Measurement System for Compliance in Tubular Structures

Ave Kludze, Anthony R. D'Amato, & Yadong Wang*

Department of Biomedical Engineering, Cornell University, Ithaca, NY

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*Students: akk86@cornell.edu**
Mentors: ard223@cornell.edu, yw839@cornell.edu

ABSTRACT
Tubular structures such as blood vessels, intestines, and the trachea are common in various life forms. This paper describes a measurement system to test the mechanical compliance of tubular structures. The novelty of the system lies in its hardware and software. Here we use vascular graft as an example to demonstrate the utility of the system. A fully synthetic vascular graft would ideally mimic the mechanical and architectural properties of a native blood vessel. Therefore, mechanical testing of the graft material under physiological pressure is crucial to characterizing its potential in vivo performance. The device operates through a low-cost Arduino-based control system that simulates and measures cyclic fluid pressure changes over time and a laser micrometer that measures diameter changes with pressure. This system is low-cost, assuming one already has access to a laser micrometer. In contrast to previous methods, this system offers a simple, low-cost, and customizable option to measure compliance and is equipped with data acquisition/analysis programs. These programs include a MATLAB application that processes and synchronizes Arduino Uno pressure signals and LabChart Pro diameter readings. Lastly, this paper explains the hardware and software of the measurement system. The system is beneficial for testing the pressure-diameter relationship of tubular structures of varying sizes and materials.

KEYWORDS
Tubular Structures; Compliance; Data Acquisition System; Physiological Pressure; Diameter Change; Arduino Uno; LabChart Pro; MATLAB

INTRODUCTION
In many lifeforms, tubular structures are essential for organ function, cellular transport, and structural stability.[1] Each tubular structure can perform varying roles based on its location and composition.[1] For instance, the trachea in the respiratory system is comprised of pseudo-stratified columnar epithelium which helps transport and filter air, the esophagus in the digestive system consists of stratified squamous cells that aid in moving foods and liquids, the intestine with its brush border cells in the digestive system absorb nutrients, the ureter in the urinary system composed of urothelium passes urine, and blood vessels in the circulatory system are multilayered to withstand blood pressure and to transport blood.[1]

Recent efforts in tissue engineering have focused on developing tubular structures that can replace damaged organs after accidents or illnesses.[1] Difficulty arises in designing tubular structures that can mechanically mimic their native counterparts and work in environments that are dependent on liquid, solid, or air material exchange.[1] Compliance is an important mechanical property often used to assess the structure-function relationship of tubular vessels. Compliance can be described as the ability of a tubular structure to stretch and can be measured based on a percent change relationship between diameter and pressure. We design, build, and test a device that can measure the mechanical compliance of tubular structures. To demonstrate its utility, we have used vascular grafts as an example.

Millions of patients suffer from coronary and peripheral artery diseases. For treatment options, surgeons currently rely on autografts from one's own tissues, or synthetic grafts when autografting is not feasible.[2] Current synthetic grafts are not suitable for small-diameter blood vessel applications, where small-diameter blood vessels are defined to be less than six mm.[2] Among synthetic grafts, polyethylene terephthalate (PET), which can be described as Dacron©, or expanded polytetrafluoroethylene (ePTFE) are the most common choices in the clinic today. These grafts, however, are prone to aneurysm, infection, and the potential for long-term performance and patency in applications requiring small diameters.

Part of the challenges in developing synthetic vascular grafts lies in identifying mechanically suitable material that can withstand cyclically changing pressures, stresses, and pulsations in physiological ranges while being flexible enough to experience changes in vascular compliance that do not result in permanent deformation or rupturing.[3] This unmet need has been addressed by designing synthetic vascular grafts that are altered physically, chemically, and mechanically to improve in vivo performance and mimic the mechanical and elastic behaviors of a native blood vessel.[4] Both solution electrowriting and electrospinning are methods to produce synthetic grafts by precisely patterning elastomeric fibers to optimize mechanical stability and structural integrity.[5]

Mechanical testing of graft material at physiological pressures is therefore crucial in characterizing its viability. Vascular compliance is especially important, as compliance mismatches with native blood vessels are related to processes that result in intimal hyperplasia.[6] Compliance values of native blood vessels also provide a means of comparison with synthetic vascular grafts, allowing researchers to understand whether a synthetic graft has mechanical properties similar to a native blood vessel.[4] For example, the compliance value of the femoral artery in humans can vary between 3.8% to 6.5%/100 mmHg while the compliance value of the saphenous vein in humans is typically 1.5%/100 mmHg.[7] Although previous methods for compliance testing have been developed, many of these methods are limited due to their lack of customization, reliance on external sources or companies, and use of expensive lab equipment.[8–11]

This paper describes a low-cost, user-friendly, and open-source data acquisition/analysis system that allows continuous recordings of pressure signals, diameter readings, and time points, which are used to calculate vascular compliance. This low cost assumes that one already has access to a laser micrometer. This measurement system is currently suitable for non-porous tubular structures and it simulates physiological ranges by inducing cyclic fluid pressure changes based on responses from a submersible water pump, pressure transducer, and a ball-valve.

METHODS AND PROCEDURES

Compliance Calculation Theory

This project draws on the supplementary methods of Wu, Wei to calculate vascular compliance.[12] As noted in the introduction, compliance can be calculated as a percent change in diameter between systolic and diastolic pressures. In trial 1, the systolic pressure was selected to be 150 mmHg and the diastolic pressure was 75 mmHg. In trial 2, the systolic pressure was 160 mmHg, and the diastolic pressure was 75 mmHg. These values were chosen to represent native blood pressures at high or systolic and low or diastolic pressures for arterial grafts. Compliance (%/100 mmHg) was calculated using **Equation 1** where D_{high} is the graft diameter at systolic pressures, D_{low} is the graft diameter at diastolic pressures, P_{high} is the systolic pressure, and P_{low} is the diastolic pressure. The diameter may be in any unit, but the pressure must be in mmHg. The 10,000 functions to convert to the % 100 mmHg units. In general, the calculation of the compliance of tubular structures will take the same form as **Equation 1** but will differ in the pressure and diameter ranges. For example, fluid suspension of food particles slowly flows through the intestine and nonetheless gives rise to compliance values based on a pressure-diameter relationship.

$$C = \frac{D_{high} - D_{low}}{D_{low}(P_{high} - P_{low})} * 10{,}000 \qquad \textbf{Equation 1}$$

Water Flow Diagram

As the density of water is nearly equivalent to the density of blood, this project used water flow to mimic the movement of blood through a native blood vessel.[13] The medium of flow can differ in other tubular structures and may require submersible pumps that can flow such mediums. A simplified diagram that only depicts the path of water flow through the compliance testing device is shown in **Figure 1**. Water first flows from the submersible water pump to the pressure sensor, the graft, and finally the ball valve. The ball valve is normally closed. The ball valve opens once it reaches the systolic pressure of 150 mmHg in trial 1 and 160 mmHg in trial 2. This opening of the ball valve allows for a decreased build up in pressure and thus graft compression. The ball valve closes at pressures below 75 mmHg. This closing of the ball valve allows for high pressure to build up within the graft so that it may experience expansion. The water eventually flows back into the reservoir once the ball valve is open. The process is repeated for cycles as water exits from the submersible water pump. This whole process results in diameter changes.

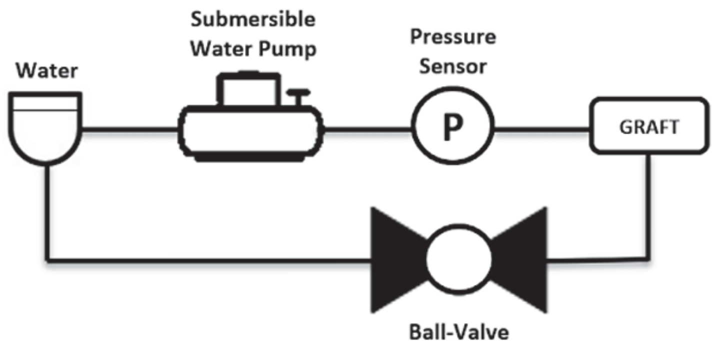

Figure 1. Piping and instrumentation diagram (PI&D) of water flow

Hardware Description

The measurement system consists mainly of electrical hardware as shown in **Figure 2**. The measurement system is powered through a 5 V power supply to the Arduino Uno and 12 V power supply to the ball valve. The system output is transmitted via a serial monitor using a USB, allowing for integration into other systems or software. In this project, the serial communication is read through PUTTY, which will be described in the *Software Description*.

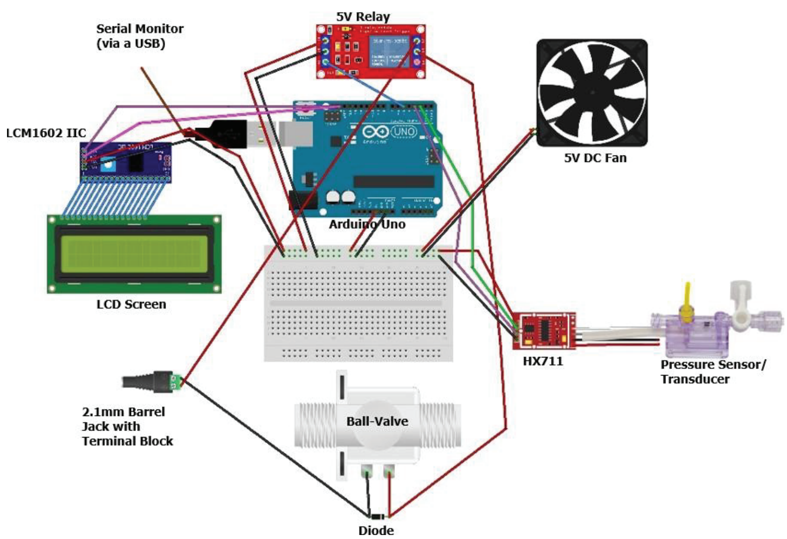

Figure 2. Wiring diagram of the pressure measurement component created with fritzing.

Each electrical component carries out a specific function: Arduino uno controls circuit components according to computer code; ball valve controls the flow of water and the build-up of pressure within the device; Edward Truwave pressure transducer relays the pressure information in mmHg and transmits data to Arduino; HX711 weighing sensor module increases the strength of the signal from the pressure transducer (e.g., the pressure transducer signal is in microvolts and Arduino only reads the signals in volts); 5 V relay module acts as a switch that turns off and on the power supply to the ball valve; LCD screen functions as an external display system for water pressure in mmHg; LCM1602 IIC acts as an adaptor that simplifies LCD wiring to the Arduino; barrel jack acts as a plug for 12 V power supply; 5 V DC fan functions as a ventilator to prevent potential overheating of the device; diode functions to prevent frying of relay circuitry, voltage spikes, and back emf.

The reduced bill of materials with key components is listed in **Table 1**. The measurement system offers a low-cost, customizable, and open-source option for compliance measurement. This system is low-cost, assuming one already has access to a laser micrometer.

Component	Quantity	Total Cost (USD)	Vendor	Part Number
Arduino Uno	1	28.5	Arduino	A000066
Motorized Ball Valve ¼"	1	34.9	U.S. Solid	JFMSV00027
Truwave Pressure Transducer	1	34.95	Edwards-Lifesciences	PX6001
HX711 Load Cell Amplifier	1	3.7	DIYmall	FBA_FZ0728X2
5V One Channel Relay Module Relay Switch	1	3.7	HiLetgo	3-01-0340
5V DC Cooling Fan	1	3.9	Aokin	8010
I2C 1602 LCD Display Module	1	5.99	GeeekPi	B07S7PJYM6
12V DC Power Connector (Barrel Jack)	1	2.99	Posdou	819356
480GPH Submersible Pump (1800L/H, 25W)	1	16.99	VIVOSUN	N/A
Solderless Prototype PCB Breadboard	1	0.99	Deeoee	7545924028
Total Cost Key Components		136.7		

Table 1. Reduced bill of materials with key components/totals only. It should be noted that the laser micrometer is not included in this calculation.

HX711 Load Cell Amplifier & Edwards-Truwave

The HX711's primary purpose is to amplify signals from pressure transducers or load cells and transmit these signals to a microcontroller such as the Arduino Uno. To obtain a pressure signal, the HX711 functions as a differential amplifier to get the difference between two voltage pins. This is necessary since the pressure transducer reads in the microvolt range (sensitivity 5.0μV/V/mmHg ± 1%) whereas the Arduino Uno reads in the volt range.

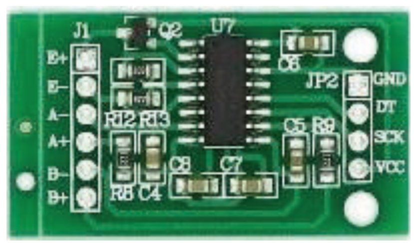

Figure 3. HX711 - Load Cell Amplifier 24-Bit ADC Converter. Image taken from Aerial Net.[14]

The HX711 load cell amplifier and its pins are shown in **Figure 3**. To acquire a signal, 4 of the 5 output pins are needed on the Edwards Truwave pressure transducer. These outputs are VCC, GND, SIGNAL+, and SIGNAL-, where pressure is proportional to (SIGNAL+ minus SIGNAL-), as shown in **Figure 4**.

At the start of the project, the pressure transducer appeared to be a strain gauge-type bridge with four connections. The fifth connection was likely a screen for a monitor cable. The output locations were proprietary information. However, the exact output locations were identified using resistance measurements between pairs of wires (e.g., V+ and V- or Signal+ and Signal-). Later, the company's patent confirmed the connections.[15]

Figure 4. Pin map for Edwards-Pressure Transducer.

The electrical connections between the HX711 and Edwards-Pressure Transducer are displayed in **Figure 5**. The pressure transducer pins V+ (5V), SIGNAL+, SIGNAL-, and V- (GND) are connected to on E+, A+, A-, and E- on the HX711.

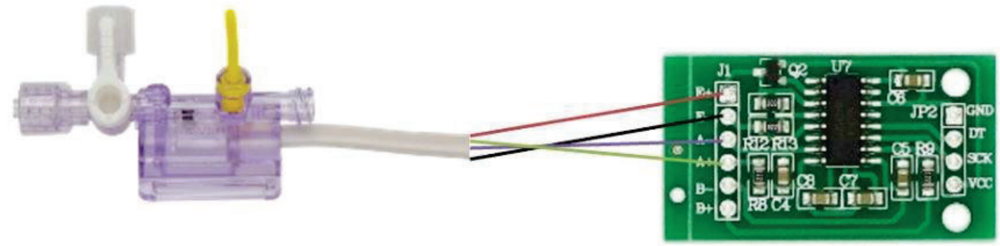

Figure 5. Pin map for Edwards-Pressure Transducer to HX711.

The HX711 pins GND, DT, SCK, and VCC have standard connections to the Arduino Uno. GND was connected to the ground on the breadboard, VCC was connected to the 5 V on the breadboard, SCK was connected to digital pin 2, and DT was connected to digital pin 3. Finally, the default sample rate of the HX711 is 10 Hz. To increase the sampling rate to 80 Hz, a hardware change on the HX711 must be made.[16] It is necessary to increase the sample rate of the HX711 to 80 Hz because a higher sample rate provides for more data points over a given period, allowing for a finer resolution of the data. In addition, a higher sampling rate allows for the capturing of subtle changes in data that may be missed at a lower sampling rate, especially when time-sensitive measurements are taken.

3D-Printing (Fusion Autodesk)

An enclosure was created with Autodesk Fusion to surround the electrical components and the Arduino Uno. Gates were made for the USB connector, 12 V DC Power Supply, pressure sensor wires, ball valve wires, and LCD. Additionally, a screwable lid was created to fix the enclosure. The cable grip glands were super-glued in the enclosure to prevent tugging of the pressure transducer. The 12 V DC barrel jack was superglued to prevent the movement of the power supply components. Lastly, both the LCD and the relay switch were screwed onto the enclosure. The print orientation for the 3D-printed enclosure and cover are shown in **Figure 6** and **Figure 7**. The final 3D-printed enclosure and lid configuration are shown in **Figure 8**.

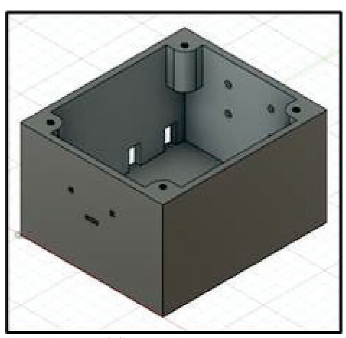

Figure 6. Print orientation for the 3D-printed enclosure. The enclosure is 117 mm in length, 135 mm in width, and 79.763 mm in height.

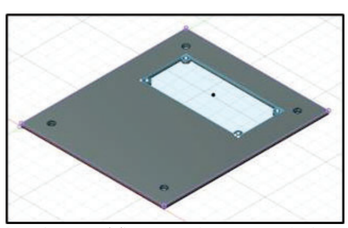

Figure 7. Print orientation for the 3D printed cover. The cover is 117 mm in length, 135 mm in width, and 2.381 mm in height.

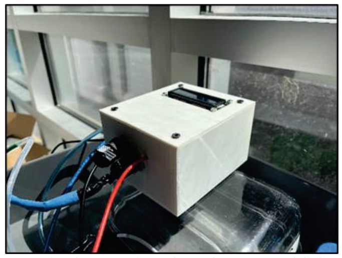

Figure 8. Final 3D-printed enclosure and lid configuration.

Hardware Build Instructions (Summarized)

1. Order an Edwards-Truwave Pressure Transducer and the wiring components listed.
2. Print the enclosure and cover lid using a 3D printer and the associated Autodesk Fusion files.
3. Isolate the top four wires on the Edwards-Truwave Pressure Transducer. Cut the plastic between each wire so that each wire pin is isolated from the other.
4. Perform a hardware change as indicated in the section of HX711 (Sampling Rate), which will increase the sampling rate to 80 Hz.
5. Solder the wires of each pin to the HX711 using the configuration in Figure 5 and then connect the HX711 to the Arduino Uno.
6. Calibrate the Edwards-Truwave Pressure Transducer using a baumanometer as indicated in the Pressure Calibration section.
7. Connect the hardware components as indicated in the Wiring Diagram section.
8. Glue the breadboard, Arduino Uno, and 12 V barrel jack to the bottom of the 3D-printed enclosure.
9. Screw the LCD to the cover lid and the 5 V relay module to the enclosure.
10. Glue the four wires of the Edwards-Truwave Pressure Transducer while leaving a gap between each wire.
11. Electrical tape the four wires to prevent potential tugging and damage of the wires.
12. Glue the grip cable glands into the 3D-printed enclosure. Connect the Edwards-Truwave Pressure Transducer wires to the grip cable gland and then tighten the grip cable gland.
13. Assemble the cover lid and enclosure by screwing both parts together.

Software Description

The Arduino Uno is an open-source microcontroller that processes analog and digital inputs and output pins. In this project, the Arduino Uno functioned to process signals from the Edwards-Truwave Pressure Transducer and display these reads through the serial monitor/plot (e.g., pressure versus time). It also controlled the LCD and ball valve as well as other electrical components listed in the Wiring Diagram subsection. The programming libraries used in this project include HX711.h, Wire.h, and LiquidCrystal_I2C.h. The program first calculated the water pressure, displayed the pressure on the LCD, opened/closed the ball valve based on water pressure, and then repeated the process. The LCD is mainly an accessory that is used in the scenario where one does not wish to look at the serial monitor. The LCD refreshes the pressure value displayed every time the void loop is executed in Arduino Uno. In other words, every time the water pressure is calculated. Therefore, the serial monitor is the best for viewing the data and its changes over time. PUTTY was used with Arduino to read data from the serial monitor and save it onto a .csv file. LabChart Pro was used to record diameter readings versus time and save them onto a .xlsx file. To account for differences in sampling rates and time delays, a MATLAB application processed and synchronized both signals based on the identification of peaks. The data acquisition/analysis workflow is shown in **Figure 9**.

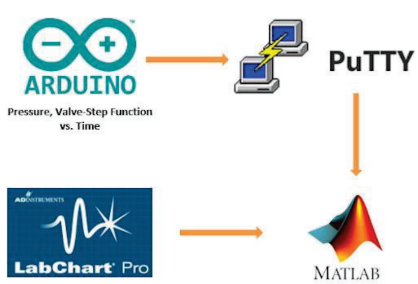

Figure 9. Data acquisition workflow.

The full operation/device protocol, programming code, and instructions are provided on GitHub and Google Drive.[17, 18]

Operation Instructions (Summarized)

1. Setup the system by connecting the submersible water pump, pressure sensor, vascular graft, ball valve, and laser micrometer as indicated in **Figure 1** and **Figure 10**.
2. Load the Arduino Uno code, serial_plott_water_valve_and_TruWave_pressure_sensor_HX711_lcd_.ino, onto the Arduino Uno. The Arduino USB cable should be connected to the Arduino Uno.
3. Load the LabChart Pro program file, 20180627_CETS_Compliance.adiset, onto LabChart.
4. Plug in the 12 V DC power supply to the barrel jack.
5. Place the submersible water pump inside the water reservoir and connect the plug to a power supply.
6. Record pressure signals and time points by PUTTY.
7. Record diameter readings and time points by LabChart.
8. Save the Arduino data files as a .csv and the LabChart data files as a .xlsx.
9. Load the MATLAB code, compliance_data_sync.m, onto MATLAB.
10. Rename the file variables in the MATLAB program according to the saved file names.
11. Run the MATLAB program and save the output files. A video of the measurement system and photographs can be viewed in Google Drive.[19]

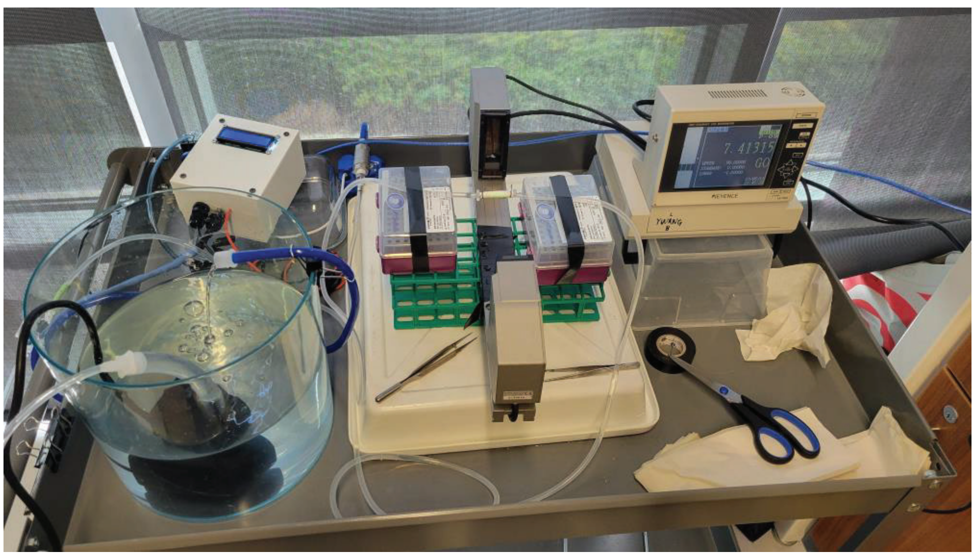

Figure 10. Final experimental setup of the measurement system.

RESULTS

Pressure Calibration (Edwards Truwave Pressure Sensor)

The pressure transducer was calibrated using a baumanometer that reads from 0 mmHg to 300 mmHg. The calibration curve was obtained from the pressure gauge and load signal (ADC value) readings. The ADC value is a digital signal read from Arduino, which corresponds to a pressure signal. The pressure signals were recorded in increments of 20 mmHg with the corresponding ADC value. The range for pressure acquisition is from 0 to 300 mmHg. The pressure versus ADC value plot is shown in **Figure 11**.

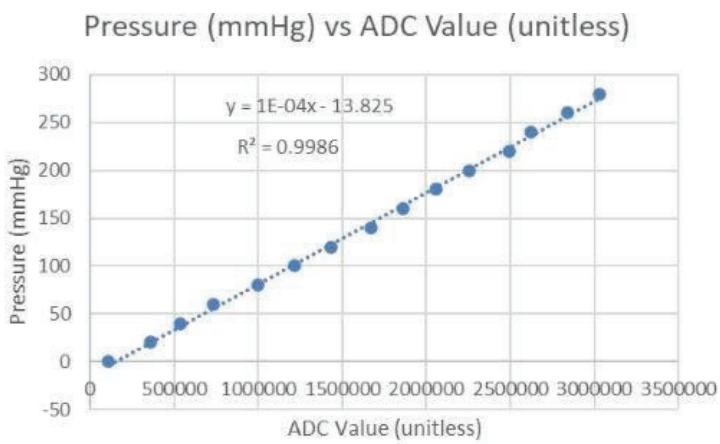

Figure 11. The ADC value recorded by the Arduino Uno and the corresponding pressure values in mmHg. The R2 coefficient shows a strong linear correlation and the regression line is used to calibrate the device.

The coefficient of determination of the linear least-squares fitted the data, R2 > 0.99, suggesting very strong linearity and minimal noise.

Pressure, Diameter, and Compliance versus Time Plots

A graph of pressure versus time, diameter versus time, and synchronized data with compliance values are shown in **Figure 12**, **Figure 13**, and **Figure 14** below. For all plots, the green stars represent the peak at either a maximum or minimum. A second trial run was performed using a graft of different material properties. The plots can be viewed in **Figure 15**, **Figure 16**, and **Figure 17**. All of the plots and the associated data can be viewed in Google Drive.[20]

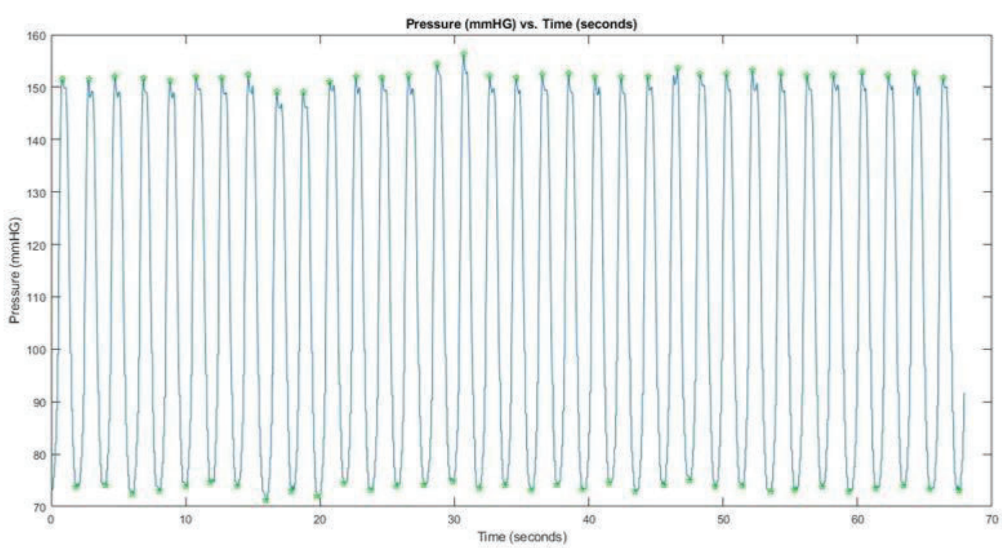

Figure 12. A plot of pressure signals in mmHg versus time points in seconds plots generated from MATLAB for the first trial run.

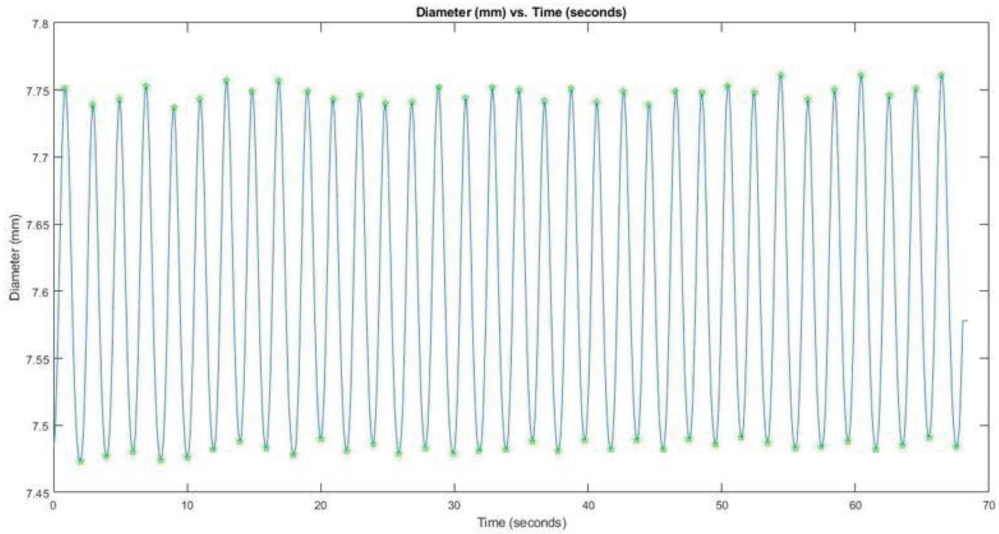

Figure 13. A plot of diameter readings in mm versus time points in seconds generated from MATLAB for the first trial run.

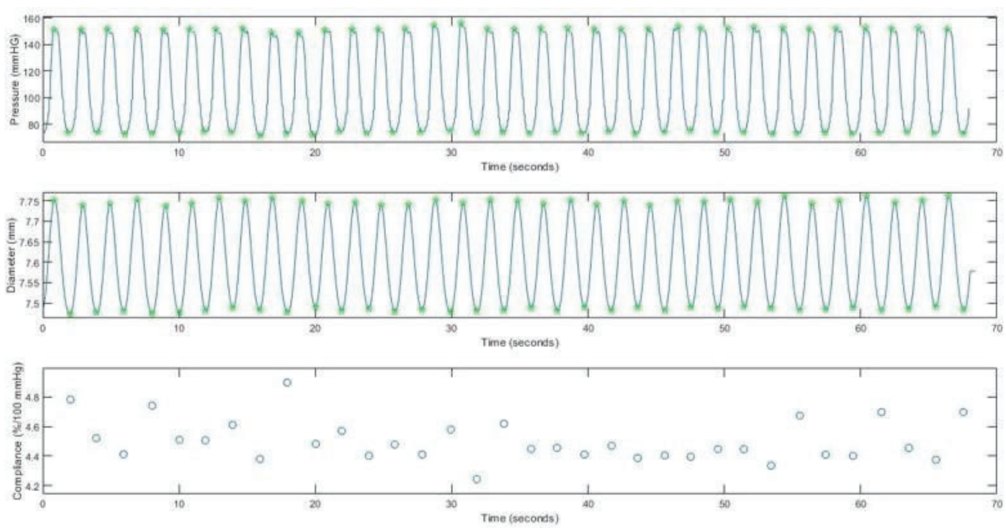

Figure 14. A plot of synchronized pressure, diameter, and compliance readings generated from MATLAB for the first trial run.

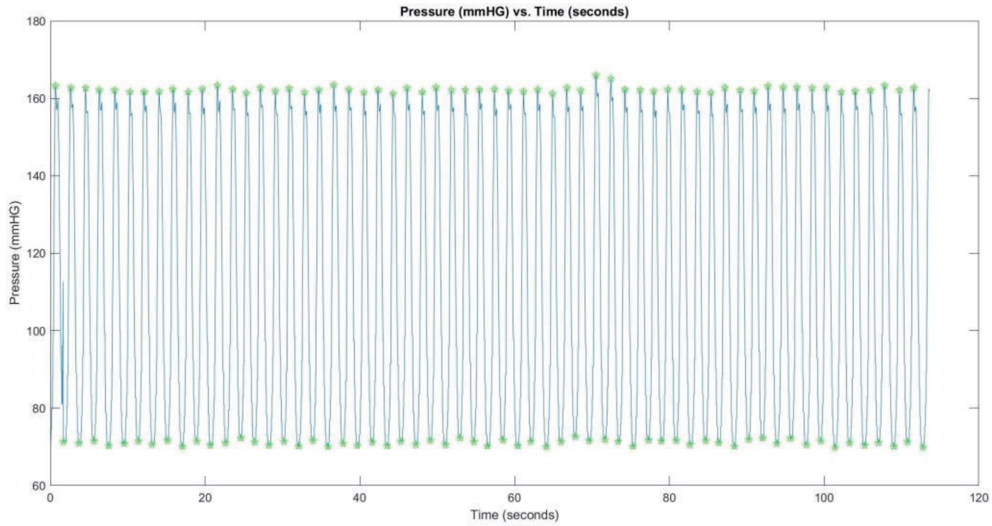

Figure 15. A plot of pressure signals in mmHg versus time points in seconds plots generated from MATLAB for the second trial run.

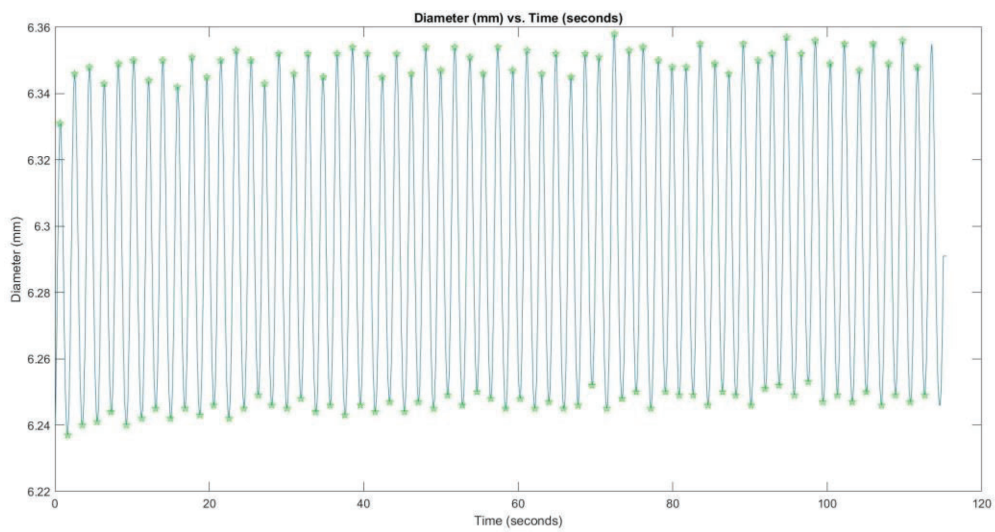

Figure 16. A plot of diameter readings in mm versus time points in seconds generated from MATLAB for the second trial run.

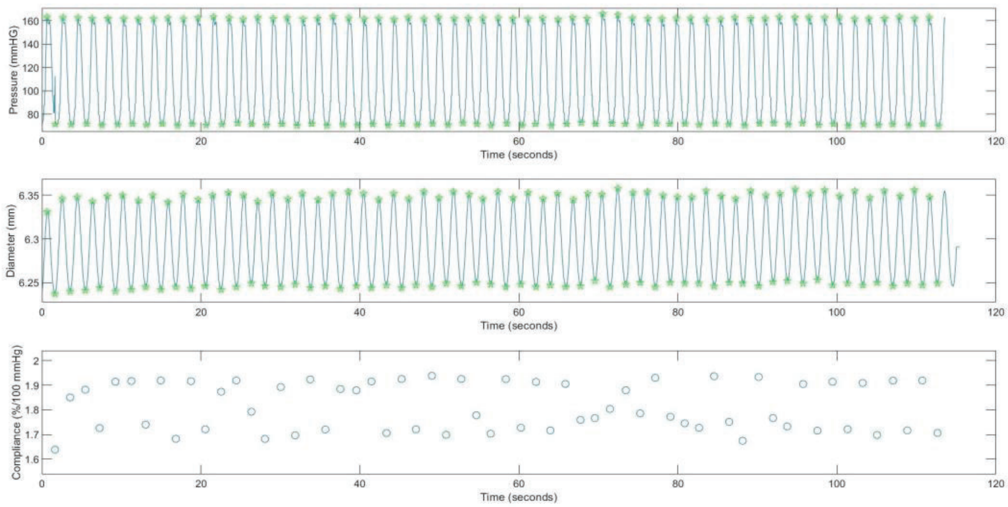

Figure 17. A plot of synchronized pressure, diameter, and compliance readings generated from MATLAB for the second trial run.

DISCUSSION

The main objective of the project was to develop a measurement system for compliance in non-porous tubular structures with vascular grafts as an example. The vascular grafts used in the project were arterial grafts though they were not optimized to match arterial compliance. The grafts functioned as a test sample for the measurement system. The system's significance lies in its ability to acquire compliance for non-porous tubular structures of varying material properties and dimensions. The system successfully measured pressure signals and diameter readings and subsequently calculated compliance. The Edwards Pressure Transducer used in this project was able to measure small changes in pressure signals and relay that information to the Arduino Uno, as it is a reliable transducer used in other projects.[21] This system was operational throughout the entirety of the trial runs. Each trial produced graphs of similar waveforms, particularly pressure signals and diameter readings that demonstrated oscillatory behavior as expected. Both trials 1 and 2 produced plots of similar behavior, indicating the device's consistency in measuring and computing data with no dependence on the tubular structure at hand.

The MATLAB program successfully synched different datasets by calculating time delays and identifying peaks as maximums or minimums in both the pressure versus time plot and diameter reading versus time plot as indicated in **Figure 12**, **Figure 13**, **Figure 14**, **Figure 15**, **Figure 16**, and **Figure 17**. The MATLAB program accounted for possible irregularities in data collection by introducing a five-second delay in recording data.

The system's operational range for pressure was sufficient to mimic physiological conditions. The main determinant of the pressure attained was the ball valve. The ball valve functioned to respond to pressure signals based on a program that opens or closes it once certain pressure thresholds are reached. It should be noted that a high enough flow rate on the submersible water pump is needed for pressure to be generated. As shown in **Figure 1**, the submersible water pump (VIVOSUN 480GPH Submersible Pump) releases a high stream of water that leaves the pump, hits the closed ball valve, and thus leads to a buildup of pressure. The pressure is relieved and subsequently decreased once the ball valve is opened at a certain threshold. Therefore, the ball valve allows for pressure to build up or to be relieved while the submersible water pump allows for a constant stream of high-pressure water to move within the system. The ball valve sets the pressure range based on the threshold programmed in Arduino Uno, which can only be achieved if there is a high enough flow rate on the submersible water pump.

The current VIVOSUN 480 GPH Submersible Pump had a maximum pressure of 170 mmHg. The VIVOSUN Submersible Pump has 210 GPH, 400 GPH, or 660 GPH versions that could lead to different pressure ranges depending on the users' specific need.

It should be noted that during the study, the location of the submersible pump and the water reservoir was moved from the bottom shelf of the cart to the top shelf of the cart as shown in **Figure 10**. When the submersible pump and the water reservoir were at the bottom shelf, the pressure range plateaued to about 110 mmHg and did not reach a high enough threshold to open the ball valve, in contrast to the reservoir at the top shelf with a pressure range between 75 mmHg to 150 mmHg. This suggested that gravity played an effect, and thus, it is recommended that all system components are leveled on the same plane, including the tubing within the system.

The compliance versus time plots were calculated as shown in **Figure 14** and **Figure 17**. The plots showed that compliance varies with time but stays within a certain range. Thus, the best approximation of graft compliance would be the average of all individual

Unlike previous systems for compliance testing, the system described in the paper does not rely on external sources or companies and offers customization for future users. For example, the DynatekLabs' DCT Dynamic Compliance Tester verifies % radial compliance under FDA, ISO, AAMI, and ASTM testing guidelines, but it does not offer customization and requires outsourcing from the company to test vascular compliance.[8]

The Universal Testing Machine (MTS Systems Corporation) uses a 50 lb. load cell and displacement velocity to correlate linear force and displacement to compliance, but it does not test compliance of the graft under physiological fluid pressure ranges as the system described in this paper.[10]

The Cardiovascular Regenerative Engineering Laboratory Marquette-MCW has a vascular graft test station to ISO 7198 standards that can measure dynamical radial compliance and burst strength under physiological pressures but does not make use of Arduino hardware or software to customize different components.[22]

The system in the paper is not capable of measuring dynamic radial compliance to ISO 7198 standards.[23] The system was not tested to ISO 7198 standards. The ISO 7198 standard has a 50-70 beats per minute requirement for the cycle rate. The cycle rate of the system in seconds can be approximated by dividing the number of cycles by the total time, providing cycles per second. Beats per minute can be calculated by multiplying the cycles per second by 60. The cycle rate of the system was approximately 30 beats per minute where **Figure 12** shows 35 cycles within approximately 70 seconds and Figure 15 shows 60 cycles within approximately 120 seconds. The system in the paper had a fixed and non-adjustable cycle rate that was not hardcoded in Arduino. Although the cycle rate of the system was not tested to ISO 7198 standards, one possible solution to adjust the cycle rate would be to change the flow rate of the VIVOSUN submersible pump, which is currently at 480 GPH, by using other VIVOSUN submersible water pumps.

The ISO 7198 standard has a requirement that a system can be cycled between 50-90 mmHg, 80-120 mmHg, and 110-150 mmHg. The system in the paper was not tested to ISO 7198 standard and was primarily tested for aortic pressure ranges, specifically between 75-150 mmHg in trial 1 and 75-160 mmHg in trial 2. This range was chosen based on our test samples which were arterial grafts. Although the system was not explicitly tested for ranges in the ISO 7198 standards, we believe that is capable of operating within the ranges stated by making changes to the system. First, the minimum and maximum pressure ranges, as determined by closing and opening of the ball valve, are hardcoded into the Arduino Uno as H_limit for high water pressure limit and L_limit for low water pressure limit. If one keeps the flow rate of the submersible pump used in this paper constant (480 GPH), the system should be able to cycle between 80-120 mmHg and 110-150 mmHg by changing the H_limit and L_limit in the Arduino Code, especially since the largest pressure range tested was between 75 mmHg to 160 mmHg. The 50-90 mmHg pressure range would require additional tests of the system to confirm its performance.

A limitation of this device is that it was largely dependent on the pressure transducer. The data collected depends on the accuracy of the linear regression curve with respect to the pressure transducer's readings, so damage to the transducer would produce inconsistent results. Moreover, if one wishes to change the pressure transducer, then the transducer must be recalibrated. A second limitation was the space requirement, as the experimental setup requires a large lab space to account for the device components as shown in **Figure 10**.

CONCLUSIONS

The measurement system described in this paper presented a cost-effective and customizable option to obtain compliance with tubular structures. The results demonstrated that the system and its associated programs operate as intended, allowing researchers to compare tubular structures of different lengths and material properties. There is potential for future improvements in this measurement system. The device currently supports only non-porous tubular structures. The electrical components could be replaced with cheaper options that would still allow the device to function properly.

The 3D printed box's STL files could include holes for the cable grips or the barrel jack, which would remove the need to drill holes. Lastly, a flow rate sensor could be inserted into the device so that it may quantify flow rate and produce flow rate versus time plots. This would further standardize the protocol by offering another means of analysis.

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ABOUT THE STUDENT AUTHOR

Ave Kludze is a recent graduate from Cornell University. He graduated with a bachelor's degree in biomedical/medical engineering with a concentration in molecular, cellular, and systems engineering. He also worked as an academic excellence workshop facilitator and teaching assistant in calculus for engineers, multivariable calculus for engineers, differential equations for engineers, linear algebra for engineers, and biomedical transport phenomena. He plans to continue to conduct research in the field of cardiovascular biology and/or cardiology.

PRESS SUMMARY

Tubular structures are common in various lifeforms and organ systems. The device described here has applications for testing how a tubular structure responds to different pressures, using a vascular graft as an example. These synthetic grafts must be fabricated so that they are physically, chemically, and mechanically comparable to native blood vessels. To assess a graft's viability mechanically, vascular compliance testing is performed at varying physiological pressures. This is important since autografts from one's own tissues, or synthetic vascular grafts when autografting is not feasible. This project focuses on a measurement system to characterize compliance in non-porous tubular structures based on an Arduino-control system, laser micrometer, and data analysis/acquisition programs.