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We still need a real-time hemodynamic monitor for CPR

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Legendary resuscitation researcher, Max Harry Weil, once said that performing CPR was rather like flying a Boeing 747 without instruments. His 1997 review, “Cardiopulmonary resuscitation: a promise as yet largely unfulfilled”[1], rings as true today as when it was first penned. In this issue of ***Resuscitation*** the article by Jesús Ruiz, Erik Alonso, and their coworkers, entitled “Reliable extraction of the circulation component in the thoracic impedance measured by defibrillation pads”[2], reports significant incremental progress toward clinically meaningful patient monitoring during resuscitation. This task is diabolically difficult from an engineering standpoint. The signal created from low blood flow is in most cases very small, and the noise created by mechanical artifacts of chest compression and occasional intense pulses of high voltage electricity can be very large. The signal to noise ratio for any kind of hemodynamic monitoring in resuscitation is thus frustratingly small. Nevertheless, Ruiz and coworkers have found a sweet spot for physiologic monitoring between the noisy intervals of chest compression at the same time that automatic ECG analysis is being done by an automatic external defibrillator (AED). Specifically, they developed technology to analyze the thoracic impedance signal recorded between AED pads to discriminate pulsatile rhythms from pulseless electrical activity. Their goal was not to quantify blood flow, but simply to extract a binary signal: pulse or no pulse. They succeeded, showing proof of concept and technical feasibility. Their technique to discriminate pulsatile from non-pulsatile rhythms could significantly improve the safety of AEDs by decreasing the risk of unnecessary shocks and perhaps by decreasing the risk of prolonged, unneeded periods of chest compression.

This clever technical advance must be carefully implemented and carries with it some abuse potential. As the authors point out in their discussion, the worst failure mode of such technology would be false positive detection of a pulse. Such a signal might cause rescuers to prematurely stop CPR that could have been live-saving. Another potential downside to this concept is that users might be tempted to interrupt CPR more frequently to check for an impedance pulse. Such over-checking ("stop for a minute") could paradoxically reduce survival, because when a perfusing rhythm is not present, periods with no chest compressions are periods with zero perfusion. The accuracy of an automated pulse detection system, therefore, must be high, and the zero flow time required for a pulse check must be minimized. Fortunately, proper technical implementation of the Ruiz concept is quite possible and easy to envision. The pulse check algorithm, for example, could be inhibited if ventricular fibrillation is detected, thus avoiding false positive signals from atrial contractions or from gasping. The impedance pulse sensing algorithm could be made to run in tandem with ECG rhythm analysis algorithm without increasing diagnostic time significantly. Hence a realistic near term goal of creating practical enhanced AEDs for future clinical trials is quite reasonable.

What the world really needs, however, is a quantitative hemodynamic monitor that works in genuine cardiac arrest, even when supported by vigorous chest and/or abdominal compressions and accompanied by occasional defibrillator shocks. With such technology rescuers could know immediately how well they are doing and could vary their technique to maximize artificial circulation in a given patient. Ideally such a monitor would be minimally invasive and applicable both in the hospital and in the field. For instance, end tidal carbon dioxide concentrations can be measured in intubated patients[3], the amount of CO_2 returned to the lungs and excreted being proportional to blood flow. However the accuracy of the method is highly dependent on the constancy of ventilatory tidal volumes, and despite its availability for decades, $ETCO_2$ monitoring during CPR has not achieved widespread clinical use. Doppler ultrasound is another candidate technology. Grunau's neglected study of Doppler ultrasound monitoring of systemic blood flow during CPR, published in the year 1978 and involving only 12 patients[4], intriguingly concluded "Doppler blood flow monitoring allowed evaluation of effectiveness of cardiac massage; immediate recognition of electromechanical dissociation; . . . and estimates of changes in cardiac output. When the hemodynamic consequences were immediately obvious [to rescuers], both ineffective chest compression and pauses longer than five seconds during effective chest compression were not tolerated by those in attendance, for whom the Doppler flow signal often became the primary reference." Although Doppler measurements are typically operator dependent and vulnerable to motion artifacts, to say nothing of high voltage shocks, the concept of immediate feedback regarding circulating blood flow during resuscitation is powerful and appealing.

My own mentor, L. A. Geddes, a legend and pioneer in the field of biomedical engineering[5, 6], organized laboratory courses at Baylor College of Medicine and Purdue University, in which students routinely performed open chest CPR in anesthetized dogs. The animals had indwelling catheters to record instantaneous aortic pressure waveforms, visible on a strip chart recorder. Ventricular fibrillation was induced electrically. The instructions to students took less than 30 seconds and were as follows. "Squeeze the heart rhythmically with one or both hands. Release pressure to let the heart fill. Vary your style to maximize the area under the blood pressure waveform." The students, who had never done such a thing before, began tentatively and awkwardly. The first few squeezes produced puny pulses. Within perhaps a dozen squeezes, however, they routinely generated aortic pressures of 100/50 mmHg or better. In this model of real cardiac arrest naïve rescuers experienced just-in-time learning, taking less than one minute, and achieved nearly 100 percent success. The secret of their success was biofeedback. The ability to see immediately a measure of blood flow, along with simple verbal encouragement from instructors to create more area under the blood pressure curve, worked wonders. Some students required a little extra coaching to actively open the hands to allow filling of the heart. When they did this, curve area improved with the very next compression, and the lesion was learned. Students quickly adapted their technique to squeeze out nearly normal stroke volumes. Forward flow then became limited by the rate of venous return, not by the effectiveness of ventricular compressions. The Boeing 747's now had an altimeter, and even novice pilots did not crash.

Raising the dead is, admittedly, a difficult task. Yet my memorable experience both as a student and as an instructor in Dr. Geddes' course convinces me that improved results are indeed possible, if rescuers can somehow know immediately how well they are doing and have sufficient latitude to vary their technique as the situation requires. The history of interposed abdominal compression (IAC) – CPR is quite instructive here[7-10]. This technique, which involves alternating external chest and abdominal compressions, delivered manually by two rescuers[7], has been extensively studied in the laboratory and in clinical trials. Over twenty-five separate studies in animal models and in mechanical or computer models show that the addition of abdominal compressions to otherwise standard CPR essentially doubles blood flow[10]. In turn, Sack's clinical studies[9, 11], as well as two meta-analyses of aggregate human data[12, 13], show that when IAC-CPR is implemented in human cardiac arrest victims, the rates of return of spontaneous circulation and short term survival are also approximately doubled. This result is quite remarkable. It could well have been otherwise. Variables associated with the underlying disease states of patients or variables associated with the quality of post-resuscitation critical care could easily have swamped the effects of a few minutes of improved artificial circulation. But they didn't. The act of providing improved blood flow during a brief interval of CPR can indeed translate into improved outcome.

Accordingly, monitors that can allow rescuers to fly the Boeing 747 with instruments—allowing them to improve the strength and depth of chest compressions[14], to add abdominal compressions, or to recognize the deterioration of circulation when CPR is interrupted for any reason[15]—could well be profoundly impactful in a field that has seen little improvement in overall results, excepting early defibrillation, while flying blind[16, 17]. Monitoring the circulatory system during CPR in human patients, especially outside the hospital, remains a grand challenge for biomedical engineers, owing to the low blood flow state, the very large motion artifacts, and the very large electrical artifacts from defibrillator shocks. Brave researchers such as Ruiz, Alonso, Aramendi, Kramer-Johansen, Eftestøl, Ayala, and Gonzalez-Otero deserve all the encouragement they can get.

Conflict of interest statement

The author has no conflicts of interest.

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