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An Innovative Triboelectric Stent Sensor: Prospective Cardiovascular Health Monitor Device

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AN INNOVATIVE TRIBOELECTRIC STENT SENSOR: PROSPECTIVE CARDIOVASCULAR HEALTH MONITOR DEVICE

A Thesis

By

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ABSTRACT

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Previous research that has focused on TENGs have lacked the proper application of this energy generator. Currently, heart disease remains the leading cause of death in the United States. With increasing demand for self-sustainable medical devices, this nitinol health monitor sensor device (NHMS) integrates the TENG applications with medical applications. The NHMS features memory shape nitinol electrodes that preserves the device structure while using PDMS and PVDF triboelectric effect to measure heart rate, blood pressure, and breathing patterns. Three constant pressures were measured in this study. At a constant pressure of stage 1, the NHMS produces an average AC of .31 volts. At stage 2, the NHMS produced .49 volts, and at stage 3, the NHMS produced .71 volts. Several beats per minute (bpm) were measured and clear readings were obtained from 30 bpm to 180 bpms. Furthermore, additional applications for energy harvesting and defibrillator capabilities are explored. Implications are discussed.

DEDICATION

To my beautiful wife Karla, there are no words to describe how thankful to God I am for you. You are my answered prayer, my best friend, my cheerleader, and the love of my life. Holding fast to God and each other, we can conquer anything. This master's degree is yours, and all I have is yours now and forever. I love you Karla Cecilia Vidaurri.

A mi hermosa esposa Karla, no hay palabras para describir lo agradecido que estoy con Dios por tu vida. Tu eres mi oración contestada, mi mejor amiga, mi animadora (porrista), y el amor de mi vida. Aferrándonos a Dios y al uno al otro, podemos sobresalir en cualquier circunstancia. Esta maestría es tuya, y todo lo que tengo es tuyo hoy y para siempre. ¡Te amo Karla Cecilia Vidaurri!

To my parents Antonio Vidaurri and Maria Vidaurri Romero, thank you for the unconditional support. At a young age, you all taught by example, values which I guard in my heart and mind. Thank you for teaching me to work hard and above all else, for encouraging me to build a relationship with God. You are both a blessing in my life, I love you all very much.

A mis padres, Antonio Vidaurri y Maria Vidaurri Romero, gracias por todo su apoyo incondicional. Desde pequeño me ensenaron con ejemplo, valores que guardo en mi mente y corazón. Gracias por motivarme a echarle ganas y más que nada, por encaminarme en el camino de Dios. Ustedes son de gran bendición en mi vida, los quiero mucho padre y madre.

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To Dr. Javier Macossay-Torres, thank you for your assistance, guidance, and kindness during my graduate career. Your lectures, stories, and support allowed me to identify my passions in the field of chemistry and polymers.

To Dr. Karen Lozano, I appreciate all the time and support you gifted me in order to enhance my success. I am very grateful to have gotten to know you in my time at UTRGV.

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CHAPTER I

INTRODUCTION

With the looming threat of resource depletion in today's modern society, the demand for self-sustainable and wearable medical devices has increased significantly. Triboelectric Nanogenerators (TENGs) possess the capabilities to efficiently produce and harvest electrical energy from mechanical energy in a small-scale and self-sustainable manner [2]. A triboelectric effect is created when two composite material surfaces come into contact, the flow of electrons between the two surfaces initiates to balance the potential, ultimately generating an electric current [10]. In addition, TENGs are biocompatible and cost-effective, making them especially appealing for biomedical use [4].

Moreover, heart disease remains the leading cause of death in the United States, with Coronary Artery Disease (CAD) being the most common type of heart disease [5-6]. CAD occurs as a result of plaque accumulation in the walls of the coronary arteries, ultimately leading to hardening and narrowing of the arteries, and may eventually lead to organ failure [22]. To combat this issue, stents are often introduced and inserted into patients who suffer from atherosclerosis and other coronary artery diseases to expand the arteries and improve blood flow to the heart [20, 21]. Coronary stents are flexible and exhibit tremendous radial strength due to their scaffold structure and construction [21]. Here, in this project, we develop a distinct and innovative TENG-powered Smart Stent device that serves as an implanted tactile sensor to

monitor pulse, blood pressure, and electrodes of the heart while allowing for adequate blood flow to the heart. The structural design and concept of the coronary stent were incorporated into this device and modified to better suit the functionality of a health monitoring device.

Nitinol, a nickel-titanium alloy, has become highly regarded in the biomedical industry due to its super-elasticity and pseudo-elasticity— or thermal shape memory behavior [11]. Its effect is reversible between austenite, a gamma phase metal, and martensite. Martensite is a steel crystallized structure that allows nitinol to change shape. When heated at high temperatures, martensite will turn into austenite, allowing nitinol to return to its original shape [23]. Nitinol's distinct features make it especially favored in medical devices that are required to be implanted or inserted through arteries with complex pathways and has become especially popular for the design of cardiovascular stents [11]. Another vital component of Nitinol's features is its strong corrosion resistance, which is imperative as stents are expected to maintain integrity until surgical removal is necessary [22].

In this project, we utilize poly (vinylidene fluoride) (PVDF) and polydimethylsiloxane (PDMS) as the coating of the nitinol wires for their outstanding features, most prominently their salient abilities to produce a Triboelectric Effect [18]. PVDF presents as five different crystalline polymorphs-- α, β, γ, δ and ε phases. β phase PVDF generates the best piezoelectric properties due to its significant dipole moment, which can be achieved through quenching and annealing among other specific conditions. [19]. To attain the greatest results of electric current, β phase PVDF was chosen as the ideal standard for PVDF coating of the Nitinol wires. Furthermore, PVDF is highly favored due to its large remnant polarization and good thermal stability, while PDMS is highly regarded due to its biocompatibility and highly elastic abilities [12, 19]. It is

essential that both PVDF and PDMS are biocompatible as the Smart Stent will be surgically implanted into the arteries.

Health care monitoring sensors have also gained considerable recognition in the biomedical industry due to their abilities to detect vitals and data from the human body in the form of mechanical energy to better assist in medical diagnoses and health assessments [3]. This medical device would utilize the otherwise “wasted” energy produced from the constriction of the arteries to sense abnormal heart rates and harvest the energy to power the device itself [13].

About 3 million people in the United States have implantable pacemakers due to old age, heart diseases, and other heart disorders, including arrhythmias— which are prevalent in about 1.5% to 5% of the general population [14, 15]. Although pacemaker insertion surgical procedures are considered minimally invasive, risks and complications can occur during the surgery and postoperative [8, 16]. Battery exhaustion is found to be the factor of greatest concern in regards to implantable pacemaker reliability, resulting in longevity being one major drawback of permanent pacemakers [17]. When artificial pacemakers are no longer able to function properly, they must be surgically replaced, which can be costly and potentially lead to further complications for the patient.

This project focuses on innovating a self-powered Smart Stent device that monitors health and relies on TENG, thereby eliminating the need for traditional battery sources. Thus, this nitinol health monitor sensor NHMS serves as an implanted tactile sensor to monitor pulse and blood pressure.

CHAPTER II

METHODOLOGY

2.1 Shaping and Annealing of Nitinol

Nitinol was used as the electrodes. The Nitinol was purchased with an activation temperature of 30^0 Celcius. The nitinol annealing process is as follows: First 3cm of 4 nitinol wires were twisted and intertwined with each other, after 3cm the wires were separated. The wires were then secured with stainless steel clamps and were heat treated with a blow torch. Immediately after heat treatment the nitinol wires were quenched in oil and cleaned. A second set of wires were similarly made for the opposing electrode. Both electrodes were then weaved together like a Chinese finger trap with a length of 15cm and a diameter of 1cm with the ends left separated. Both electrodes were secured, heat treated, quenched, and cleaned. After the application of the triboelectric materials, the ends were intertwined, heat treated, quenched, and cleaned. New coating of triboelectric materials was established on the ends of the electrodes.

2.2 Doping of Nitinol wires in Polydimethylsiloxane (PDMS)

PDMS (184 Silicone Elastomer, Dow corning Co. Ltd.) and PVDF were used as the triboelectric materials for the NHMS.The PDMS fabrication process is as follows: The PDMS and curing agent were mixed in a weight ratio of 10:1 by stirring with a magnetic stir rod for 10 minutes and degassed in an ultrasonic resonator for 10 minutes. One of the nitinol electrodes was coated with the PDMS using the dipping method and dried overnight at 120º C in an oven.

2.3 Doping of Nitinol wires in Poly (Vinylidene Fluoride) (PVDF)

The PVDF fabrication process is as follows: an oversaturated PVDF solution was made using PVDF and DMF. The solution was stirring overnight at 70º C with aluminum foil to prevent degradation. The second electrode was coated with the PDMS using the dipping method and immediately hydro dipped to obtain the PVDF beta phase. The electrode was left to dry for 5-10 minutes at 120º C in an oven. The PVDF was constantly checked for PVDF deterioration and would immediately stop drying with any sign of deterioration.

After the application of the triboelectric materials, the ends were intertwined, heat treated, quenched, and cleaned. A new coating of triboelectric materials was established on the ends of the electrodes.

CHAPTER III

RESULTS

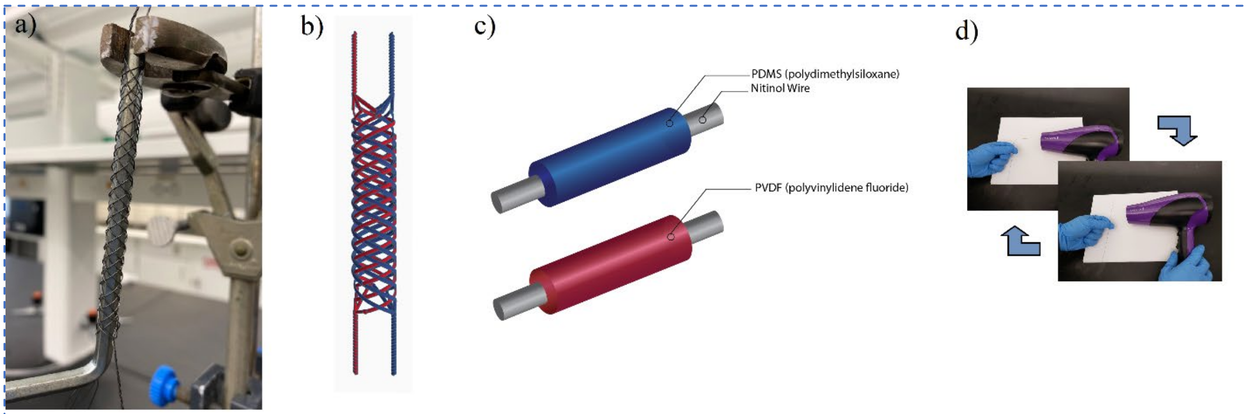

Figure 1: Schematics of NHMS. a) Picture of the NHMS. b) 3D view of the NHMS. c) Components of the NHMS. d) Memory shape capability of nitinol at 30^0C.

Figure 1 depicts the schematics of the Nitinol health monitoring sensor (NHMS) with a real-life view of the sensor in Figure 1a). The photo depicts the weaving of the nitinol wires intertwined like a Chinese finger trap with a metal rod in between to show the hollow structure of the NHMS. This structure is the established structure of the NHMS that was permanently placed through the annealing and quenching procedures of the nitinol wires. Figure 1b) and 1c) show the 3D Model of the NHMS with Figure 1c) showing the composition of the sensor. The models depict two opposing coated electrodes that disperse into four color coded opposing electrodes that intertwined with each other. The opposing electrodes converge to their corresponding polar

electrodes at the end of the sensor. Figure 1d) show the capabilities of nitinol's memory shape at 30^0 Celcius.

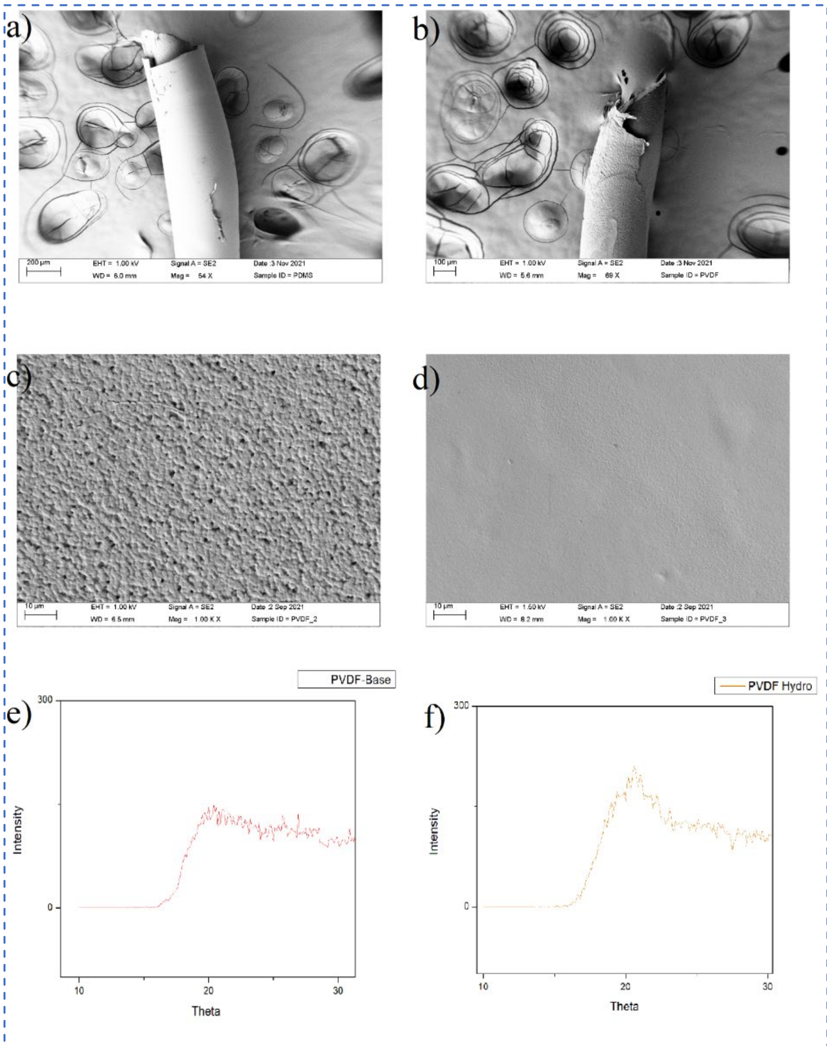

Figure 2: Characterization of NHMS. a) SEM of PDMS. b) SEM of PVDF. c) SEM of base PVDF. d) SEM of hydrodipped PVDF e) XRD of base PVDF. f) XRD of hydrodipped PVDF.

Figure 2 shows the SEM of PDMS and the PVDF coating of the nitinol wires in a) and b). The PDMS acts as a non-polar opposing layer with rough characteristics as shown in the SEM while the manufacturing process of the PVDF creates a polar smooth piezoelectric/triboelectric layer as

shown in the SEM. A comparison of the PVDF manufacturing method is shown on c) and d). Figure 2e) shows the XRD of basic PVDF while f) shows beta-phase PVDF polar film produced through the manufacturing process.

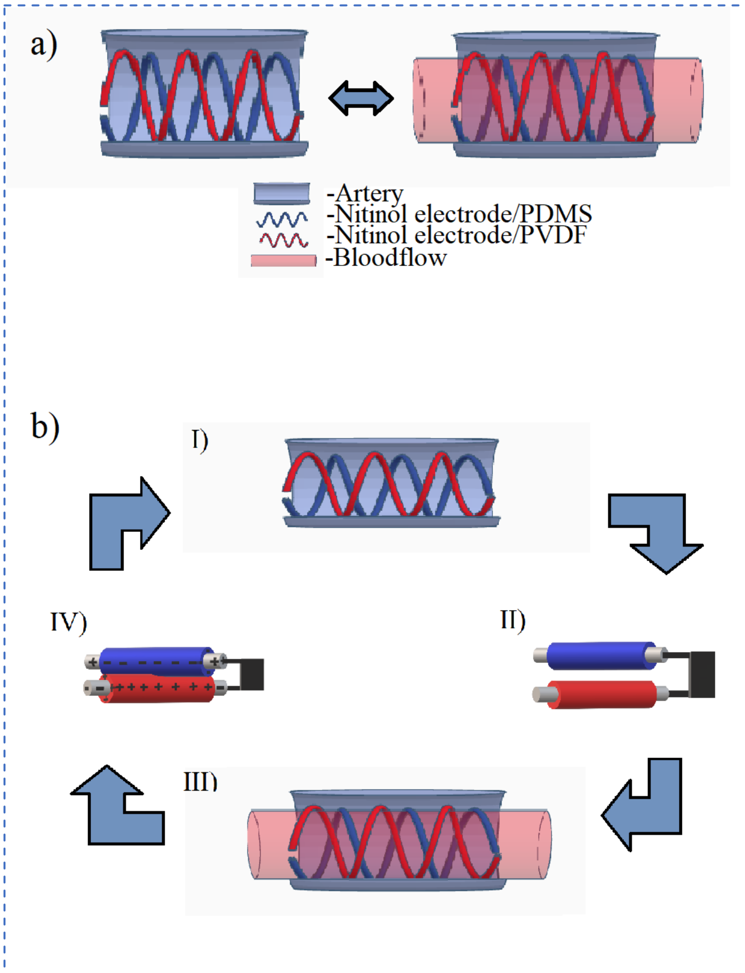

Figure 3: Mechanism of NHMS. a) Resting & active phase of NHMS in the artery. b) Mechanism of NHMS in an artery. I) Resting phase of an artery. II) separations of NHMS due to body heat. III) active phase of an artery. IV) Compression of NHMS due to blood flow.

Figure 3 depicts the overall mechanism and the data produced from the NHMS. Figure 2a) portrays the contact separation process of the NHMS as it is placed in an artery of the human body. Figures I) and II) show the resting phase of an artery with the NHMS. In this phase the heat of the human body with an average of 37º Celsius resets the established structure of the NHMS with an activation temperature of 30º Celsius. Figure iii) and iv) depict the active phase of an artery with the NHMS. As the cardiovascular system pumps blood throughout its system, the pulse and pressure of the blood flow compresses the NHMS producing opposite polarities and electron floe for the nitinol electrodes. The artery then enters the resting phase and the nitinol sensor restructures itself to its established shape which is the separation phase of the NHMS. Thus, the pulse and heat cycle repeat itself without any interference.

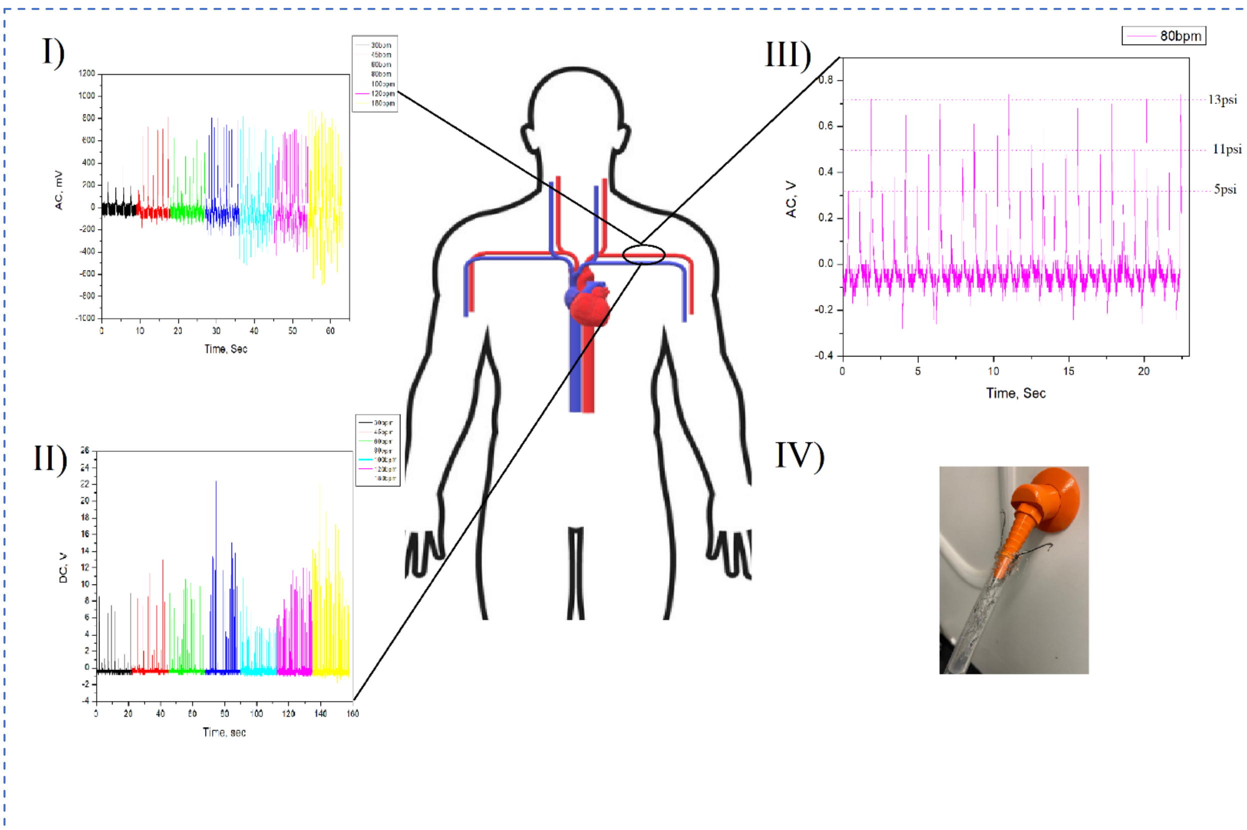

Figure 4: Sensor capabilities of the NHMS. I) AC in mV of different bpms at no constant pressure. II) DC in V of different bpms at no constant pressure. III) AC in V of alternating pressure of 5psi, 11psi, and 13psi at 80bpm. IV) MAkeshisft Artery.

Figure 4) shows the accumulated data of the simulated artificial artery with the NHMS. Figure 2, III) illustrates the alternating current in volts of the sensor at stage 1 of 5psi, stage 2 of 11psi, and stage 3 of 13psi. The constant pressures alternate from 5 to 11 to 13psi and repeat. This figure shows a constant plateau with an average of .31V at stage 1, a constant plateau with an average of .49V at stage 2, and a constant plateau with an average of .71V at stage 3. This shows that this HNMS has the capabilities of tracking and sensing different arterial pressures as shown by the data collected. This device can be furthered developed and customized to monitor blood pressure with definite accuracy. Figure 2, I) and II) continues to show beats per minute at no constant pressure. The graph shows a contrast from 30 bpm, 45 bpm, 60bpm, 80bpm,100bpm, and 120bpm with precise indication of every beat. Further adaptation and enhancement can provide an accurate reading of the heart rate in the cardiovascular system. Figure2, II) shows the direct current in volts of the NHMS from 30 bpm, 45 bpm, 60bpm, 80bpm,100bpm, and 120bpm with no constant pressure. The highest DC voltage was recorded at 24 Volts. This figure depicts that the sensor can be modified to produce DC voltage that can not only be used as a sensor but as a nanogenerator for similar type of cardiovascular devices. With further adaptation the device is capable of recharging similar type of cardiovascular devices and prolong battery life. The NHMS can be customized to act as a defibrillator. The AB nodes produce a voltage of .13 volts to contract the heart. The NHMS maximum output of 24V can travel through the device and through the sensor and into the cardiovascular system as shown in Figure 4.

CHAPTER IV

DISCUSSION

In this study, we developed a heart-health monitoring smart stent device that relies on TENG as its main power source to promote sustainability and cost-effectiveness in the biomedical industry. The voltage and current of the NHMS was measured with alternating constant pressures applied to the sensor stent. In addition, AC and DC was measured with different bpms at no constant pressure. The maximum AC energy output was recorded at 1000mV at 180bpm along with a DC of 24V at 180bpm. When measuring at a constant pressure of 5psi, an average of .31V was recorded at 80bpm. When measuring at a constant pressure of 11psi, an average of .49V was recorded at 80bpm. When measuring at a constant pressure of 13psi, an average of .71V was recorded at 80bpm. Thus, the recorded voltage and current reveal that correlation can be made between arterial pressure and voltage. Moreover, a correlation can be made between signals, time, and beats per minute in the cardiovascular system. Most importantly, the output from the NHMS showed defibrillating capabilities, health monitoring applications and energy generating applications. Consequently, in order for this device to function properly, electrical engineering customizations need to occur to detect any heart rate and electrical activity read by the NHMS. However, During the production process, ensuring that PDMS coatings don't disintegrate in the arteries can prove itself to be the biggest challenge. The removal of the PDMS layer may resolve the issue of the decomposition of PDMS into the

cardiovascular system and transform this sensor from a TENG to a PENG. However, without a layer of the opposing nitinol layer, deterioration of nitinol could be detrimental to the cardiovascular system. Future research studies need to address this concern. Furthermore, the application of health monitoring with the materials utilized in this project can be further enhanced to develop a Smart Pacemaker Sensor.

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APPENDIX

APPENDIX

FIGURES

Figure 1

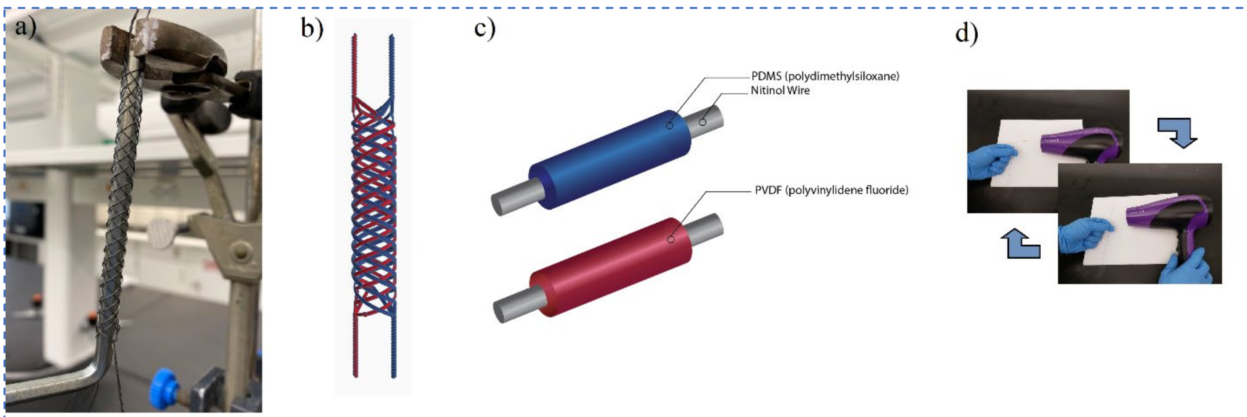


Figure 2

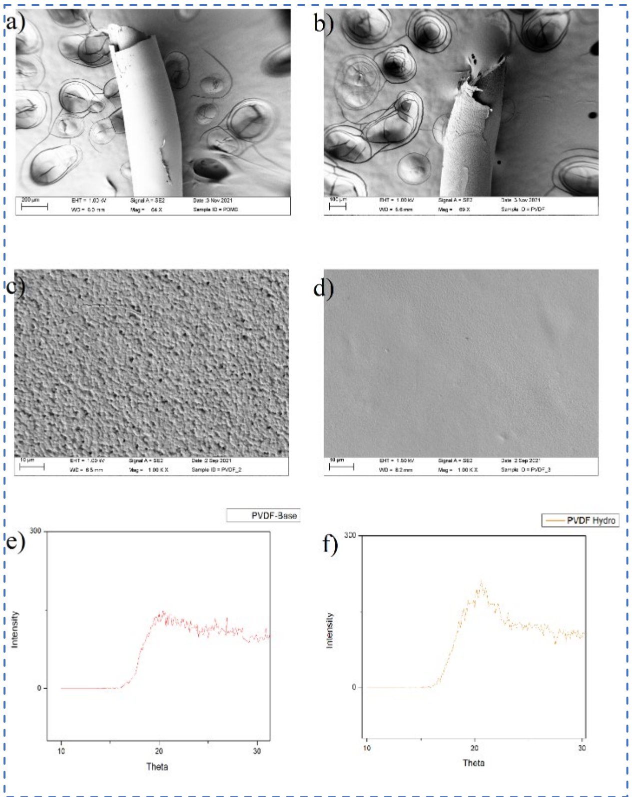


Figure 3

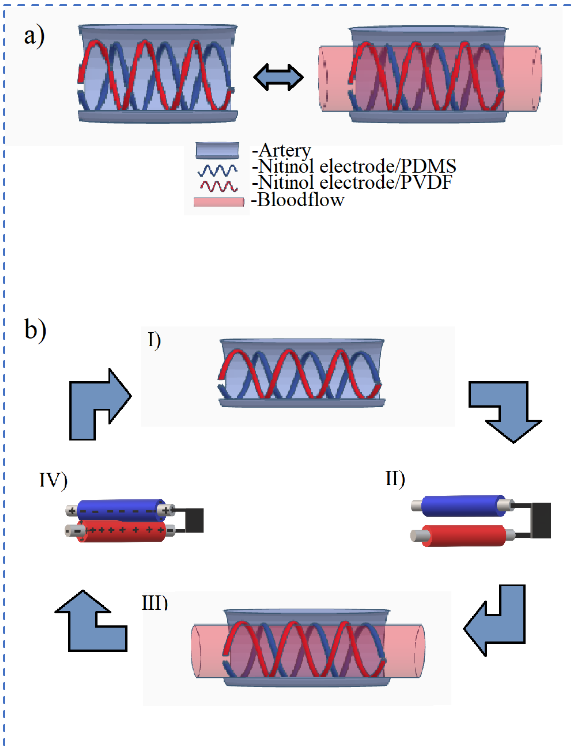
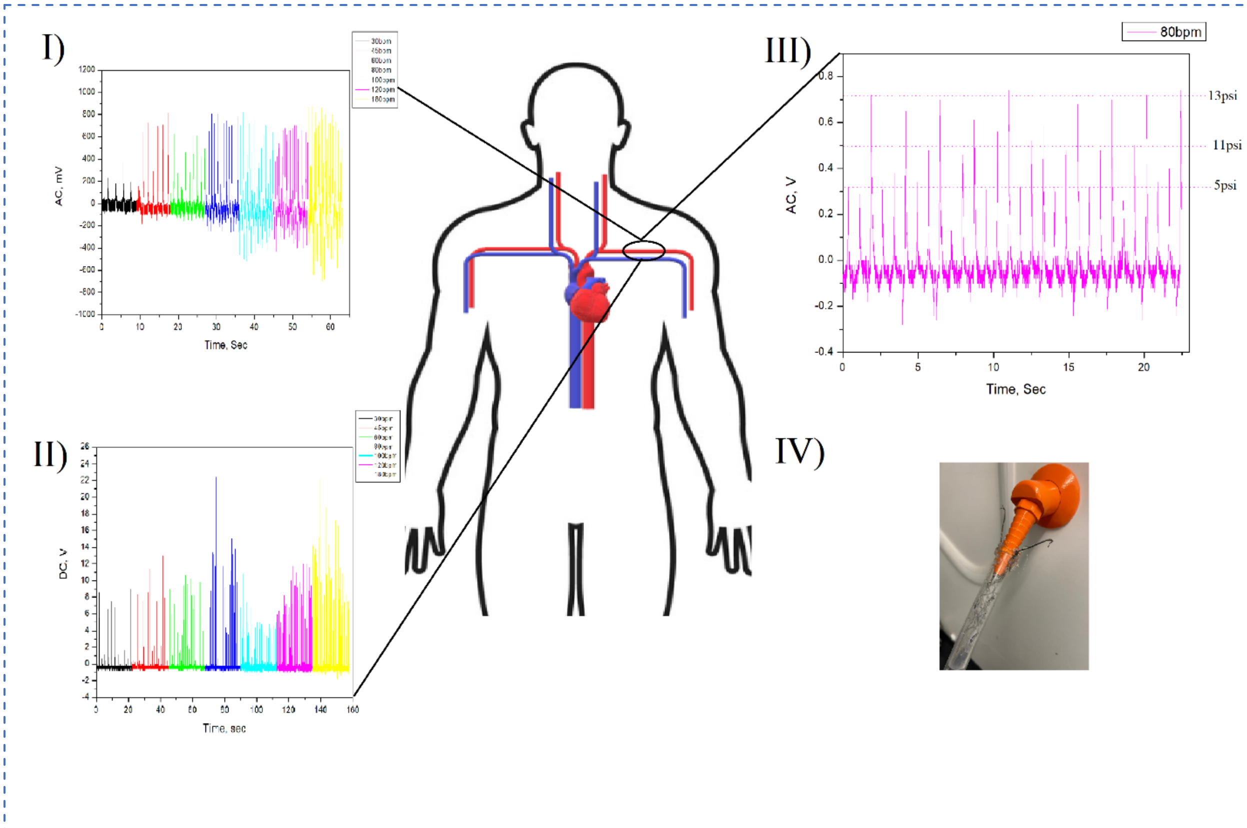

a)
-Artery
-Nitinol electrode/PDMS
-Nitinol electrode/PVDF
-Bloodflow
b)
I)
II)
III)
IV)

Figure 4


I)
AC, mV
Time, Sec
30bpm
45bpm
60bpm
80bpm
100bpm
120bpm
180bpm
II)
DC, V
Time, sec
III)
80bpm
AC, V
Time, Sec
13psi
11psi
5psi
IV)

BIOGRAPHICAL SKETCH

Ulises Genaro Vidaurri Romero was born and raised in Brownsville, Texas. Ulises began his education at the University of Texas-Pan American, which later merged and became the University of Texas Rio Grande Valley. He completed his Bachelor of Science in Chemistry in December 2018. After working as a chemistry technician for one year, he pursued a Master of Science degree, where he graduated in December 2021. During his tenure as a graduate student, Ulises was a member and lead graduate student of the Photonic and Energy Research Lab at UTRGV. Ulises became involved in research since his undergraduate career and has since then presented at several conferences. Ulises plans on pursuing job opportunities in the areas of science and engineering focusing on polymers and materials. Ulises can be reached by email at uvid19@gmail.com.