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Low cost circulatory pressure acquisition and fluid infusion rate measurement system for clinical research

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ABSTRACT

Acquiring patient physiological waveforms is useful for studying hemodynamic management and developing medical monitoring systems. A low cost, Arduino controlled data acquisition system acquires arterial pressure waveforms (Edwards Lifesciences TruWave compatible) and measures fluid infusion rate using hanging scales. This system can be used at the same time as a clinical monitor, enabling recording of patient arterial pressure and fluid delivery for clinical research. The system is powered via a USB connection, which additionally provides serial output, aiding compatibility and customisation. A simple software user interface, developed in Python, shows outputs. Each data acquisition system, including all necessary connection cables costs ~US$90 and is multiple-use.

Specifications table

Hardware name	HeartView Data Acquisition System
Subject area	• Biomedical Engineering • Medical sensor
Hardware type	• Clinical research tool • Flow sensor and pressure data acquisition system • Clinical hemodynamic monitoring research applicable • Edwards Lifesciences TruWave pressure sensor compatible
Open source license	Creative Commons Attribution-ShareAlike 4.0
Cost of hardware	~US$90
Source file repository	https://doi.org/10.17605/osf.io/24zuh

1. Hardware in context

Hemodynamic monitoring and interventions in the intensive care unit (ICU) aim to ensure adequate circulatory function, and thus organ perfusion, through managing cardiac output and systemic vascular resistance [1–4]. Typically, several

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hemodynamic variables are continuously monitored in the ICU, primarily arterial and venous blood pressures, [2,5]. However, these variables can be insufficient for diagnosing and managing circulatory shock [2]. Increasingly, computational models/ algorithms are being developed, which aim to optimally use ICU monitoring systems and their wealth of clinical data for improving patient outcomes [6–13]. These physiological models have the capacity to provide more effective measurements and protocols for circulatory management [6,7].

Clinical validation of novel hemodynamic monitoring methods is challenging because hospital devices are often a closed system, for which it is challenging/ costly to extract the required numerical data [14]. Off-the-shelf platforms for saving numeric data are expensive, and lack functionality for acquiring high-resolution physiological waveform data, [14] making them less suitable in a research context. Vital Recorder [15], a free data acquisition tool, can acquire high resolution waveform signals but still requires a Medical Information Bus (MIB) port to obtain data from patient monitors. In the case of Philips monitors, and potentially others, installation of this MIB hardware is at a significant additional cost. Overall, such requirements lock data into proprietary systems, creating barriers to trialing new monitoring algorithms.

This low-cost open-source data acquisition system allows continuous recording of arterial pressure signals from Edwards Lifesciences TruWave pressure transducers, a common clinical pressure transducer, while also allowing monitoring with a clinical monitor. This pressure acquisition circuit is similar to [16], but is shared in a fully reproducible manner as part of a larger data acquisition system. Additionally, this device monitors fluid infusion rate using hanging scales, similar to [17], but at a much lower cost than $US999 for the device in [17]. Fluid infusions are a main therapeutic input used to control arterial blood pressures, thus this data acquisition system is useful for research about monitoring cardiovascular response to fluids and inotropes, a major problem area [2].

Overall, while not a commercially available clinical monitoring solution, which often entail significant costs and technical support, this simple system can be used to acquire patient signals in intensive care, or other patient monitoring situations for research purposes. The system is effective, low-cost, and readily customisable for a range of hemodynamic research to enable faster innovation and better medical technology solutions.

2. Hardware description

The device consists of electrical hardware for data acquisition and transmission via USB in a 3D printed housing, an electrical load cell sensor in a 3D printed housing, and connectors. The pressure acquisition part of the device is Edwards Lifesciences TruWave compatible, a widely used pressure-transducer brand. The device could readily be modified to be compatible with other analog output clinical pressure transducers.

The main electrical hardware is a single printed circuit board supporting an Arduino Nano controller (ATmega328p) and two INA828 instrumentation amplifiers. The circuit operates from a 5.0 V power supply, connected via USB. The system output is via serial using the USB connection, thus is simple and easy to integrate into other systems. A simple graphical user interface developed in Python programming language (Python Software Foundation, USA) can be used to view and save signals. The program provides data output as.csv files.

Overall, this simple device is useful for research because it is readily adaptable to meet specific research requirements, and is very low cost compared to commercial data acquisition solutions for intensive care unit monitoring. Importantly, this device can be used to record at the same time as a clinical monitor, without requiring an additional pressure catheter insertion. The device provides a foundation for analysis and development of hemodynamic monitoring devices. It is:

- Low-cost
- Non-additionally invasive
- Edwards Lifesciences TruWave compatible
- Simple
- Customisable

3. Design files summary

The design files are all available at https://doi.org/10.17605/osf.io/24zuh. The file locations specified in Table 1 are relative to the base of this directory, as implemented in OSF's components.

Table 1
List of design files.

Design filename	File type	Open source license	File location
Production Files			
DAQ_Housing_Base.stl	3D-printable	CC BY-SA 4.0	DAQ/
DAQ_Housing_Lid.stl	3D-printable	CC BY-SA 4.0	DAQ/
DAQ_PCB.zip	Contains Gerber and drill files	CC BY-SA 4.0	DAQ/

Table 1 (*continued*)

Design filename	File type	Open source license	File location
Arduino_read.ino	Arduino project	CC BY-SA 4.0	DAQ/
Loadcell_Housing_Base.stl	3D-printable	CC BY-SA 4.0	Hanging Scales/
Loadcell_Housing_Lid.stl	3D-printable	CC BY-SA 4.0	Hanging Scales/
GUI.zip	Contains executable software application	CC BY-SA 4.0	User Interface/
Cable_Cover_A.stl	3D-printable	CC BY-SA 4.0	Connectors/
Cable_Cover_B.stl	3D-printable	CC BY-SA 4.0	Connectors/
Source Files			
DAQ_Housing_Base.FCStd	FreeCAD project	CC BY-SA 4.0	DAQ/
DAQ_Housing_Lid.FCStd	FreeCAD project	CC BY-SA 4.0	DAQ/
DAQ_PCB.pro	KiCAD Project	CC BY-SA 4.0	DAQ/
Loadcell_Housing_Base.FCStd	FreeCAD project	CC BY-SA 4.0	Hanging Scales/
Loadcell_Housing_Lid.FCStd	FreeCAD project	CC BY-SA 4.0	Hanging Scales/
GUI_main.py	Python File	CC BY-SA 4.0	User Interface/
GUI_setup_exe.py	Python File	CC BY-SA 4.0	User Interface/
Cable_Cover_A.FCStd	FreeCAD project	CC BY-SA 4.0	Connectors/
Cable_Cover_B.FCStd	FreeCAD project	CC BY-SA 4.0	Connectors/

CAD files: Physical design was done in FreeCAD. The data acquisition (DAQ) PCB housing (DAQ_Housing_Base.FCStd, DAQ_Housing_Lid.FCStd) and load cell housing (Loadcell_Housing_Base.FCStd, Loadcell_Housing_Lid.FCStd) are given here. Both housings consist of a base and lid, secured closed with M3 machine screws. The DAQ housing has a feature allowing it to slot into an Edwards TruClip pressure transducer holder. Additionally, a cable cover (Cable_Cover_A.FCStd, Cable_Cover_B.FCStd) is given. This small part is glued around the RJ-45 connector for the top surface of the DAQ housing, providing splash resistance should any fluid drip from above.

Electronics: PCB design was done in KiCAD, filename DAQ_PCB.pro. Local library files are included for both the schematic and PCB footprints. While the PCB is designed to be connected with RJ-45 connectors, it could be modified to accept any other required connector. The design is rudimentary, but has been shown to have acceptable noise characteristics from use (see Section 7 for data). This rudimentary design provides a proven foundation for more advanced configurations. Production files for the PCB are provided in file DAQ_PCB.zip.

Software: A simple Arduino code is included (Arduino_read.ino), which enables data recording of signals at 500 Hz over a serial port (baud rate = 115200). Additionally, a very simple computer application for recording of data is provided. The source code is in GUI_main.py, the executable package is in GUI.zip, and the executable package can be built using GUI_setup_exe.py. The application plots recorded waveforms real-time, and saves them to.csv files. This simplicity, again, creates a simple but robust platform upon which more complex software interface applications can be developed if desired. The signal acquisition workflow is shown in Fig. 1.

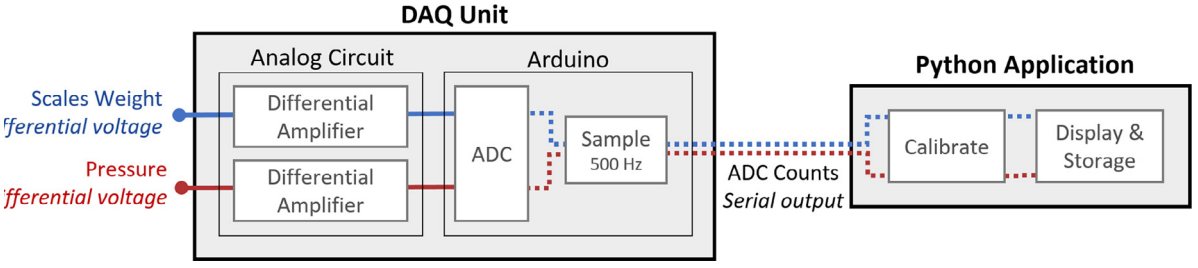

Fig. 1. Signal acquisition workflow, reading left to right.

4. Bill of materials summary

The complete bill of materials can be found at https://doi.org/10.17605/osf.io/24zuh. Table 2 contains the critical components and subsystem totals for costing and ease of reference.

Table 2
Reduced bill of materials showing key components and totals only.

Component	Qty	Total Cost (USD)
Key Components		
Edwards Connector IBP Cable	1	$29.99
Arduino Nano ATMega328	1	$20.70
INA828	2	$11.16
Load Cell 3 kg	1	$1.40
System totals		
DAQ Unit	1	$42.12
Hanging Scales	1	$6.77
Connectors	1	$38.71
Total Device		**$87.61**

5. Build instructions

The main steps for construction of the device are:

1. Place an order for the PCB and the appropriate sensors. Due to shipping this step is often the slowest process.
2. Print the DAQ housing base and lid, load cell housing base and lid, and connector cover parts A and B with an appropriate layer height (e.g. 0.15 mm). The orientation for printing of all 3D-printed parts is shown in Fig. 2, with support materials indicated.
3. Populate the PCB in accordance with DAQ_PCB.pro. Note, the Arduino should be mounted on pin headers.
4. Make hybrid RJ-45 - Edwards pressure connector. Cut the Edwards head off the pressure connector, and an RJ-45 head off one RJ-45 connector. Strip the wires of each, and resolder them using the configuration in Fig. 3.

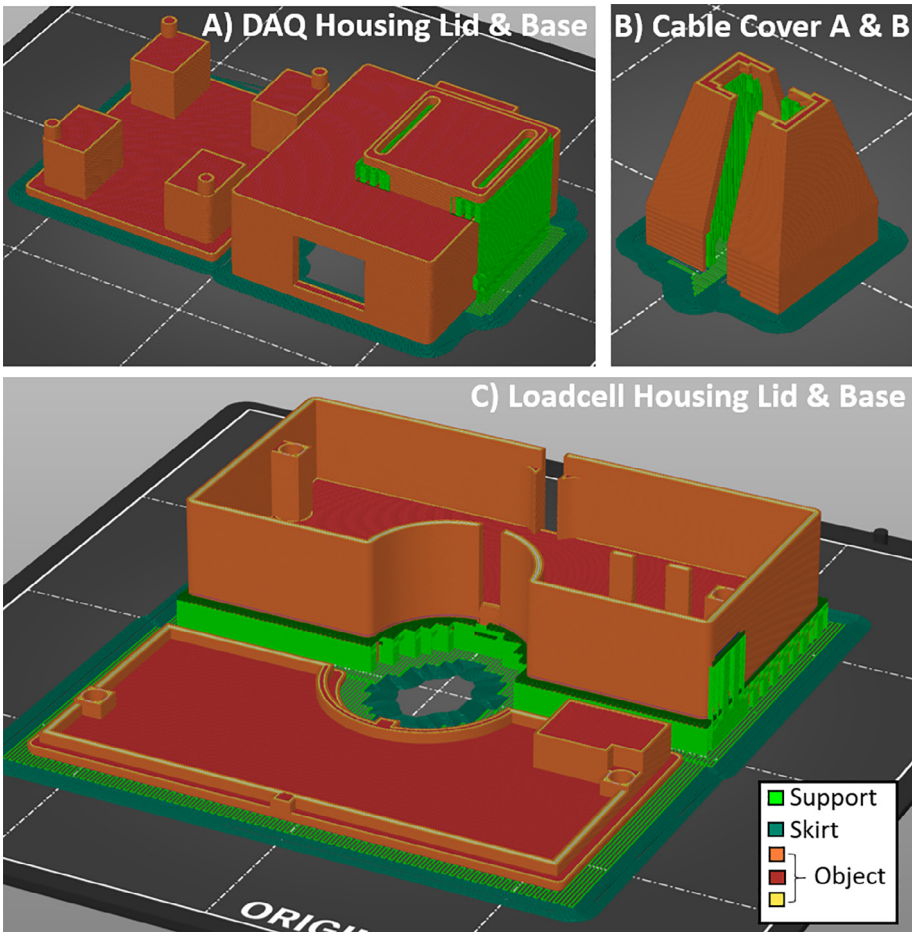

Fig. 2. Print orientation for the 3D printed components, with support materials indicated.

5. Assemble DAQ housing as shown in Fig. 4, and hanging scales as shown in Fig. 5. The load cell wires need to be soldered to an RJ-45 port, using the configuration in Fig. 5.
6. Assemble the cable cover on the remaining RJ-45 connector. Glue parts A and B together around the RJ-45 connector head.

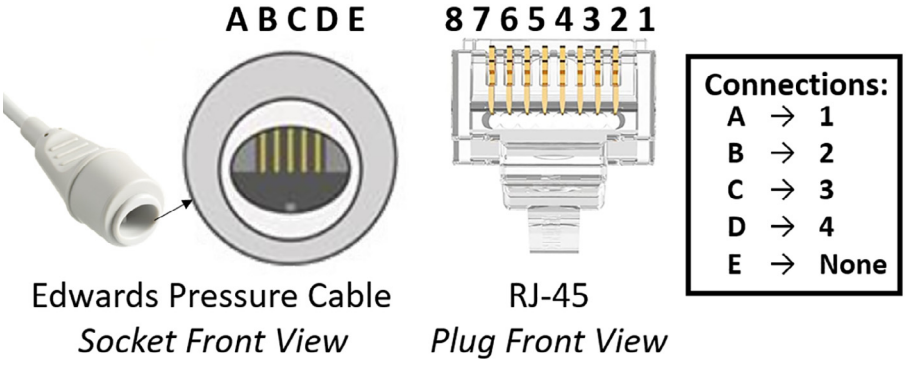

Fig. 3. Pin map for hybrid Edwards-Pressure to RJ-45 connector.

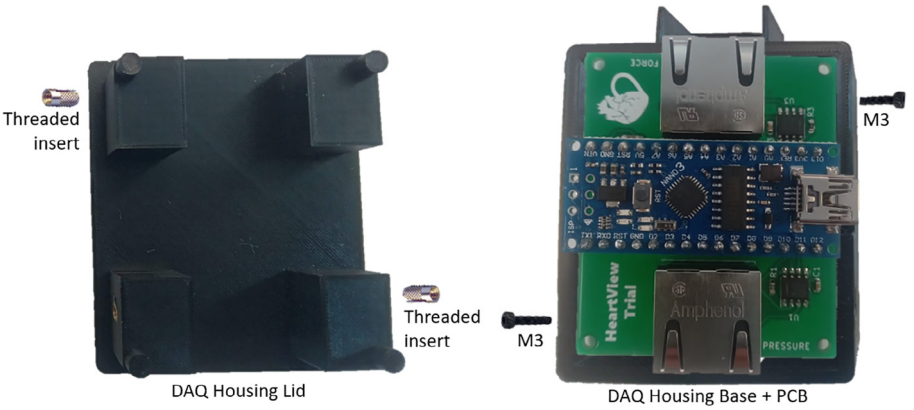

Fig. 4. Example of DAQ assembly.

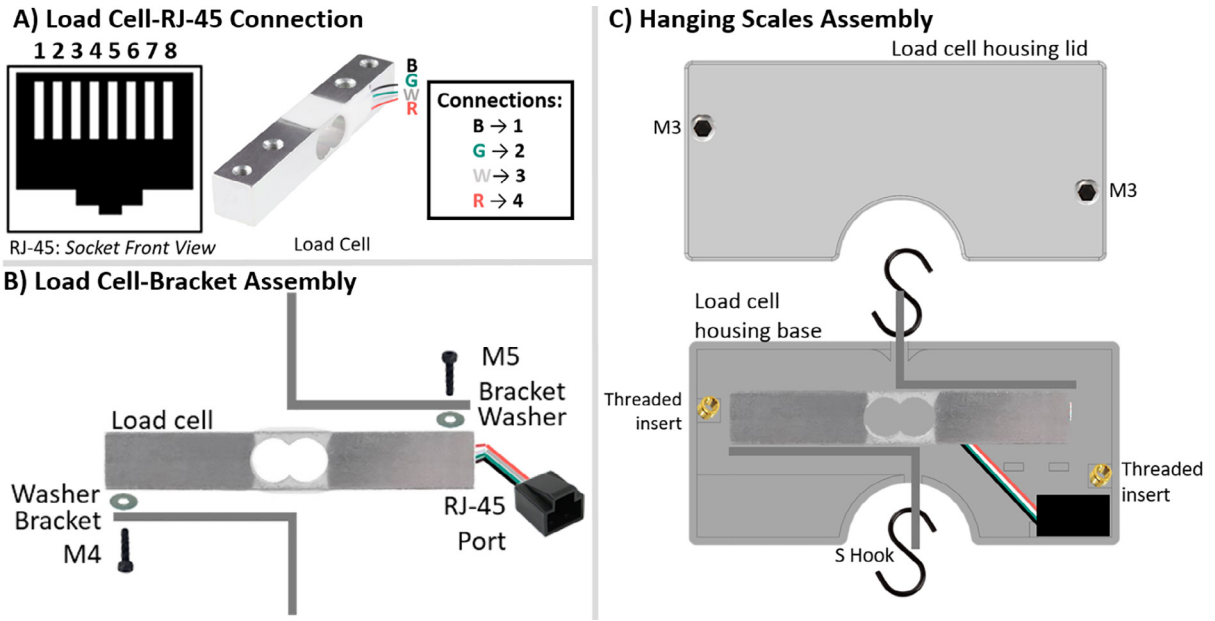

Fig. 5. Hanging scales assembly, including pin connections for load cell to RJ-45 port.

6. Operation instructions

Once built, the device can be used as follows:

- **Set-up Arduino**: Load Arduino code, Arduino_read.ino, onto the Arduino Nano.
- **Set-up the system:**Hang fluid bag from hanging scales, and connect scales to DAQ using RJ-45 connector, securing the connection with the cable cover. Attach an Edwards TruWave pressure transducer to the DAQ via the hydrid pressure transducer - RJ-45 connector. Connect the DAQ to a computer via the USB connector. A diagram of the system setup is shown in Fig. 6.
- **View outputs using the HeartView application:** Unzip GUI.zip to a local file directory and open HeartView_application.exe. The application will not open unless the DAQ unit is connected. The application shows the fluid bag weight and pressure signals in real-time, for a 5-s window. Buttons can be used to 'Start', 'Reset', and 'Stop & Save' recordings, and to 'Close' the application. Fig. 7 shows an example of the application.

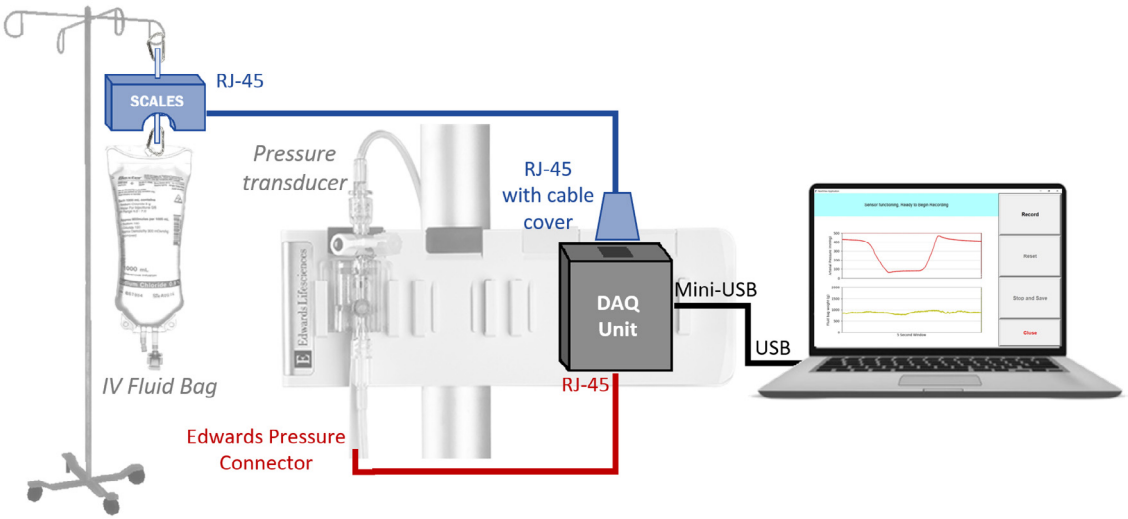

Fig. 6. Example of setup and connection of HeartView system components.

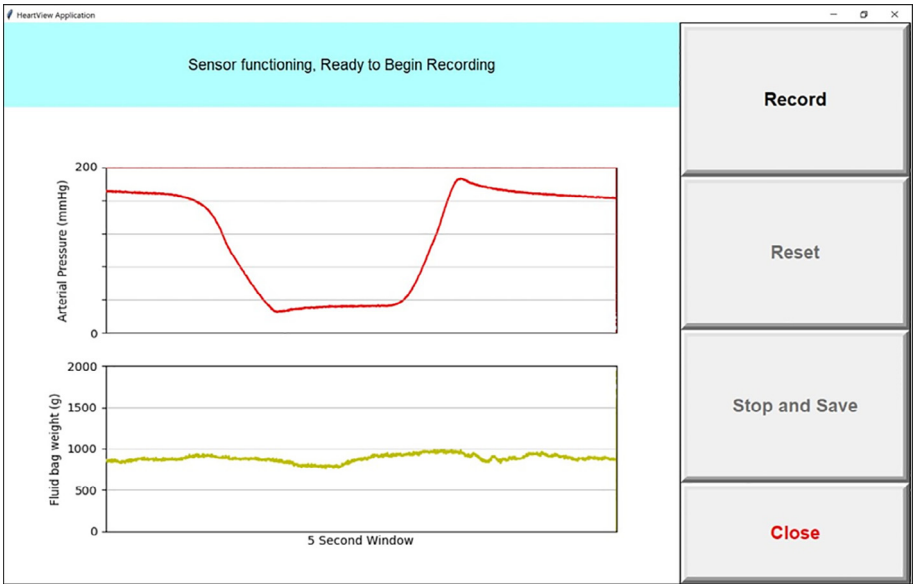

Fig. 7. Example of HeartView application.

- **Calibrate the device:** The load cell can be calibrated by using known weights hung from the sensor. The pressure transducer can be calibrated using a water column. Load cell calibration is recommended to account for the weights of the angle bracket and attachments, which are expected to vary. Calibration values can be entered into the Python application (GUI_main.py).

Other operational considerations include:

- This is a research tool, not a medical device. While able to read data from clinical pressure monitoring systems, it does not replace a clinical monitoring system. However, it is useful for acquiring patient pressure signals for research, and for testing the properties of clinical pressure transducers.
- The device is used around water/fluids and care should be taken to avoid exposing electronic components to liquids. Note, the housings provide some water resistance, and a cable shield was designed to shield the DAQ unit from water leaking from above.

7. Validation and characterization

Calibrating the device as described in Section 6, calibration curves were obtained for the pressure and load signal, shown in Fig. 8. The coefficient of determination of the linear least-squares fit to the data, $R^2 > 0.99$ in both cases, indicates very good linearity of the sensors and a lack of noise.

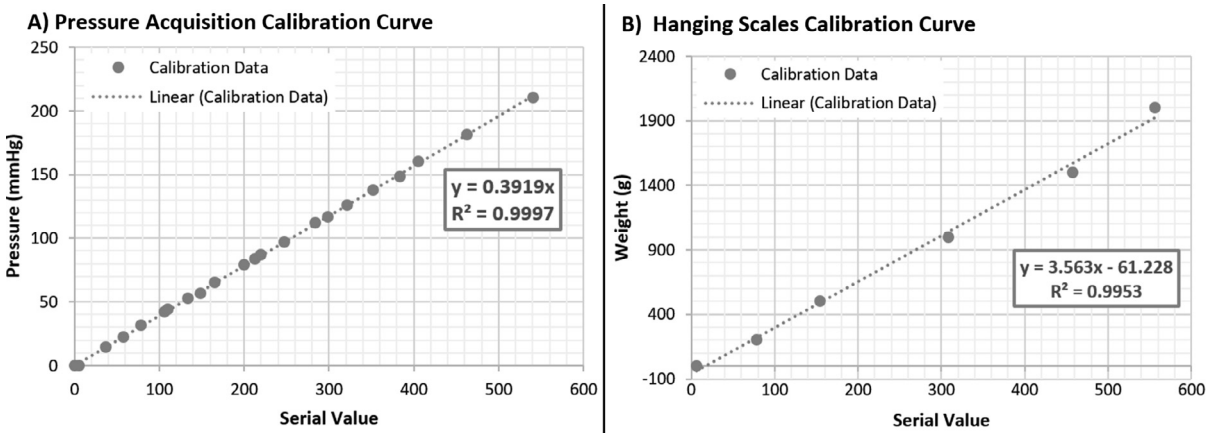

Fig. 8. Calibration results for pressure sensor and hanging scales.

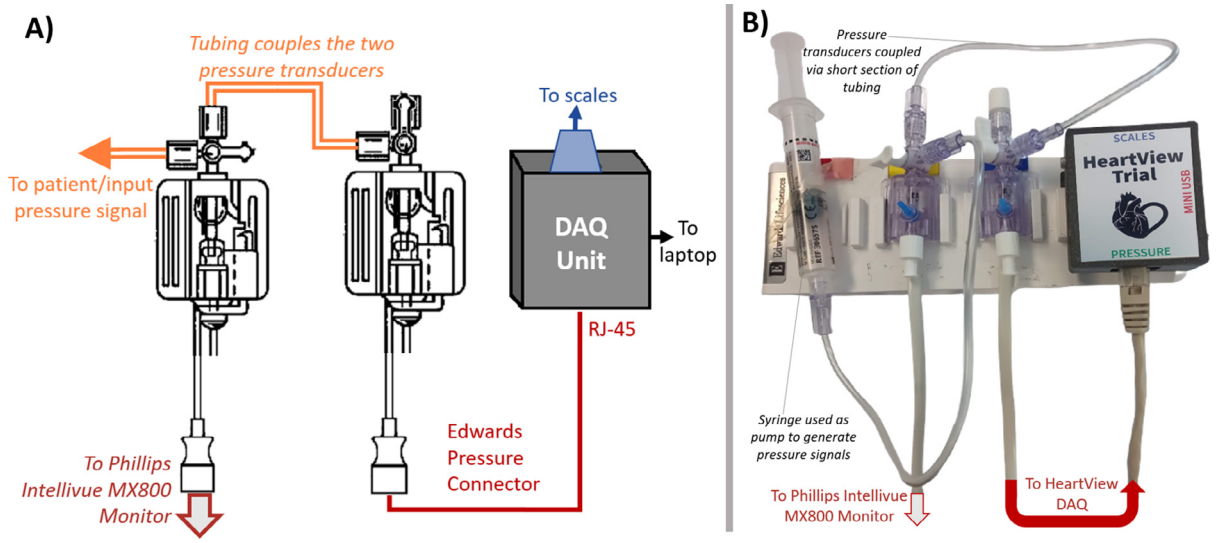

Fig. 9. Pressure transducer coupling configuration for simultaneous pressure measurement by Philips monitor and HeartView DAQ. A) Schematic, B) Photo of equivalent setup, using a syringe as a pump for validation.

The operational range for pressure acquisition is 0–200 mmHg, and for the load cell is 0–2 kg (corresponding to 0–2 L saline). The resolution for pressure is 0.4 mmHg, and 6 g for the load cell, corresponding to an ADC-input voltage increment of 0.0049 V. This resolution is sufficient to capture clinically meaningful pressure changes, which are 5 mmHg or larger, and fluid delivery, which is typically 100–500 ml. The resolution is limited by the 10-bit ADC used as part of the Arduino Nano, and resolution could be improved with different ADC. Signals are recorded with a sampling rate of 500 Hz, and an alternative sampling rate could be set in the Arduino code (Arduino_read.ino).

While the calibration procedure effectively validates the general function of the load and pressure sensors, the device was also validated in a hospital setting based on its intended clinical use with the intended clinical sensors and devices, over a clinically relevant operational range.

The pressure signal acquisition was directly compared to a Philips Intellivue MX800 Monitor. Two pressure transducers were coupled by a short section of tubing, allowing them to simultaneously record the same pressure signal, as shown in Fig. 9. For validation, a pressure signal was manually generated using a syringe as a pump. However, a similar configuration can be used to measure patient pressure signals by both systems simultaneously. For quantitative comparison, photographs of the Philips monitor were captured, and graph points were extracted and synchronised with the HeartView system record-

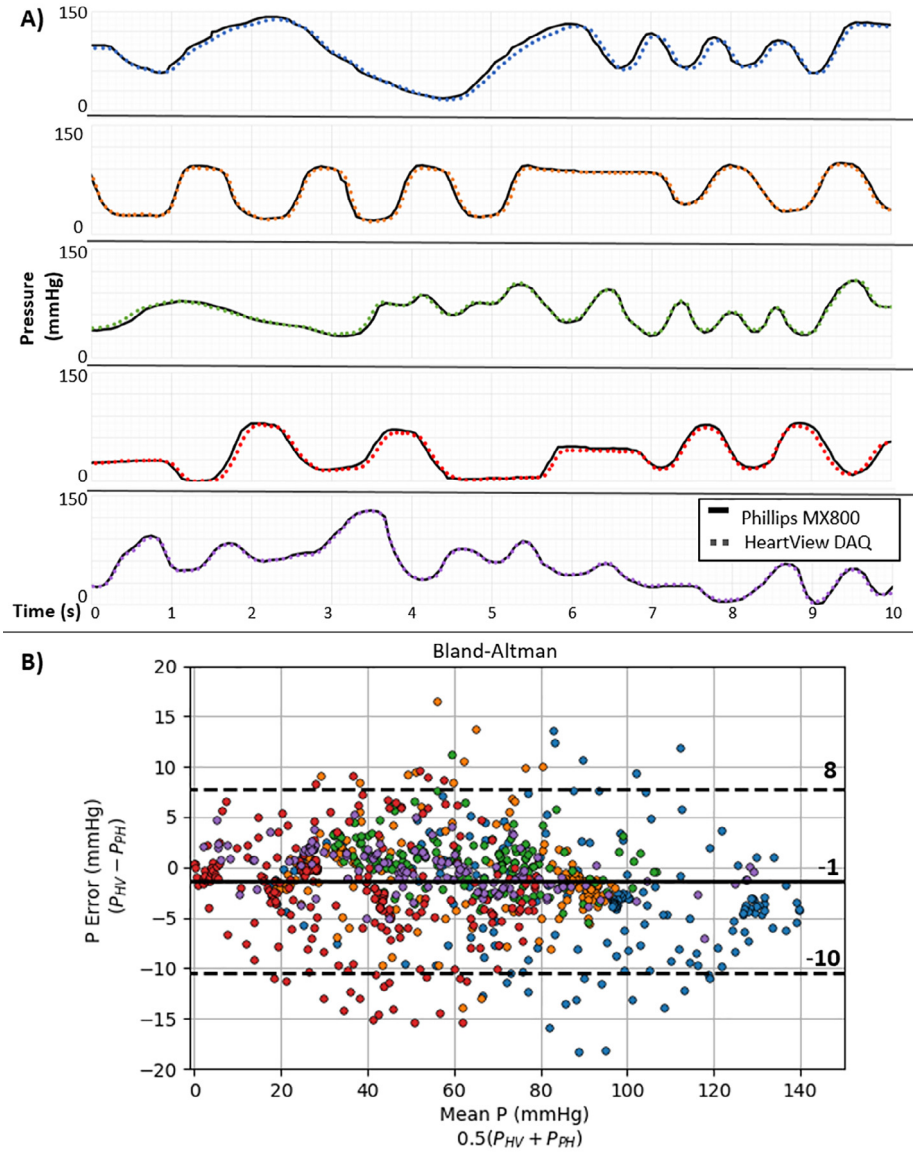

Fig. 10. A) Pressure signals measured by HeartView DAQ and Philips MX800 simultaneously. B) Bland–Altman agreement of Philips MX800 (P_{PH}) and HeartView DAQ (P_{HV}) pressure acquisition. Colours indicate errors from each of the 5 corresponding plots in A.

ing. Five 10-s samples were recorded. and the waveforms from both systems agreed well in all cases, as shown in Fig. 10A. Fig. 10A shows both systems deliver very similar pressure waveforms, which are mostly indistinguishable. Differences are largest when there is a small phase shift between the two signals and gradients are large. The error between the HeartView system and Philips monitor for the data in Fig. 10A. was used to generate the Bland Altman plot in Fig. 10B. Overall, errors are close to zero across the measurement range, and the range of errors is small. Bland–Altman mean bias and limits of agreement (±2 standard deviations) were −1 [-10, 8] mmHg, as shown in Fig. 10B.

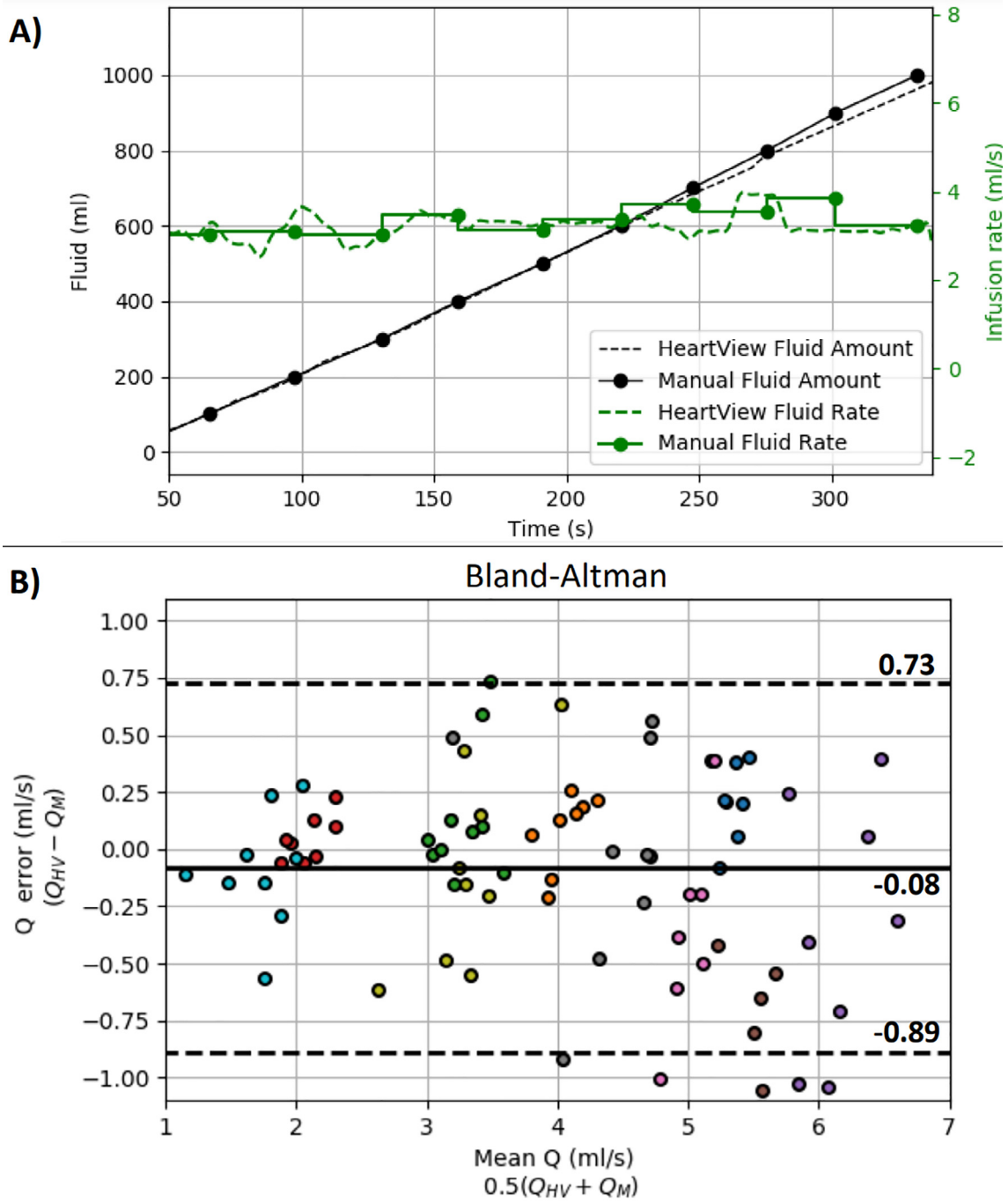

Fig. 11. A) Example of one fluid drain test, showing fluid amount and rate signals measured by HeartView DAQ and manually. B) Bland–Altman agreement of manual (Q_M) and HeartView DAQ (Q_{HV}) fluid rate measurement. Each colour indicates a different fluid drain test.

The fluid infusion rate measurement was validated by weighing a fluid infusion bag as it drained into a container at different rates. This was done ten times using a range of fluid bag heights. The fluid bag weight was recorded with HeartView DAQ, and the time taken to drain 100 ml increments was also recorded manually. The HeartView DAQ load cell signal was filtered with a 5th order Butterworth low-pass filter with an 0.15 Hz cut-off frequency. Fluid rate was then calculated by differentiating the load cell signal and filtering further with a 20-s window moving average filter. This filtering and differentiation occurred in a post-processing Python script. An example of these results from one fluid bag drain test is shown in Fig. 11A. This figure shows the weight, and thus volume of fluid decreased at a constant rate as the bag drained. The infusion rate and fluid amount measured by both methods is similar. Using errors from all ten fluid bag drain tests, a Bland–Altman plot was generated showing mean bias and limits of agreement (±2 standard deviations) as −0.08 [-0.89, 0.73] ml/s, as shown in 11B. Overall, the plot shows the range of errors is small, with a low median bias.

Human and Animal Rights

No human or animal studies were conducted in the design of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Rachel Smith received her BE(hons) specializing in Biomedical Engineering from the University of Auckland in 2018. She is currently a PhD candidate at the University of Canterbury (2018-present). Her research focuses on using engineering and computational methods to improve healthcare and our understanding of physiology, in particular the cardiovascular system. The model-based systems she has developed aim to improve clinical care and outcomes, and reduce costs.