A CSV file will be generated containing the pressure-only loops and also the reference loops if available. The exported data contains the values of the loops last generated and displayed in the pressure-volume graph.

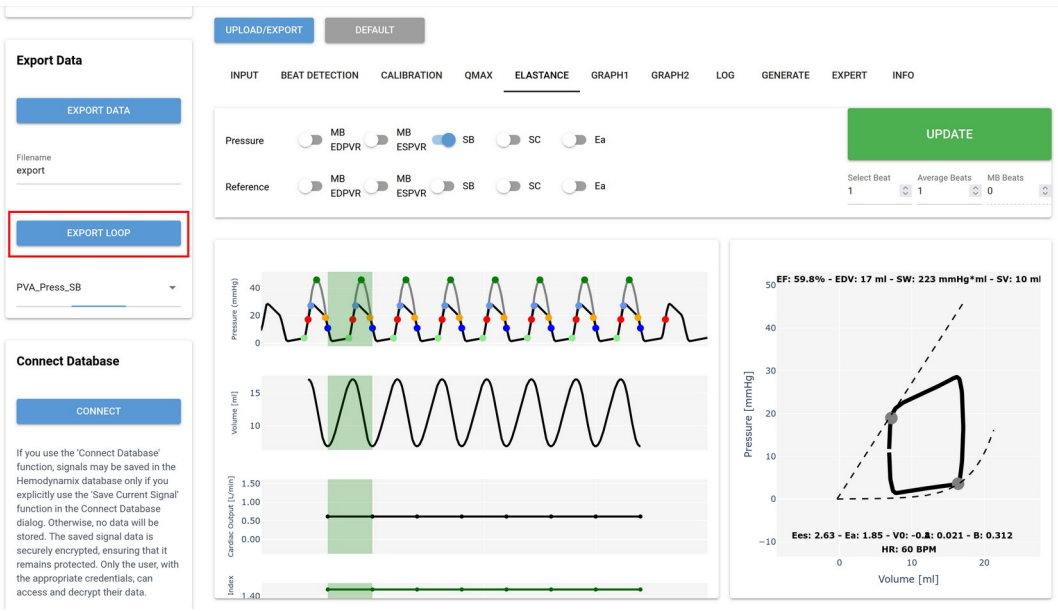

Figure 6.2: Exporting loops by clicking on the EXPORT LOOP button.

Header of the exported CSV file:

Index	PressVolume	Pressure1	RefVolume	Pressure2

Table 6.2.1: EXPORT LOOP header of CSV file.

The columns Pressure1 and Pressure2 contain the same values. Additionally if SB is activated in the ELASTANCE tab the PVA Loop can be also exported:

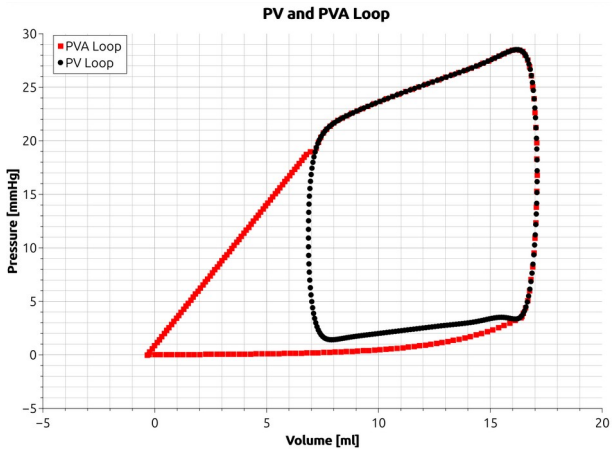

Table 6.2.2: Exported PV and PVA Loop.

6.3 Exporting log

The analysis log records all actions performed, such as changes to settings, ensuring complete documentation of the analysis. It can be accessed in the LOG tab of the menu.

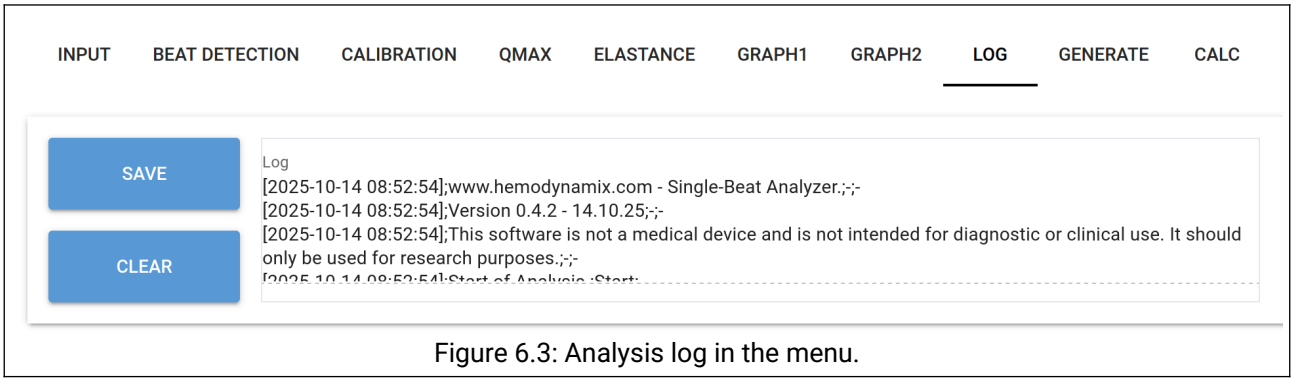

Figure 6.3: Analysis log in the menu.

The log can be exported as a TXT file by clicking the SAVE button. If imported to a spreadsheet software the semicolon can be used to seperate text from values.

7. Generating signals

Under the 'GENERATE' menu tab, a simple pressure signal generator is available. Users can define the values of the four pressure points—End-Diastolic Pressure (EDP), Beginning Systolic Pressure (BSP), End-Systolic Pressure (ESP), and Beginning Diastolic Pressure (BDP). Additionally, two time parameters, t1 and t2, can be set to define the slopes of the isovolumic contraction and relaxation phases. There are also settings to introduce an occlusion effect (exponential decrease or increase of amplitude), afterload effect (exponential decrease or increase of ESP) and a respiration effect (addition of sinus to the pressure). The heart rate can be changed in the element HR and and arryhthmic effect can be added by increasing Arr. The element Smooth adds additional smoothing to the generated beats and Noise adds a gaussian noise effect before the additional smoothing is added. EDPVR multiplies an exponential function to the EDP points to either increase or decrease them with time.

After adjusting the parameters press „GENERATE“ to load the curves.

The default settings generate a normal right ventricular pressure waveform:

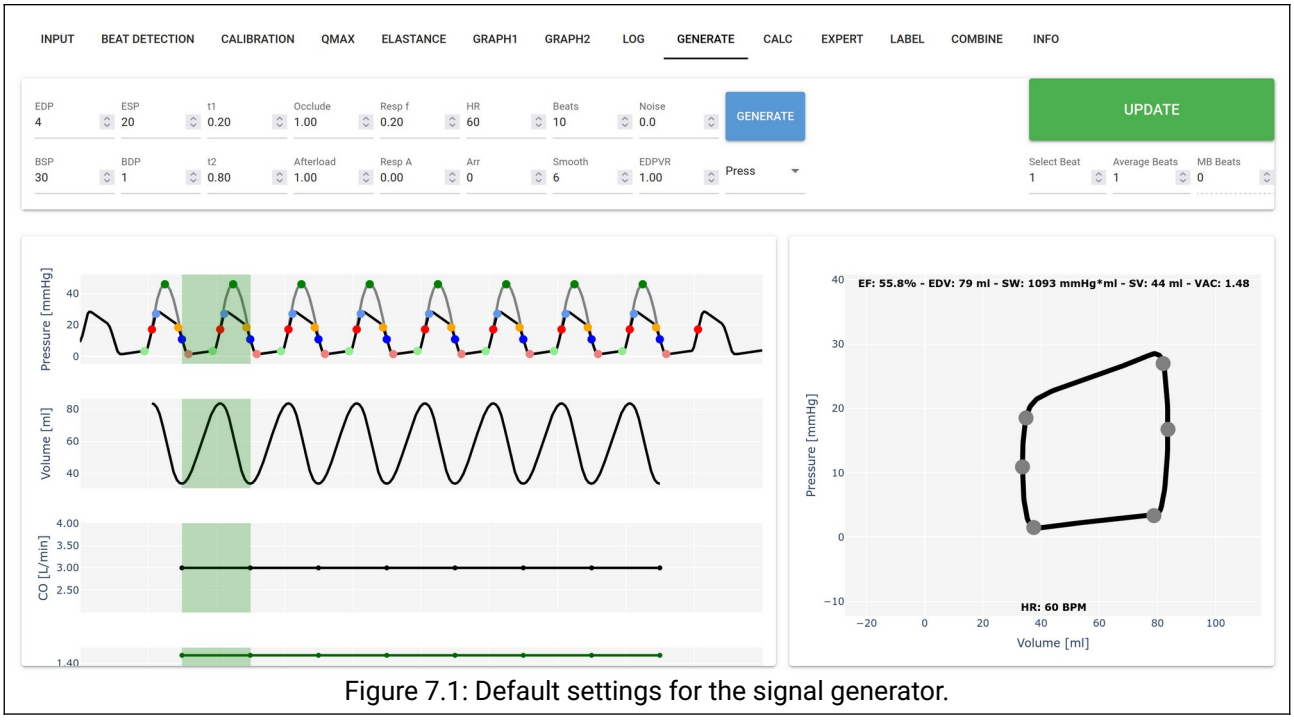

Figure 7.1: Default settings for the signal generator.

To generate a normal left ventricular pressure waveform you can use the following settings:

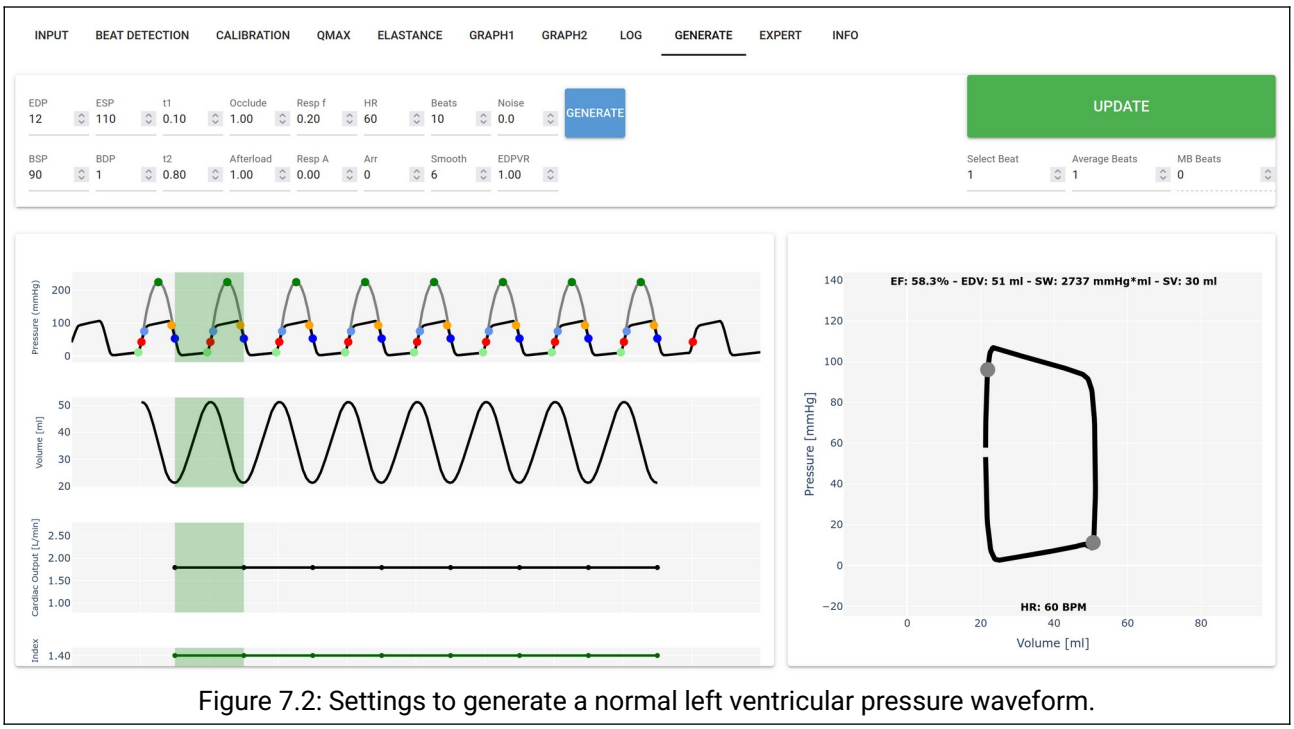

Figure 7.2: Settings to generate a normal left ventricular pressure waveform.

8. Algorithms

The Algorithms section will be updated once the corresponding publications have been released.

8.1 First derivative

The first derivative of the ventricular pressure signal (dpdt) describes the rate of change of pressure over time. In the Single-Beat Analyzer, this derivative is computed using numerical differentiation with the NumPy function np.gradient().

To calculate dpdt, the software evaluates the difference between adjacent pressure values over time. A central difference approach is applied, estimating the derivative at each point by considering the difference between the preceding and following pressure values. For the first and last data points, a forward and backward difference method is used, respectively.

The dpdt curve is used to identify key pressure points, such as the maximum rate of pressure increase (dpdtmax) and maximum rate of pressure decrease (dpdtmin). These points are used to define beat boundaries and for further calculations, including isovolumic pressure estimation and ventricular-arterial coupling analysis.

By determining dpdt, the analyzer enables the identification of relevant waveform features for pressure signal analysis.

8.2 End-diastolic pressure

End-diastolic pressure (EDP) is determined by drawing a downward tangent at the dp/dt_max point and selecting the first time point at which the percentage difference between the measured pressure and this tangent exceeds the user-selected **EDP Detect** threshold (from the **Qmax** tab).

8.3 Beginning-systolic pressure

Beginning-systolic pressure (BSP) is determined by drawing a upward tangent at the dp/dt_max point and selecting the first time point at which the percentage difference between the measured pressure and this tangent exceeds the user-selected BSP-ESP **Detect** threshold (from the **Qmax** tab).

8.4 End-systolic pressure

End-systolic pressure (ESP) is determined either (i) by the tangent method described above or (ii) by computing the time-varying elastance from pressure and volume and reporting ESP at the time point of maximum elastance.

8.5 Isovolumic pressure

The isovolumic pressure Pmax represents the pressure the ventricle would achieve if the outgoing valve remained closed, meaning the ventricle contracts against a constant end-diastolic volume. Isovolumic pressure can be estimated using non-linear regression by fitting a sinusoidal function to the isovolumetric contraction and relaxation phases of the ventricular pressure waveform [7].

Alternatively, Pmax can be calculated using the Tangent Intersection Method, where two tangents are constructed at the pressure points where the first derivative reaches its maximum (dpdtmax) and minimum (dpdtmin). The slopes of these tangents are determined by the respective first derivative values, and their intersection can be transformed into Pmax [1], [2], [3].

Another approach is the Spline Interpolation Method, where a spline is constructed to estimate Pmax.

8.6 Pressure-derived flow

Pressure-derived flow is calculated as the difference between Pmax curve and the pressure curve, see also [5].

8.7 Coupling and Afterload

The ventricular-arterial coupling (VAC) or in case of the right ventricle the RV-PA coupling is calculated as:

Coupling = (Pmax-ESP)/ESP

In a similiar fashion a pressure-based ejection fraction [8] can be calculated as:

EF = (Pmax-ESP)/Pmax

The afterload index is calculated as the ratio of the beginning-systolic pressure and the end-systolic pressure:

Afterload Index = BSP/ESP

8.8 Stroke volume

In the Single-Beat Analyzer (SBA), stroke volume (SV) is primarily calculated as the difference in volume between the time points dpdtmax and dpdtmin:

SV = V(t_dpdtmax)−V(t_dpdtmin)

The only exception is the SV displayed in the pressure-volume graph, which is calculated as the difference between the maximum and minimum values of the averaged volume signals.

8.9 Pressure-derived volume

For the algorithm describing the pressure-derived volume see [5].

8.10 Averaged beats

A total of N selected beats are identified based on the first derivative of the pressure signal. Each beat is defined from the minimum of the first derivative (dpdtmin) of the previous beat to the dpdtmin of the current beat.

To ensure consistency in beat length, all selected beats are interpolated to match the average time span of all beats. The beats are then summed and divided by N to compute the averaged waveform.

9. Software versions covered by this IFU

Version	Release Date	Comment
0.4.2	14.10.25	-

Table 9.1: Software versions covered by IFU.

10. Revision History

Rev.	Date	Author	Description of Changes
00	10.03.25	F. Glocker	Initial release - v0.1.76
01	25.03.25	F. Glocker	Update to v0.1.77
02	08.04.25	F. Glocker	Update to v0.1.78
03	15.06.25	F. Glocker	Update to v0.2.3
04	14.10.25	F. Glocker	Update to v0.4.2

Table 10.1: Revision History.

11. References and Literature

Nr.	Publication
1	Shih H, Hillel Z, Declerck C, Anagnostopoulos C, Kuroda M, Thys D. An algorithm for real-time, continuous evaluation of left ventricular mechanics by single-beat estimation of arterial and ventricular elastance. J Clin Monit. 1997 May;13(3):157-70. doi: 10.1023/a:1007387315948. PMID: 9234085.
2	Gaertner M, Glocker R, Glocker F, Hopf HB. Pressure-based beat-to-beat right ventricular ejection fraction and Tau from continuous measured ventricular pressures in COVID-19 ARDS patients. Pulm Circ. 2023 Jan 6;13(1):e12179. doi: 10.1002/pul2.12179. PMID: 36718290; PMCID: PMC9817071.
3	Kremer N, Glocker F, Schäfer S, Rako Z, Yogeswaran A, Seeger W, Hopf HB, Tello K. Precision cardiac monitoring: algorithmic real-time assessment of right ventricular function in pulmonary hypertension. ESC Heart Fail. 2024 Aug;11(4):2469-2472. doi: 10.1002/ehf2.14833. Epub 2024 Apr 30. PMID: 38689380; PMCID: PMC11287341.
4	Singh I, Oakland H, Elassal A, Heerdt PM. Defining end-systolic pressure for single-beat estimation of right ventricle-pulmonary artery coupling: simple… but not really. ERJ Open Res. 2021 Aug 23;7(3):00219-2021. doi: 10.1183/23120541.00219-2021. PMID: 34435035; PMCID: PMC8381254.
5	Kremer, N., Glocker, F., Schaefer, S., Janetzko, P., Yogeswaran, A., Rako, Z., Thal, B., Hopf, H.-B., Seeger, W., Ghofrani, H.-A., Heerdt, P. M., & Tello, K. (2025). Method for generating right ventricular pressure–volume loops in routine practice. Journal of Heart and Lung Transplantation. Advance online publication. https://doi.org/10.1016/j.healun.2025.09.002
6	Klotz S, Hay I, Dickstein ML, Yi GH, Wang J, Maurer MS, Kass DA, Burkhoff D. Single-beat estimation of end-diastolic pressure-volume relationship: a novel method with potential for noninvasive application. Am J Physiol Heart Circ Physiol. 2006 Jul;291(1):H403-12. doi: 10.1152/ajpheart.01240.2005. Epub 2006 Jan 20. PMID: 16428349.
7	Sunagawa K, Yamada A, Senda Y, Kikuchi Y, Nakamura M, Shibahara T, Nose Y. Estimation of the hydromotive source pressure from ejecting beats of the left ventricle. IEEE Trans Biomed Eng. 1980 Jun;27(6):299-305. doi: 10.1109/TBME.1980.326737. PMID: 7390526.
8	Heerdt PM, Kheyfets V, Charania S, Elassal A, Singh I. A pressure-based single beat method for estimation of right ventricular ejection fraction: proof of concept. Eur Respir J. 2020 Mar 12;55(3):1901635. doi: 10.1183/13993003.01635-2019. PMID: 31771999; PMCID: PMC7885179.
9	Senzaki H, Chen CH, Kass DA. Single-beat estimation of end-systolic pressure-volume relation in humans. A new method with the potential for noninvasive application. *Circulation*. 1996;94(10):2497-2506. doi:10.1161/01.cir.94.10.2497

Table 11.1: References and Literature.