Time to resuscitate cardiopulmonary resuscitation! The 3R/CPR: Refill-Recoil-Rebound.

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Method Article

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Abstract

Introduction Sudden cardiac arrest (SCA) remains a major health issue worldwide with gloomy outcomes due to poor perfusion of cardiopulmonary resuscitation (CPR), deemed unsuitable for hemostatic conditions, cardiotorsal anatomy, electrophysiology and thoracic biomechanics. Alternatively, we propose a new management, implementing rational mobilization of stagnant blood: *manually* with a novel technique of cardiac massage and *mechanically* with a circulatory flow restoration (CFR) device.

Methods Simulated chest compressions were performed through the 5th intercostal space in professional Lifeguards volunteers, placed in the left lateral decubitus position with raised legs and abdominal compression.

Expected results Compared to CPR, bypassing the sternal barrier, *refilling* the heart and then compressing the chest with a *recoil-rebound* maneuver (3R / CPR) can significantly promote ROSC. Results of CFR device were previously demonstrated.

Conclusion 3R/CPR adapts human morphology promoting adequate perfusion and ROSC safely, under all circumstances. Preclinical computational models can confirm the effectiveness of 3R/CPR versus CPR.

Introduction

“Science is nothing but trained and organized common sense” **Thomas Huxley** [1]

Over 1,250,000 incidents of sudden cardiac arrest (SCA) occur yearly, in North America and Europe, most often due to cardiac arrhythmia, rather than other cardiomyopathies which are usually preceded with symptoms and signs [2-6].

Etiologically, SCA can be identified by the abrupt discontinuity of organs’ perfusion following sudden ***asystole*** of the systemic ventricle, whether fibrillated or knocked-out, due to *pathophysiological* cardiac-extracardiac disorders, *physiopathological* events *or* intentionally *induced*; In-hospitals (IHCA) or Out-of-hospitals (OHCA) [7-14].

Current cardiopulmonary resuscitation (CPR) combines *four* therapeutic modalities, namely, mid-sternal chest compressions, whether manually or mechanically; mouth-to-mouth ventilation; DC shock; and invasive-CPR which includes injection of epinephrine, mechanical ventilation, extracorporeal membrane oxygenation (ECMO) known as E-CPR, implantable cardioverter defibrillators (IDC), and direct cardiac massage with cardiopulmonary bypass (CPB) under certain circumstances [15-23].

Despite progress and medical advances, the therapeutic impacts of CPR remain quite poor with a 30-day survival rate of approximately 2% [24, 25]. Most of the CPR survivors succumb within 24h after the return of spontaneous circulation (ROSC), due to multiple organs failure as result of inadequate organs' perfusion during the procedure [26].

On the other hand, cardiac arrest has become a safe procedure, performed daily by cardiac surgeons, and in almost 100% of cases the heart defibrillates and beats again after being knocked-out for a significant length of time in patients with cardiomyopathy.

This makes CPR one of the most controversial therapeutic concept in modern medical history, which requires an entire overhaul of the concept with extensive scientific research.

Previously, we have demonstrated the benefits of prioritizing immediate restoration of circulatory flow dynamics over exhorting return of heartbeat, using a noninvasive low-pressure extracorporeal pulsatile device [27], applicable in refractory and postarrest [28].

The goal of this study is to present a new technique of chest compressions to be used in the early onsets of cardiac arrest, adaptable to cardiovascular pathophysiology and thoracic biomechanics promoting potential improvements of current CPR outcome. A safer, less traumatic, more effective procedure, which can be used by a bystander and/ or a rescuer in less exhaustive efforts, outside or inside hospital environments.

INSUFFICIENCY OF CURRENT CPR

The main goal of CPR is rapid ROSC while ensuring adequate perfusion of vital organs during the procedure. In other words, we need to create an action potential at the conducting system, particularly in the walls of the right atrium (RA) and septum, while hypothetically delivering sufficient stroke volume through the aorta by compressing / decompressing the left ventricle (LV), which is almost impossible for several reasons.

As a reminder, CPR has been adopted at random in the early 1960s, following successful experiments of a pioneering engineer while proving the concept of external defibrillators on canine models [29]. However, morphologically, dogs are sorely different from humans, which makes CPR incompatible with the pathophysiology and biophysics of our cardiovascular system. For example, with a more obtuse sternocostal angle in dogs, chest compressions are performed through the left chest wall while the canine model is placed on the right side and DC shocks are delivered in anterolateral position. Besides, dogs have a well-developed coronary network promoting more frequent ROSCs in canine models unlike human and porcine models [30].

Yet, this clinical discrepancy in CPR raises a *quaternary therapeutic dilemma* that must be meticulously analyzed and resolved.

For example, CPR which is supposed to effectively manage throughout *four* phases of cardiac arrest, namely, *early onset*; *refractory*; *postarrest*, and prophylaxis, collides with *four* concomitant pathophysiological barriers that must be overcome, which are: *hemostatic state*; *electrophysiology*; *cardiotorsal anatomy*; and *thoracic biomechanics*.

First, following the *hemostatic* condition, within 30 seconds of cardiac arrest, the left-heart side which normally contains ≤10% of blood volume (BV) becomes almost empty with an aortic pressure (AP) =0 mm Hg. Similarly, the adult heart which roughly contains ≤ 400 mL of BV, unequally divided between its chambers, becomes nearly empty as part of the intracardiac blood moves backward–forward through the low-pressure valveless vena cavae and the pulmonary artery. Consequently, the stagnant venous capacitance increases, and the venous pressure rises from ≤ 0mm Hg to ≥20 mm Hg [31].

Second, a heartbeat starts from within the heart by the action potential at the conducting system, particularly inside the right atrium (RA) and septum. In other words, blood flow dynamics control heartbeats, biochemically, with the combinations of neurohumoral factors that create polarization-

depolarization activities at the *pacemaker* cells of the conducting system, and mechanically, via the pulsatile impacts of shear stress and wall stress, since the 21st day of gestation [32]. The superiority of blood flow dynamics in controlling heartbeat over the autonomic nervous system is demonstrated with the denervated hearts transplant patients [33]. Likewise, disturbed RA wall stress can induce variant types of arrhythmias, e.g., post Mustard arrhythmias [34].

Third, anatomically, the heart is anchored in the body by the great vessels (Dr. Claude Beck) [35]. As depicted in Fig.1, several centimeters separate the sternum from the free wall of the right ventricle (RV), which is followed by the interventricular septum and then the left atrium (LA) and LV. And then in case of cardiac arrest and placing the victim on a supine position the heart becomes further distant from the sternum, pushed backward by the mediastinum*.

And finally, it is also fundamental to consider, the cylindrical shell-shape thoracic cage, particularly the ribs' orientations and their movements on the axis of their attachments between 2 hard and fixed boney structures (sternum and spines) helped by the sternocostal, costochondral, costovertebral, and costotransverse joints [36,37].

Although victims of SCA are quite diverse (e.g., gender, age, etiology, ...), however, they all share the same abovementioned pathophysiological barriers, which must be overcome.

DISADVANTAGES OF CURRENT CPR

Hemorheologically, at least a stroke volume ≥ 140 mL, delivered by the LV, in pulse pressure (syst. BP ≥80 mm Hg) and shear rate (≥ 40 / min) with a coronary perfusion pressure ≥ 15 mm Hg, are required to ensure adequate organs perfusions and promote ROSC [38]. Hence, it becomes an impossible task to achieve with CPR causing serious complications in the victims.

For example, manual or mechanical mid-sternal chest compressions are performed vigorously and strongly (e.g., ≥ 8 to 16 bar / in^2), in total disregard of thoracic biomechanics, hoping to deliver stroke volumes from the distant near-empty LV through the hard bony sternum to compress movable soft mediastinal and cardiac structures. Also, the high frequency of chest compressions (≥100 bpm) restricts recoil of the thorax as well as venous return during decompression and does not adapt the capillary pressure cycle (40 bpm) [39-41]. In addition to the fact that the thoracic cage becomes more fragile,

prone to trauma due to the loss of muscle tone of the intercostal muscles. As a result, mechanical CPR devices are contraindicated in pediatrics and less frequent in females due to mammary glands trauma.

Likewise, while mouth-to-mouth ventilation provides insufficient tidal volume for victims [42], the entire concept of ventilation during cardiac arrest has no substantial benefit due to the lack of gas exchange at the alveolar level.

Similarly, due to the anterolateral position of the AED electrodes, which is effective in dogs unlike humans, most DC shocks deviate from the electric field and nearly 4% reach the heart requiring more powerful energy (≥ 300 joules) for compensation. Consequently, skin burns occur in more than 25% of patients, in addition to other complications such as tachyarrhythmia, thromboembolic events and pulmonary edema have also been reported after strong DC shocks [43]. It is also important to remind that the prolonged depolarization period after strong DC shocks promotes myocardial necrosis and electroporation of the precious pacemaker cells which represent approximately 1% of cardiomyocytes [44,45].

Apart from the employment of ECMO, the benefits of the invasive-CPR procedures, remain controversial because of the hemostatic condition [46]. For example, attempts to improve cerebral perfusion with intravenous hypertonic saline and/or nitrates [47-49], did not change the significant numbers of brain damage in postarrest victims [50]. However, ECMO requires skilled squads guided by ultrasounds for its installation via empty flattened arteries, which makes its use in OHCA more difficult [51, 52].

* Cardiac surgeons used to switch-off the ventilation to avoid hurting the still beating heart during sternotomy.

Methods

Therapeutic approach

In this study, we were able to pattern the proposed therapeutic method through the clinical observations of lifeguards for OHCA and cardiac surgeons for *induced* IHCA.

According to the Utstein style [53], lifeguards have the best results of OHCA with ROSC In addition to their rapid intervention, we believe that the Heimlich's maneuver, which is constantly practiced by lifeguards for evacuating the aspired water, mobilizes massive amount of the hepato-splanchnic blood via the

inferior vena cava which directly stimulates the conducting system promoting ROSC, even without CPR in more than 70% of drowning victims [54,55].

In open-heart surgery, with the advancements in myocardial reperfusion procedures, ROSC most often occur in over 90% without DC shock. Even with denervated heart transplants or sacrifice the sinus node artery as occasionally during arterial switch procedures, the patient most often recovers a sinus rhythm. Perhaps one of the most impressive demonstration of ROSC in cardiac surgery is practiced by a pioneering cardiac surgeon* to wean his patients from CPB, by abrupt clamping of the venous lines which refills the RA instantly creating a snap effect at the conducting system with an immediate defibrillation of the heart.

Therefore, to create similar intracardiac hemorheological effect enhancing ROSC:

- We need to overrule the sternal barrier and bring the heart closer to the chest wall.
- We need to *refill* the nearly empty heart.
- We need to *recoil* properly the chest wall and the mediastinal-parenchymal structures surrounding the heart.
- We need to induce a sudden *rebound* effect at the internal thoracic structures, including the intracardiac blood to create a snap effect at the conducting system of the heart (e.g., likewise Sir Yacoub's method).

PROCEDURE

The 3R/CPR: Refill-Recoil-Rebound

We have been assisted in this study by one of the most experienced Lifeguards' squads from Greece which has the highest drowning records in Europe [56].

Steps:

1. Avoid panic, always seek help, call 911 and do the following until they arrive.
2. Place the victim on the left recovery (lateral recumbent) position. Clear the airways. Loosen all tight and restrictive garments (e.g., belt, bras). Place and press your right hand at 5^{th} intercostal space. Check if there is still a palpable heartbeat (Fig.2A, B&C).

In case of cardiac arrest:

1. *Refill maneuver*: raise the patient's legs and hip in tilting the head to be kept in a Trendelenburg position e.g., with pillows. Gently compress the infradiaphragmatic compartment (hepato-splanchnic) e.g., wrapping the victim's trunk with big towel, sheet. Victims can be easily lifted from their waist (Fig.3A).
2. Adjust the victim's position by pushing his/her chest backward with the right hand and forearm and pushing his/her flank forward with the right thigh (Fig.3B).
3. *Recoil maneuver*: with both hands compress and push the chest backward-upward at the 5th intercostal space, while blocking the victim's back with both thighs and leaning forward on the victim's body in compressing the right chest wall with both forearms, to increase chest recoil in a nearly circumferential manner.
4. Maintaining the *recoil* maneuver for few seconds (Fig.3C).
5. *Rebound maneuver*: sudden release of both hands and all sites of chest compression (Fig.3D) to create a water hammer-like mechanism inside the heart with a snap effect on the conducting system.
6. *DC Shock*: after 2 minutes of *recoil-rebound* maneuvers without ROSC, a DC shock of 100J will be delivered in the anteroposterior position by placing the electrodes on the sternum and between the scapulae (Fig.4).
7. In case of non-response, repeat the *recoil-rebound* for another 2 minutes then try a 150J DC shock. If unsuccessful, repeat the maneuver with a final DC shock within an interval of 3-4min.

- In case of ROSC, keep the victim in the left recovery position with a slight relaxation of the abdominal compression, until transfer to Cardiac Centers.
- In case of absence ROSC, continue the 3R / CPR maneuver until transfer to Cardiac Centers.
- In neonates and infants, as far as we can perform a proper circumferential chest compression we may continue with the present technique (Fig.5).

Precautions

The *rebound* maneuver, in our study, was demonstrated by compressing the abdomen*, the lower intercostal spaces and water bags, because it should not be attempted in living person as it may provoke ventricular fibrillation like in Commotio Cordis syndrome.

* Attending Sir Magdy Yacoub's operative sessions at the Royal Brompton and Harefield Hospitals (UK) in the early 90th.
* A *rebound* test is frequently applied by surgeons when checking for appendicitis tenderness.

Discussion

Compared to current CPR, the proposed 3R/CPR technique can potentially improve outcome of SCA victims for several reasons.

First, instead of vigorously and inconceivably compressing the victim's sternum, the technique provides a more rational hemorheological effect on the conducting system promoting ROSC during the early onset of cardiac arrest. For example, the *refill* maneuver can shift a massive volume of the stagnant infradiaphragmatic venous capacitance to the cardiothoracic compartments to be handled properly with the *recoil-rebound* processes, executed according to the rules of Biomechanics of the thoracic cage [51]. This can enhance chances of ROSC, *directly* by inducing ESS and atrial wall stress in a water hammer-like mechanism with a snap effect at the conducting system, and *indirectly* by improving the myocardial perfusion due to the increased RV preload [57-60]. Second, the induction of chest compressions through the 5^{th} intercostal space while leaning on the victim body in the left recovery position, provides a nearly circumferential stress (hoop stress) on the cylindrical shell-like thoracic cage in respecting ribs' movements axis, which will be more effective and less traumatic for the victims as well as less exhaustive for rescuers. On the other hand, vigorous and strong mid-sternal chest compressions of CPR induce deviated longitudinal stress and provoke the well-known complications of CPR [61-63]. Third, the technique provides additional compressions to the heart by the surrounding mediastinal structures, which can literally explain the untold in many peculiar CPR proposals in the literature. These include studies suggesting a new technique of CPR in prone position, or pulmonary inflation procedures tested in asphyxiated dogs during apnea or bradycardia, rather than cardiac arrest. Fourth, the left recovery position, which allows the rescuer to secure the victim's airway, also helps to avoid confusing cardiac arrest with similar clinical presentations. As, a bystander who cannot distinguish between unconsciousness, cardiogenic shock, or cardiac arrest case, can easily feel the victim's heartbeats in the first two conditions (Fig.2C).

In correlation with other CPR modalities, as far as ventilation is pointless due to the hemostatic condition, it is preferable to continue the 3R / CPR without interruption until ROSC and / or arrival of emergency squads and transfer the victim toward cardiac center. Also, since controversies between chest compression first or DC shock remain unsettled, we should remind that there is still a lack in the literature of studies demonstrating an immediate ROSC following a first DC shock. In addition, the sensitivities of the conventional ECG system, even measured with 12 leads, remain questionable [64], which probably raises more doubts about the accuracy of the AED data obtained with two anterolateral chest electrodes. Thus, it is more convenient to perfuse and predispose the cardiac tissue with the 3R/CPR first before any trial of DC shock to avoid unnecessary damage by electroporation of the rare pacemaker cells.

In the absence of ROSC, the pursuit of 3R / CPR will ultimately contribute to successful management of the refractory and postarrest phases.

Refractory & postarrest

As is done in cardiac surgery, ensuring organs' perfusion with CAD is a top priority in case of cardiac arrest. Also, as it is unwise to flog a tired horse, CAD must be continued in postarrest until full recovery with the restoration of endothelial functions e.g., angiogenesis-apoptosis interdependency [65]. This has been clearly demonstrated in the literature showing that reversible brain damage could be obtained once adequate perfusion was maintained as early as possible during cardiac arrest [66]. Also, as shown in (Table 1), we have encountered complete recovery in patients after more than 30 min of cardiac arrest and who had significant brain damages, confirmed by an intraoperative electroencephalogram (EEG) and/or postoperative computed tomography (CT) scans. These could be supported with evidence of postmortem cellular viability and variant delay in organs biodegradation [67,68].

This explains the increased recommendation of ECPR (ECMO) nowadays [46,69,70]. Nevertheless, in addition to the difficulty of its installation, ECMO induces a steady-flow perfusion mode that furtherly deteriorates the endothelial dysfunction condition as in postcardiotomy syndrome [71-74]. Also, relying on vasopressors to improve hemodynamics worsen endothelial dysfunction conditions by increasing vascular resistances and myocardial oxygen consumption, most likely to end in organ failure and requirement of CAD. This may be worsened by suppressing the important role of the respiratory pump as a master-key circulatory driving force and a potential generator of ESS [75].

As is known, maintaining good metabolic processes in a multicellular organism like a human being depend on organs' microcirculation which is controlled by plurality of endothelial mediators of vasodilators induced by ESS [76-78]. We have previously demonstrated the crucial role of ESS in controlling hemodynamics, microcirculation, and metabolism with new generations of pulsatile CADs, regardless of the heart condition whether, healthy, dysfunctional, or even arrested [79].

Accordingly, unlike ECPR, the employment of a non-invasive CFR device [27], can mobilize a massive amount of stagnant blood volume (≥4 liters) in a pulsatile mode promoting ESS with improvement microcirculation and cellular metabolism, regardless to heartbeat. In addition, the CFR device's vest, associated with a passive oxygen insufflation device serves as a noninvasive mechanical ventilator with a nasogastric tube could be useful during refractory cardiac arrest and in postarrest to prevent excessive ventilation in maintaining the pulmonary ESS [75].

Prophylaxis

Trials of predicting and preventing incidents of pathophysiological SCA, are well defined and in constant progress in cardiology, e.g., Brugada syndrome [80]. However, we are more concerned about the high frequency of physiopathological OHCA during physical exercise. As most of these incidents occur due to a momentary disturbed impulses transmission through the conducting system of a healthy heart. A similar phenomenon is occasionally encountered in open-heart surgery as ventricular fibrillation may occur even without cardiomyopathy like in-vivo experiments, following hasty surgical manipulations. Therefore, we intend to devote our next work to the prophylaxis of SCA in sports, especially since one of our patents (pulsatile suit) [81], has been infringed and currently in use by sports elites, but in an unscientific manner that almost does worse than good.

Limitations

Encountered with the clinical discrepancy of animal models and the risk of commotio cordis in clinical volunteers, we based our 3R / RCP proof-of-concept on fundamental scientific medical knowledges, analysis of clinical observations of lifeguards and cardiac surgeons, as well as on more rational organized common senses (**Thomas Huxley**).

Perspectives

According to recent recommendations from the United States Food and Drug Administration [82], we are planning to demonstrate the benefits of the 3R/CPR versus CPR via computational models and/or cadavers [83, 84]. According to the FINER criteria for a good research question and the phases of evaluation of new therapies, we believe that the 3R/CPR technique is feasible, interesting, novel, ethical and relevant [85, 86].

Conclusions

Outcome of SCA victims remain poor due to insufficiency of current CPR. Unlike conventional chest compression, the 3R/CPR can adapt to pathophysiological conditions and thoracic biomechanics,

providing rational exploitation of the stagnant blood, promoting ROSC, in a less traumatic and exhausting manner, in all ages and genders. Rapid application of 3R / CPR, right up to the quick installation of a CFR device, regardless of ROSC, can dramatically improve SCA results.

Declarations

Ethical Approval and Consent to participate

We have the approval and consent of the Lifeguard Instructors participated in the demonstration of this study.

Consent for publication

We have the consent of the Lifeguard Instructors for the publication of their images in this study.

Availability of supporting data

Available on request.

Competing interests None

Funding None

Authors' contributions

SN conceived the design and development of the technique as well as the authorship of the manuscript.

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Regarding the people in the study, we confirm that they have no objection to publishing their images as they are our friends and volunteers/partners in the study, and we mentioned their names in the acknowledgment as well.

Abbreviations

SCA: Sudden cardiac arrest; CPR: Cardiopulmonary resuscitation; 3R/CPR: Refill, recoil, rebound cardiopulmonary resuscitation; IHCA: In-hospital cardiac arrest; OHCA: Out-of-hospital cardiac arrest; DC: Direct-Current; AED: Automated external defibrillator; ICD: Implantable cardioverter defibrillators; ECMO: Extracorporeal membrane oxygenation; ECPR: Cardiopulmonary resuscitation with the employment of extracorporeal membrane oxygenation; CPB: Cardiopulmonary bypass; ROSC: Return of spontaneous circulation; CFR: Circulatory flow restoration; ESS: Endothelial shear stress; RA: right atrium; BV: Blood volume; AP: Aortic pressure; LA: Left atrium; LV: Left ventricle; Syst BP: Systolic blood pressure; RV: Right ventricle; ALCAPA: Anomalous left coronary artery from the pulmonary artery; ECG: Electrocardiogram; EEG: Electroencephalogram; CT: Computed tomography; CAD: Circulatory assist device; FINER: Feasible, interesting, novel, ethical, and relevant.

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Table

Tableau 1: Results of open CPR in patients subjected to ≥ 30 min of cardiac arrest:

	Age (Sex)	Etiology	CPR (invasive)	DC shock	CPB	Scan	EEG	Drawbacks	Recovery
1	74y (F)	Rupture aortic arch	Ö	—	Ö	Ö	—	Ö	Full
2	3h (M)	Congenital aortic sten.	Ö	—	Ö	Ö	—	Ö	Full
3	31y (F)	Rupture LV	Ö	—	Ö	Ö	Ö	Ö	Full
4	30y (F)	Extracard.*	—	Ö	Ö	Ö	Ö	Ö	t

F = female; M= male; y = years; h: hours (newborn); Sten. = stenosis; LV = left ventricle; *Extracard. = extracardiac cause of ventricular fibrillations during thoracoscopic surgery for a pneumothorax in young athletic doctor; CPB = cardiopulmonary bypass; EEG = electroencephalogram; Survival = 3 deaths = 1 = n 1 Electric Shock; Ö= yes; — = none; t = expired.

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