Design of a low-cost, portable, and automated cardiopulmonary resuscitation device for emergency scenarios in Ecuador.

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***Abstract*— Approximately 90% of patients who suffer out-of-hospital cardiac arrest die [1]. In these cases, when a cardiopulmonary resuscitation (CPR) maneuver is needed, rescuer fatigue is a problem because more than 2 minutes of continuous CPR translates in defective delivery of the resuscitation technique [2]. In rural areas, this problem has two main components: first, lack of access to trained professionals with adequate emergency medical equipment, and second, the long delay to receive immediate medical care [3]. After the 7.8-magnitude earthquake in Ecuador on April 2016, first responders were unable to deliver CPR to hundreds of victims, resulting in preventable deaths [3]. Though automated CPR devices such as the AutoPulse, ROSC-U, and LUCAS-2 exist, the prohibitive cost of such devices (more than $12,000) make them inaccessible for hospitals in Ecuador. Therefore, there is a dire need for a low-cost, portable, automated CPR device to combat lack of access to emergency medical equipment and rescuer fatigue, while keeping patients alive long enough to endure transportation to a medical facility. To address this need, we have designed and manufactured a portable automated CPR device that costs $1290 and weights 4.5 kg. The device can be powered by any car or boat battery, and is equipped with a backup battery. Effective CPR can be administered following the American Heart Association guidelines, using a dual crank mechanism driven by a drill motor to provide at least 5-6 cm of chest displacement at 120 compressions per minute [4]. The device is easy to use, and can be operable on-site with minimal training to emergency personnel.**

Keywords—Cardiopulmonary resuscitation, low-cost, portable, automatic, emergency, medical device, Ecuador.

I. Introduction

In Ecuador, medical personnel should complete their preparation by doing community service in poor rural zones; where in most cases there is very little medical technology. Every year there are about 3940 newly graduated doctors available for rural medical centers serving a population of 5'900.400 habitants [5]. This means that in most cases the newly appointed doctor is left in charge of one rural medical center serving 1500 people without medical diagnostic technology and with help of poorly trained nurses. The available ambulances are usually inadequately equipped and, in emergency scenarios where a patient with cardiac arrest needs to be transported to a major hospital, the rural doctor has to perform CPR during the whole trip. Considering the high physical and mental demand of the CPR maneuver, it is evident that as the maneuver continues, the probability to execute it correctly decreases. A good CPR could be maintained for no more than 8 minutes by males and 2 minutes by females with good athletic condition, as indicated in a study published by Wang et al [4]. Therefore, it is clear that fatigue affects adversely the performance of CPR [4]. To aggravate the situation, un-official statistics indicate that less than 1% of the general population is qualified to perform a cardiopulmonary reanimation, so the doctors and emergency personnel are left alone in this task. The importance in developing a safe, automatic and portable CPR medical device resides in the need to have a reliable method to properly perform cardiopulmonary reanimation during emergency scenarios, like the earthquake that struck Ecuador in April 2016, leaving 670 victims [6]. Emergency response teams from several medical schools in the country estimated that dozens of victims died in the after-hours of the earthquake as a result of inadequate CPR maneuvers while they were transported to medical centers.

CPR is an emergency procedure in which a person needs to compress the thorax and assist with mechanical ventilation to a patient that has suffered cardiac arrest. According to the latest advanced cardiac life support guidelines [2], an excellent CPR is defined as compressions without interruption with an appropriate force, deflecting the chest 5-6 cm deep, at a rate of 100-120 cycles per minute, while allowing the thorax to recoil completely [2]. If the patient is intubated, there are required 6-8 ventilations per minute, and if not, 2 ventilations after 30 compression [2]. Following this guidelines, the patients could double or triple their chances of survival [3]. Unfortunately, as it is stated by the American Heart Association, "only 46% of cardiac arrest victims get CPR from a bystander and only about 10% of people who suffer cardiac arrest outside the hospital survive" [3]. Consequently, the need to create cost-effective and efficient CPR medical devices in Ecuador is extremely high. Thus, *we aim to improve early treatment for cardiac arrest cases by providing an easy-to-use CPR device that could reduce the elevated mortality rate in these cases.*

II. CPR Device Design

A. Understanding the medical physiology of the heart in health and disease.

In order to design an appropriate CPR device, we should consider some physiological aspects about the cardiovascular system with and without cardiac arrest. The heart is a pump with four chambers, the two upper chambers are the right and left atria, and the two lower chambers are the right and left ventricles (Figure 1). The heart has four valves, the tricuspid

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valve between the right atrium and right ventricle, the pulmonary valve between the right ventricle and pulmonary artery, the mitral valve between the left atrium and left ventricle, and the aortic valve between the left ventricle and the aorta. The right side of the heart is in charge of receiving venous deoxygenated blood and pumps it to the lungs for oxygen and carbon dioxide exchange. The left side of the heart receives the oxygenated blood from the lungs and pumps it to the systemic arterial system in order to perfuse tissues and maintain normal metabolic functions. The amount of blood expelled by ventricles is called cardiac output (CO) [7]. In a healthy person with a normal cardiac function, CO is about 5-6 l/min and depends on stroke volume (SV), which is the amount of blood ejected by each ventricle per beat, times the heart rate (HR) [8].

$$CO = SV * HR \tag{1}$$

In a whole cardiac cycle there are two phases: diastole and systole. It is important to know that left and right heart chambers work together, and pump the same amount of blood at the same time [8]. Diastole is the longest phase in which ventricles relax and start filling up with blood. Diastole lasts at least two-thirds of the total cardiac cycle. Systole is the process in which the ventricular muscle contracts and ejects blood either to the lungs or the systemic circulation [9].

Cardiac arrest is the cessation of cardiac activity in which heart stops pumping out blood, and there is no oxygenated blood for tissues and organs [8]. After a few minutes of cessation of blood perfusion, reversible brain injury starts [9]. Researchers have indicated that the intensity of neuropathological damage correlates well with the duration of the cardiac arrest [10]. The underlying mechanisms of the neurologic and cardiac damage are not discussed here and can be found elsewhere [10]. Many of the casualties during the Ecuador earthquake in April 2016 suffered hypovolemic shock due to hemorrhage with the subsequent cessation of cardiac activity (i.e. cardiac arrest) (Figure 1B). The medical emergency solution in this case is defibrillation and chest compressions which have to be 5-6 cm in depth in order to beat the thoracic pressure far enough so that the heart can be squeezed between the sternum and thoracic spine [11]. Chest massage and compressions would make the pressure increase in the heart chambers, making blood flow reach the brain and the coronary heart arteries [11]. Having high quality compressions could increase the chance of survival after a hypovolemic cardiac arrest with a good neurologic outcome [2].

B. *CPR Device requirements and specifications*

Table 1 includes specifications of the automated CPR device. This table is not exhaustive but includes the most important requirements to take in consideration before manufacture. A ranking system of 1-5, with 5 being highest priority and 1 the lowest, was used to determine the importance of each specification category.

III. CPR DEVICE MANUFACTURE AND VALIDATION

A. *Description of autoCPR components.*

The proposed solution to the design problem draws on a piston design inspired by the LUCAS2, Thumper®, and ROSC-U CPR devices. Our solution utilizes a crank mechanism to convert rotational motion provided by an electric motor into linear motion of a piston-like device. The device can be divided into three components: compression, frame, and electrical.

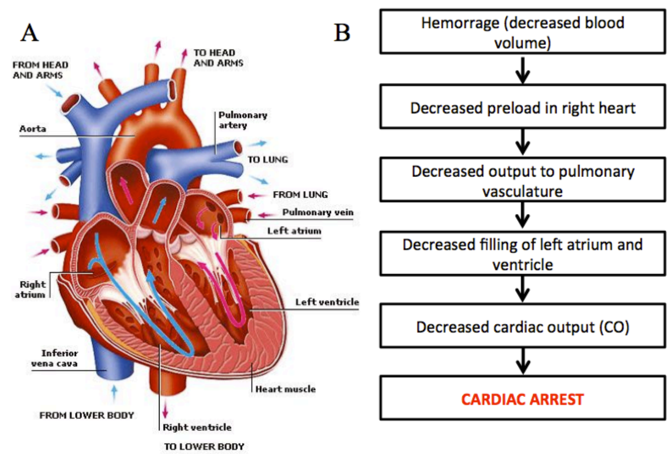

Figure 1. (A) Drawing of the normal anatomy of the human heart. **(B)** Pathophysiology of hypovolemic shock, which can lead to cardiac arrest.

TABLE I. CPR DEVICE REQUIREMENTS

Category / Ethical or Hazard	Need	Design Specification	Weight
Compression Parameters / Hazard	CPR Functionality	The device must be able to compress the chest – specifically the sternum – to a depth of 2-2.4 in. (5-6 cm) [3].	5
	CPR Functionality	The device must be able to perform chest compressions at a rate of 100-120 compressions per minute [3].	5
	CPR Functionality	The device must be able to deliver at least 150lbf of compression to achieve the desired displacement design specification and overcome chest resistance [12], [13].	5
	CPR Functionality	The chest must be allowed to fully recoil between compressions; therefore, the chest should displace 0-6 cm [3].	5
	Compression surface area	The contact surface area between the chest and piston should be no larger than 28 cm^2, the contact area of the LUCAS2 [13].	4
	Location	The piston must be aligned over the lower half of the sternum [14].	5
Patient Parameters / Hazard	Target Population	The device must be designed to administer CPR to adults [15].	4
	Target adult patient chest circumference	The device can accommodate patients with a chest circumference of 76 - 130 cm or 29.9 – 51.2 inches [16].	4
	Target adult patient sternum heights	The device can accommodate patients with sternum height of 6.7-11.9 inches [17].	4
Physical Device / Hazard	Portability	The device must be portable and fit in the back of emergency vehicles such as a police car or ambulance, which means the device should take up less than 16 cubic ft. of space [15], [18].	3
	Portability	Device must weigh less than 50 pounds per OSHA lifting guidelines [19].	3
	Easy to use in emergency situations	The device must take less than 3 minutes to assemble because CPR is most effective within 4-6 minutes after the patient collapses [20].	5
Environmental / Hazard	Withstand environmental conditions of Ecuador	The device must be able to work in a temperature range of 0-42 degrees Celsius at up to 100% humidity [15].	5
	Drop test	The device must withstand a drop test of 0.5 m as per ASTM D5276 [16].	3

Compression mechanism: The auto-CPR uses a dual crank mechanism powered by a DC electric motor to generate the necessary chest displacement for compression (Figure 2). The DC motor is powered by a 12 Volts car or boat power supply to allow continuous use during patient transportation. The motor turns the crank, which transfers the torque generated by the motor into linear compression of the chest. The mechanical design of the crank ensures 5.0-6.1 cm of displacement, and the choice of motor ensures at least 125 pounds-force of linear compressive force to be delivered via the crank mechanism to overcome chest resistance.

Frame mechanism: The frame includes an aluminum plate that the base of the crank mechanism (Figure 3). The plate is to be aligned over the lower half of the sternum of the patient (Figure 2A). A strap attached to the plate goes around the chest of the patient and is tightened using a quick-tight cam buckle. This strap/plate frame is a simple, low cost way to secure the crank mechanism over the patient and accommodate a wide range of chest sizes (Figure 2C). The autoCPR device is able to accommodate patients of varying sternum heights, with a range from 17 to 30.23 cm, and chest circumferences ranging from 76 to 130 cm.

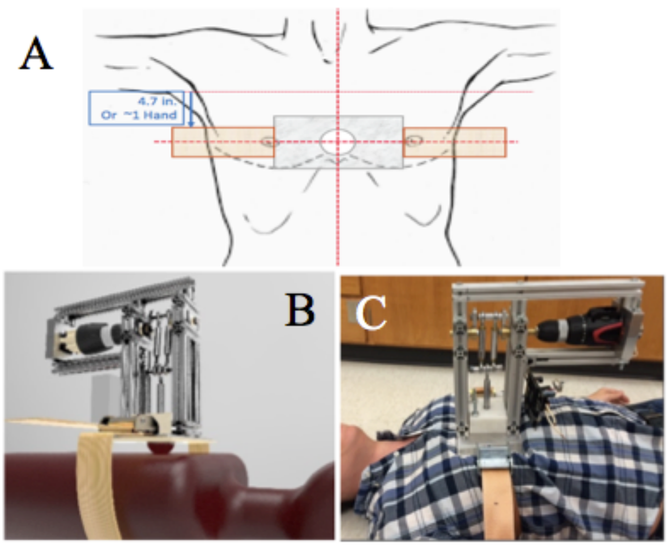

Figure 2. **(A)** Anatomical drawing of the correct placement of the autoCPR device on the chest of the patient. The compression piston is placed at the midline of the chest, between the nipples and over the sternum. **(B)** Digital rendering of the dual crank system with integrated electronics, band frame, and robust housing. **(C)** Correct placement of autoCPR device on top of a human model.

Electrical mechanism: The autoCPR device is driven using an electronic control system (Figure 4). Two jumper leads take power input from a high current 12V source. The 12V source is sufficient to power the autoCPR device because it is capable of providing at least 25 Amperes for at least 45 minutes. The power source is directly attached to a high-current motor driver capable of regulating up to 30 Amperes. The motor controller connects to a 12 Volt motor capable of delivering at least 180 inch-pounds of torque. The motor controller is connected to a simple ON/OFF switch and potentiometer. For safety purposes, both controls can turn off the device, but the ON/OFF switch is required to be ON before the device is operated. The potentiometer can regulate the current to the motor, which allows the user to easily control the rate and power of compressions.

To design the electronic circuit, all exposed wiring was eliminated, and 12AWG solid copper wiring was used to connect the motor controller to the motor. This wiring was also used to connect the motor controller to two standard jumper-bolt terminals to which leads could be safely attached to provide power to the device (Figure 5A). An electronics box was 3D printed (MakerBot Replicator+, MakerBot Industries, NY, USA) in polystyrene plastic to fit and enclose the motor controller and wiring connections. The box protects the electronics subsystem from water damage, while isolating the high-current systems from the operator and patient.

B. CPR device performance

The autoCPR has been verified to meet the compression depth and rate requirements. It has been tested to successfully achieve compression at a chest resistance of 75 pounds in a CPR manikin (Figure 5B). The design of the crank system automatically achieves a compression depth of 5.0 cm. The device can compress at a rate anywhere from 100-120 compressions per minute, which can be varied by the user with the potentiometer. An audible click from the manikin was used to verify that the device successfully achieved one compression. The device was tested to run continuously for several cycles of two minutes and 220 compressions each cycle without any problems.

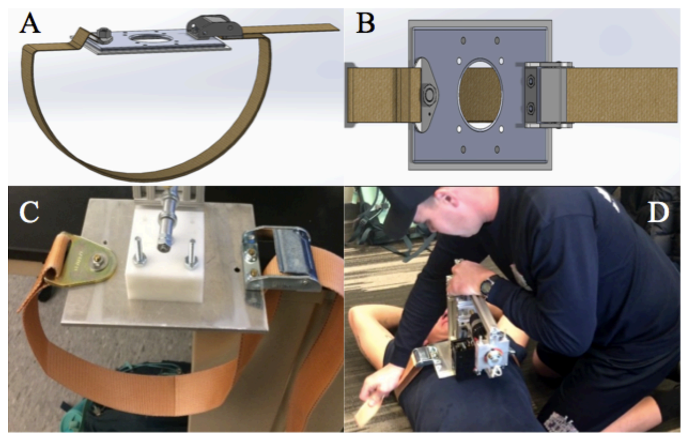

Figure 3. **(A)** CAD-generated model of the lateral view of the frame. **(B)** Top view of frame CAD model. **(C)** Frame prototype integrated with part of the compression device. **(D)** Firefighter securing the autoCPR device around the chest of a volunteer.

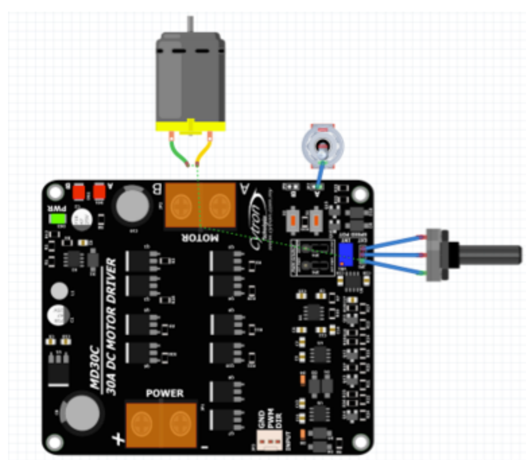

Figure 4. Layout of the electronic circuit that drives and controls the autoCPR device.

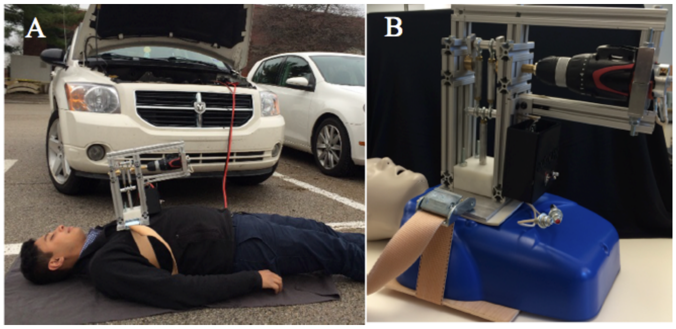

Figure 5. **(A)** The autoCPR device connected to a standard car battery using two jumper-bolt terminals. **(B)** Setup of the autoCPR device on a CPR manikin during performance evaluation.

IV. DISCUSSION AND CONCLUSION

The autoCPR device innovates in areas where existing devices don't address needs of emergency first responders in rural and developing areas. The autoCPR device has a primary focus on delivering effective CPR in the most compact, minimalist, and super-portable manner. The innovations in the crank design allow for delivering the required chest compressions. Existing devices use expensive electric actuators, while a crank and inexpensive DC motor can provide the same force and displacement required at a fraction of the cost. Innovations in the strap design allow emergency personnel to deploy the device on a patient in less than 30 seconds. The strap design also allows for a secure attachment of the device to the patient during transportation to medical facilities. The electronics component of the device allows for full versatility and portability. The device can be powered by any standard 12 Volts power source (Figure 5A). The electronics innovation is focused on powering the device from a car, boat, or auxiliary battery during transportation.

Now, the largest benefit of Manual CPR is that it requires no external instruments or special conditions in order to save lives. However, the overall survival rate for a person undergoing an out-of-hospital cardiac arrest (OHCA) is about 10%, as reported by the 2012 Utstein Survival Report published by the Cardiac Arrest Registry to Enhance Survival [21]. Much of this low survival rate has been attributed to rescuer fatigue and lack of training [22]. Because of these problems, many automated CPR solutions have been developed. The Thumper®, by Michigan Instruments, was one of the first to reach the market – the company has recently developed Life-Stat® in what seems to be an attempt to meet more modern CPR guidelines set by the American Heart Association (AHA). These two devices rely on piston-based mechanisms in order to compress the chest [23] [24]. However, neither deice is currently being sold, and neither are portable enough for use in emergency first response situations.

Another prominent device on the market is the LUCAS™ 2 by Physio-Control, Inc. The battery-powered LUCAS™ 2 consists of a support structure to place the patient in, as well as a compression mechanism, which is pneumatic-based. The compression mechanism is essentially a vertical linear actuator that pushes down on a patient at a rate of 102 strokes per minute. It can operate continuously for 45 minutes, which can be prolonged if connected to an external power supply. It takes about 4 hours to charge the battery. The system can perform only chest compressions but has the option to pause for 3 seconds between every 30 compressions to allow for rescue breaths to be administered. The assembly time for the system is about 20 seconds for Emergency Medical Service (EMS) professionals trained in the use of LUCAS™ 2. During assembly, manual CPR must be stopped in order to allow the system to fit the patient, meaning that there is a gap between manual CPR and automatic CPR [25]. A 2009 price list published by Physio-Control indicates the price of the LUCAS™ 2 system as $14,495 for sale in the United States of America [25]. Though the device does provide CPR, the high cost of the device makes it inaccessible to first responders in rural or developing areas.

The AutoPulse® by ZOLL Medical Corporation is another automated CPR device [16]. Unlike other devices, it is not piston-based. It uses load-distribution band technology to both directly compress the chest and also provide semi-circumferential thoracic compression. The device's band, or LifeBand, is the load-distributing band that can automatically wrap around the patient by analyzing the patient's size. The device can provide chest compressions with a displacement up to a 20% reduction in anterior-posterior chest depth. Despite its novel design, the AutoPulse does have height limitations and can only work with patients at or below 300 pounds. The LifeBand is single-use: a new one must be attached for each use. Training on the device is also required before using it [16]. In addition to its limitations, the AutoPulse, like the LUCAS2, is prohibitively pricey, with units available for purchase at $19,950 [26]. Its high cost makes the ZOLL AutoPulse out of reach for first responders operating in rural and developing areas.

Another product, the ROSC-U™ miniature chest compression device, is advertised as much more portable than other devices due to its low weight of around 7 lbs. It operates via an electromechanical actuator mechanism to compress the chest with a lithium ion phosphate battery source. It can perform 100 ± 5 compressions per minute and can displace the chest to a maximum depth of 5.4 cm. This equipment does not meet 2016 AHA guidelines, both in the number of compressions per minute and the maximum chest compression depth. The instructions for use guidelines recommend that only trained professionals in Basic and/or Advanced Life Support techniques, which include police-men and EMS personnel, can use this device. Another notable point is that the device can only be powered by the battery system provided. The device's limitation to only one kind of battery, its non-adherence with 2016 AHA guidelines, and the extensive training required to operate the ROSC-U, make the device inadequate for first responders in rural and developing regions like Ecuador. In addition to the device's limitations, the ROSC-U's steep price tag of $12,999 makes it unachievable for hospitals and clinics in rural and developing regions [27].

A 2014 study compared the effectiveness of automatic CPR performed by LUCAS™ 2 with that of manual CPR and found that there was statistically no difference in outcomes (30-day survival after a cardiac arrest, return of spontaneous circulation (ROSC), etc.) between the two modalities [22]. More patients also reported injuries such as chest bruises and blood in the mouth in the automatic CPR group. In a study comparing 220 OHCA cases where manual CPR was used and 66 OHCA cases where the AutoPulse® was administered, the study concluded that the AutoPulse® had a higher rate of survival to hospital, albeit caveated with the fact that the difference in survival rates and the sample sizes were not statistically significant [4] [22]. From the available literature on mechanical CPR devices, it should be noted that randomized trials testing the effectiveness of between mechanical and manual CPR lacked sufficient statistical power due to small sample sizes. Therefore, there is yet no definitive answer to whether mechanical CPR is more effective than manual CPR [21]. More research and longer randomized clinical trails are needed to find improvements to how the appropriate CPR method should be administered to increase patient survival. Nonetheless, what is known is that the existing automated CPR devices do not adequately fulfill the needs of flexibility and low-cost required by first responders in rural and developing regions like Ecuador. Thus, our autoCPR device is a promising alternative for emergency first responders to deliver adequate CPR maneuver in rural settings and increase patient survival.

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