Plenary Article

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Confirming the Clinical Safety and Feasibility of a Bundled Methodology to Improve Cardiopulmonary Resuscitation Involving a Head-Up/Torso-Up Chest Compression Technique

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Objectives: Combined with devices that enhance venous return out of the brain and into the thorax, preclinical outcomes are improved significantly using a synergistic bundled approach involving mild elevation of the head and chest during cardiopulmonary resuscitation. The objective here was to confirm clinical safety/feasibility of this bundled approach including use of mechanical cardiopulmonary resuscitation provided at a head-up angle.

Design: Quarterly tracking of the frequency of successful resuscitation before, during, and after the clinical introduction of a bundled head-up/torso-up cardiopulmonary resuscitation strategy.

Setting: 9-1-1 response system for a culturally diverse, geographically expansive, populous jurisdiction.

Patients: All 2,322 consecutive out-of-hospital cardiac arrest cases (all presenting cardiac rhythms) were followed over 3.5 years (January 1, 2014, to June 30, 2017).

Interventions: In 2014, 9-1-1 crews used LUCAS (Physio-Control Corporation, Redmond, WA) mechanical cardiopulmonary resuscitation and impedance threshold devices for out-of-hospital cardiac arrest. After April 2015, they also 1) applied oxygen but deferred positive pressure ventilation several minutes, 2) solidified a pit-crew approach for rapid LUCAS placement, and 3) subsequently placed the patient in a reverse Trendelenburg position (~20°).

Measurements and Main Results: No problems were observed with head-up/torso-up positioning ($n = 1{,}489$), but resuscitation rates rose significantly during the transition period (April to June 2015) with an ensuing sustained doubling of those rates over the next 2 years (mean, 34.22%; range, 29.76–39.42%; $n = 1{,}356$ vs 17.87%; range, 14.81–20.13%, for 806 patients treated prior to the transition; $p < 0.0001$). Outcomes improved across all subgroups. Response intervals, clinical presentations and indications for attempting resuscitation remained unchanged. Resuscitation rates in 2015–2017 remained proportional to neurologically intact survival (~35–40%) wherever tracked.

Conclusions: The head-up/torso-up cardiopulmonary resuscitation bundle was feasible and associated with an immediate, steady rise in resuscitation rates during implementation followed by a sustained doubling of the number of out-of-hospital cardiac arrest patients being resuscitated. These findings make a compelling case that this bundled technique will improve out-of-hospital cardiac arrest outcomes significantly in other clinical evaluations. (*Crit Care Med* 2019; 47:449–455)

Key Words: cardiac arrest; cardiopulmonary resuscitation; emergency medical services; head-up CPR; impedance threshold device; sudden death

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Over the past half-century, the life-saving effect of traditional cardiopulmonary resuscitation (CPR) techniques have been well documented (1–5).

Bystander-performed CPR improves the likelihood of neurologically intact survival following out-of-hospital cardiac arrest (OOHCA), and when well performed by emergency medical services (EMS) crews, CPR further improves those outcomes (2–8).

Nonetheless, traditional CPR techniques also have limitations if not performed well or implemented early enough (2–8). Also, traditional chest compression techniques may not be the optimal method to ensure blood flow to the heart, the brain, and the rest of the body (9, 10).

During CPR, vascular pressures simultaneously increase on both venous and arterial sides of the heart, particularly during compression phases (9, 10). Resulting increases in intrathoracic and intracranial pressure (ICP) can impede cerebral blood flow and compromise coronary and systemic circulation (9–14).

Experimentally, a combined multi-interventional approach to induce blood flow out of the brain and into the thorax can improve cerebral and coronary perfusion significantly during CPR (11–14). Using adjuncts that enhance venous return into the thorax during CPR, including an impedance threshold device (ITD) and suction-providing mechanical CPR techniques, outcomes are improved significantly with mild head/thorax elevation (12). Mechanical CPR devices employed in these swine models are akin to the manual active compression-decompression (ACD) device (ResQPump; Zoll Medical Corporation, Chelmsford, MA) or a LUCAS (Physio-Control Corporation, Redmond, WA) mechanical CPR device that provide a suction component at the chest wall interface (15–22). In the laboratory, head-up/chest-up chest compressions alone can create *transient* improvements in cerebral perfusion versus standard supine CPR, but when combined with ITD-ACD adjuncts (**Fig. 1**), it both improves *and sustains* cerebral and coronary perfusion (12, 14).

Accordingly, head-up/chest-up CPR is one component of a bundled approach to CPR performance (12). Each of the complementary interventions (ITD, ACD, head-up/torso-up) have different mechanisms of effect, and each can contribute independently to improved cerebral and coronary circulation. Yet combined, they are highly synergistic (12, 14). When examining the comparative individual effects of: 1) head-up CPR and 2) ACD-ITD CPR versus standard supine CPR, it was 3) the combination of all three adjuncts (Fig. 1) that provided the most significant (and sustained) synergistic improvements in cerebral and coronary perfusion pressures well beyond a simple additive effect (12).

Recognizing the potential clinical benefit of these evidence-based experimental findings, EMS system leaders in Palm Beach County, Florida, tasked themselves with analyzing the safety and feasibility of using this bundled approach in the clinical setting.

Palm Beach County Fire Rescue (PBCFR) crews were already managing patients with both ITD and LUCAS devices along with an on-scene "pit-crew" approach system wide (23). The proposed bundled approach mainly would involve the incremental addition of the head-up/chest-up component along with strategies to (initially) limit positive pressure ventilations as a way to further minimize intrathoracic pressure elevations (24).

The primary purpose of this analysis was to observe if mechanical CPR devices could be used feasibly and safely at a slightly elevated angle and also to determine if that technique, in combination with deferred positive pressure ventilation and the preexisting use of the ITD and coordinated pit-crew approach, could also measurably improve patient outcomes.

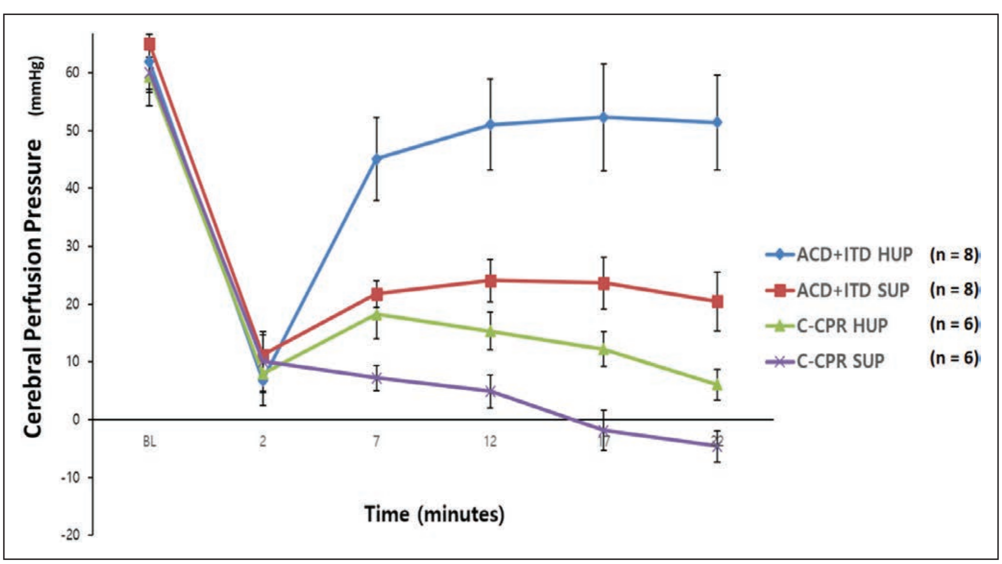

Figure 1. Prior experimental studies of porcine cardiac arrest ($n = 28$) following induced ventricular fibrillation demonstrating cerebral perfusion pressure measurements (in mm Hg) that were recorded during the first 20 min of arrest and basic cardiopulmonary resuscitation (CPR). Sequential comparisons in mean cerebral perfusion pressures with SEM were made for four scenarios: 1) conventional CPR (C-CPR) performed in a supine (SUP) position (C-CPR SUP; $n = 6$); 2) conventional CPR with a head-up/shoulders/thorax tilted up (HUP) approach (C-CPR HUP; $n = 6$); 3) CPR performed with an active compression-decompression device (ACD) used in combination with an impedance threshold device (ITD) in a supine (SUP) position (ACD+ITD SUP; $n = 8$); and finally, 4) ACD+ITD CPR combined with a head-up/shoulders/thorax tilted up (HUP) approach (ACD+ITD HUP; $n = 8$). Results indicate a synergistic and sustained interaction when the ACD, ITD, and head-up strategies are combined*. *Adapted from our previous work: Ryu H et al (12).

METHODS AND MATERIALS

The project was conducted in Palm Beach County, Florida (residential population 1.47 million), a geographically sprawling jurisdiction (2,386 square miles) that is multiethnic and culturally diverse with extremes of age and socioeconomic status. The county 9-1-1 system receives an exceptionally high volume of calls including close to 700 cases of OOHCA annually.

Despite many logistical challenges and a low frequency of bystander CPR performance, by 2014, PBCFR had become a high-functioning EMS agency that was capable of achieving successful resuscitation rates (admissions to the emergency department with spontaneous circulation) that were comparable to the corresponding statewide OOHCA outcomes.

All consecutive OOHCA cases occurring in the county and treated by PBCFR, including patients presenting with asystole, were followed prospectively over 3.5 calendar years (2014, 2015, 2016, and first half of 2017). In quarter 2, 2015 (April through June), PBCFR crews were trained, one station and shift at a time, to continue to use in-place protocols (e.g., airway patency confirmation, LUCAS CPR device, and ITD), but also to: 1) apply supplemental oxygen but defer positive pressure ventilation for several minutes, 2) solidify their pit-crew approach for rapid LUCAS placement (interrupting manual compressions for no more than 5 s) and coordinated management of the patient, and 3) several minutes later, gradually raise the angle of the entire stretcher ~20° (reverse Trendelenburg position) following LUCAS placement with concurrent advanced airway placement connected to an ITD (23, 24).

The head-up/torso-up component was created by inserting a hard-case container under a scoop stretcher to which the mechanical CPR device was attached and secured. This created a slight angle for the stretcher and CPR device with elevation of the head and torso of about 20°. The entire body remained in-line with feet angled downward. (**Fig. 2**).

All other patient care provided during the entire analysis followed the widely accepted, proscribed guidelines from the American Heart Association. Those clinical strategies did not change during the project, and certain relevant procedural changes in the dispatch center did not occur until well after the evaluation period had ended.

Quality assurance staff at PBCFR maintain a comprehensive registry of all OOHCA patients including the typical "Utstein"-style data components (25), ranging from witnessed versus unwitnessed arrest, bystander CPR performance, response intervals, clinical and electrocardiographic (ECG) presentations, defibrillation attempts, medications administered, and defined outcomes such as return of spontaneous circulation in which spontaneous circulation is restored and maintained for 5 minutes as well as successful resuscitation by EMS (in which a resuscitated patient is admitted to the hospital emergency department with sustained spontaneous circulation). Intact neurologic status (modified Rankin Score < 3) was also obtained from select hospitals capturing and releasing those data (25). Prior to 2015, however, most receiving facilities for PBCFR were not providing discharge or neurologic outcome data.

Therefore, for purposes of consistency in comparing outcomes, successful resuscitation by EMS (hospital arrival with sustained spontaneous circulation) was used in making comparisons of outcomes before, during, and after implementation of the fully bundled approach. The endpoint of neurologic status at the time of discharge was still obtained wherever possible from those hospitals reporting those data.

Implementation of the intended CPR bundle, now including head-up CPR, was accomplished over a several week period as instructors/training staff completed rounds at each station/shift sequentially during quarter 2 of calendar year 2015.

Beyond a standard chi-square "before and after" statistical comparison of mean outcomes (with $p < 0.01$ for significance), quarterly reports regarding rates of resuscitation by EMS were generated and tracked throughout the 3.5 years to identify any significant periodic variations in resuscitation rates and also to document if any incremental effect could be detected during the protocol transition period (early quarter 2 of 2015). Accordingly, comparative results were also reported in terms of the full extremes of ranges for the quarterly outcomes before and after the protocol transition period to head-up/torso-up positioning.

The PBCFR initiative was incorporated as part of a nationwide project that has received primary institutional review board evaluation (project assignment number HSR-17–4414) through the Human Subjects Research Committee of the Hennepin County Medical Center and Healthcare System (Minneapolis, MN). The project was approved and last reviewed on October 11, 2017 as a part of the National Head-Up CPR Registry study. Patient privacy was maintained using deidentified data and the conduct of the project, and its findings were considered part of an intrinsic quality assurance project conducted by a governmental public safety agency.

Figure 2. Procedure used by the emergency medical services agency to provide elevation of the head and torso during mechanical cardiopulmonary resuscitation using a LUCAS (Physio-Control Corporation, Redmond, WA) device attached to a scoop stretcher that is supported and angled upward (reverse Trendelenburg) with hard-edge case positioned toward the top end of the stretcher.

RESULTS

Over the 3.5-year prospective period of analysis, 2,322 consecutive cases of OOHCA were encountered, and outcomes were recorded in detail including complications or problems associated with the angled mechanical CPR.

With respect to that primary feasibility and safety issue, no problems or physical complications were observed or reported with the head-up/torso-up positioning (n = 1,489) over the 2 years of initial implementation. However, soon after the transition period began, rates of EMS resuscitation steadily rose as the techniques were sequentially introduced to the various responding crews with an ensuing sustained doubling of those rates (**Fig. 3**) over the following 2 years. For the initial 1.25 years (January 1, 2014, to March 31, 2015), the mean resuscitation rate for OOHCA patients (n = 806) was 17.87% with a quarterly range of 14.81–20.13%. Following the transition period, and for the ensuing 2 years (July 1, 2015, to June 30, 2017), EMS resuscitation rates for OOHCA patients (n = 1,356) rose to a mean of 34.22% with a quarterly range of 29.76–39.42% ($p < 0.001$).

These results translated into 199 EMS-resuscitated patients successfully arriving at the hospital with spontaneous circulation in calendar year 2015 (the transition year) and 226 in 2016 compared with 108 in calendar year 2014 (**Table 1**, and **Fig. 4**). Wherever tracked, neurologically intact survival rates in 2015–2017 remained similarly proportional to EMS resuscitation rates. Specifically, about 35–40% of those resuscitated by EMS ultimately achieved good neurologic status, and these proportions were similar to the observations reported prior to the transition period.

The improvements in resuscitation success applied across all subgroups, be it in terms of demographics (e.g., age, sex, race), presenting ECG rhythm or provision of bystander CPR. For example, for men (consistently constituting 62.27% of cases in 2014, 63.53% [2015], 61.68% [2016], and 65.24% [2017]; p = 0.685), the rate of resuscitation went from 15.64% to 33.57% (before and after the transition; $p < 0.001$), whereas the increase for women was 21.59% to 35.33% ($p < 0.001$). Resuscitation rates for ventricular fibrillation (VF)/ventricular tachycardia (VT) presentations before and after the transition period increased from 22.99% to 44.40% (p = 0.001), whereas non-VF/VT presentations improved from 13.58% to 30.85% ($p < 0.001$).

Likewise, when examining outcomes for subgroups of patients receiving bystander CPR, resuscitation rates rose from 19.63% in 2014 to 35.21% (2015), 29.97% (2016), and 39.76% (first half 2017) ($p < 0.001$), whereas outcomes even improved for those not receiving bystander CPR (11.98%, to 29.27%, 29.67%, and 24.11%, respectively; p = 0.001).

During the before and after evaluation periods, other key system factors typically related to better outcomes remained constant, such as average EMS crew response intervals (6:35 min/s in 2014, 6:33 [2015], 6:32 [2016] and 6:34 [2017] or the relative frequency of ECG presentations [VF/VT, asystole, pulseless electrical activity; p = 0.423]), gender (p = 0.685), arrest after EMS arrival (p = 0.386), and frequency of cases witnessed by bystanders (p = 0.362).

DISCUSSION

One of the most striking observations in this analysis was the immediate and steady increase in EMS resuscitation rates as the additional components of the bundled approach to "flow augmenting CPR" were implemented sequentially across the EMS agency. Within weeks, there was a sustained doubling of the numbers of resuscitated OOHCA patients in this high-volume, matured EMS system. The magnitude of the sudden

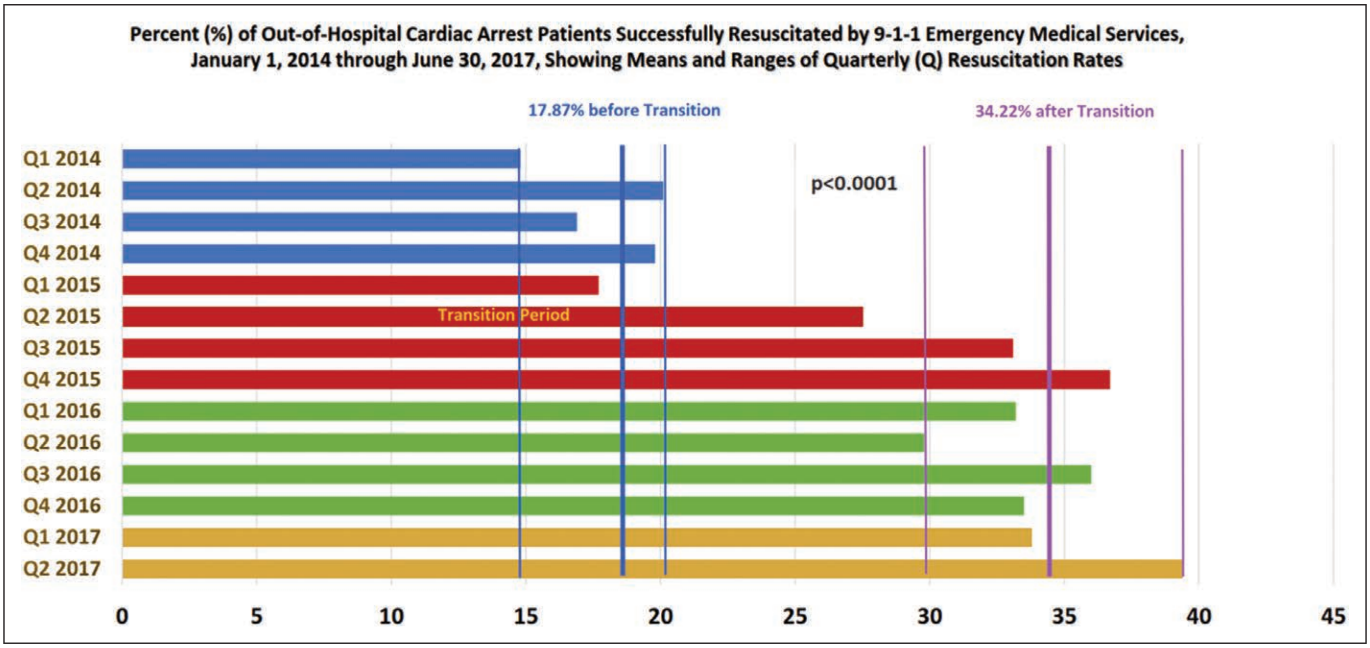

Figure 3. Graphic display of emergency medical services resuscitation rates (successful resuscitation and delivery of a viable patient with spontaneous circulation to the hospital emergency department) expressed in terms of % resuscitated using quarterly reports beginning in January 1, 2014, and ending June 30, 2017. Each *horizontal bar* represents the resuscitation rate for each respective quarter. The transition period with introduction of the full resuscitation bundle including introduction of head-up mechanical cardiopulmonary resuscitation in Quarter (Q) 2 (April, May, June) 2015 is noted. Comparison of the mean rates of resuscitation before and after the transition are in indicated by the *thick vertical lines* flanked on each side with *thinner vertical lines* indicating the respective outer ranges of quarterly rates.

TABLE 1. Tabulation of the Number of Patients Who Were Resuscitated by EMS and Delivered to the Emergency Department With Sustained Circulation, Displayed and Stratified by Each Calendar Quarter Between January 2014 and June 2017, Inclusively

Year	(% Resuscitated)	No. of Resuscitated/ No. of Treated
2014		
Quarter 1	14.8	24/162
Quarter 2	20.1	31/154
Quarter 3	16.9	22/130
Quarter 4	19.8	31/157
Total	17.91	108/603
2015		
Quarter 1	17.7	36/203[a]
Quarter 2	27.5	49/160[b]
Quarter 3	33.1	55/166
Quarter 4	36.7	59/161
Total	28.84	199/690
2016		
Quarter 1	33.2	65/196
Quarter 2	29.8	50 /168
Quarter 3	36.0	50/139
Quarter 4	33.5	61/182
Total	33.01	226/685
2017		
Quarter 1	33.8	70/207
Quarter 2	39.4	54/137
Total (half year)	36.05	124/344

[a]Prechange period.

[b]Transition period.

Percentages are expressed for the number resuscitated over the total number of patients encountered and treated during each quarterly and annual period.

improvements in an already high-functioning EMS system made it much less likely to be related to any other systemic change or unforeseen variable beyond the new procedures and associated training. This analysis deserves scrutiny within the typical context and limitations of a historical control using a multifaceted bundled care approach, but the remarkable and uniformly effective clinical results, extending across a large, complex patient population, still remain compelling.

The key variables and their relative contributions remain unclear, but the results strongly support preclinical observations that the multifaceted bundle is the most important factor (12). Each individual component was implemented to augment venous return out of the brain and into the thorax as complementary mechanisms to better refill the heart and simultaneously lower ICP. Not only are they individually effective, they are also interdependent (11, 14, 16, 19, 20, 26). Considering that the LUCAS device and ITD were already being used, the additions of deferring positive pressure respirations for several minutes and implementing head-up/torso-up chest compressions were the likely key factors driving the results. Still, it should be emphasized that, experimentally, head-up CPR provided only a slight advantage over traditional supine CPR in terms of improving cerebral perfusion, and most relevantly, it clearly was not as effective as when it was combined with ACD/ITD devices (12).

This strong experimental observation supports the notion that the significant rise in clinical resuscitation rates was the effect of the bundle and not necessarily a single factor such as head-up CPR.

Concomitantly, one could also broadly attribute outcome improvements, at least in part, to classic nuances of historical studies such as focused training, renewed logistical organization, a “Hawthorne effect”, and/or progressive experience of the team. However, much of such training and logistical concepts were already in place and already continually monitored by a motivated training and supervisory staff (23). Furthermore, the magnitude of outcome changes occurring over just a few weeks was recognized palpably throughout the system including receiving hospitals. In our collective experience, such a rapid change would not be fully attributable to historical variables alone, particularly considering the sustained improvements. Regardless, this novel clinical initiative made an irrefutable improvement in life saving for the community involved, an important observation in itself.

Studying bundled care approaches is a relatively novel strategy in the realm of CPR research where interventions are studied traditionally, one at a time. The CPR bundle used in this evaluation was derived from both evidence-based experimental and clinical information that suggested the necessity of that approach. It is also consistent with the synergistic effects of complementary therapies being researched in the treatment of other complex diseases such as therapies for heart failure, cancer, and infection with human immunosuppression virus. Although a new paradigm in CPR research, it is a familiar one in these other areas of medicine for mitigating morbidity and mortality (27).

There remain several caveats regarding the safety of the head-up approach. Our own laboratory work, and that of others, have led us to believe that the head-up process should only begin after several minutes of providing traditional supine CPR with the ITD applied to help “prime the pump” (28, 29). It is further recommended that tilting should be implemented gradually, in a specific sequence following the “priming” step, and only with concurrent use of an ITD in particular (28–31). The main admonition is to avoid going directly to the full-tilt target at the beginning of resuscitation efforts and to use appropriate accompanying adjuncts to enhance circulation as described in this analysis considering that it otherwise may even be harmful hemodynamically (28–31).

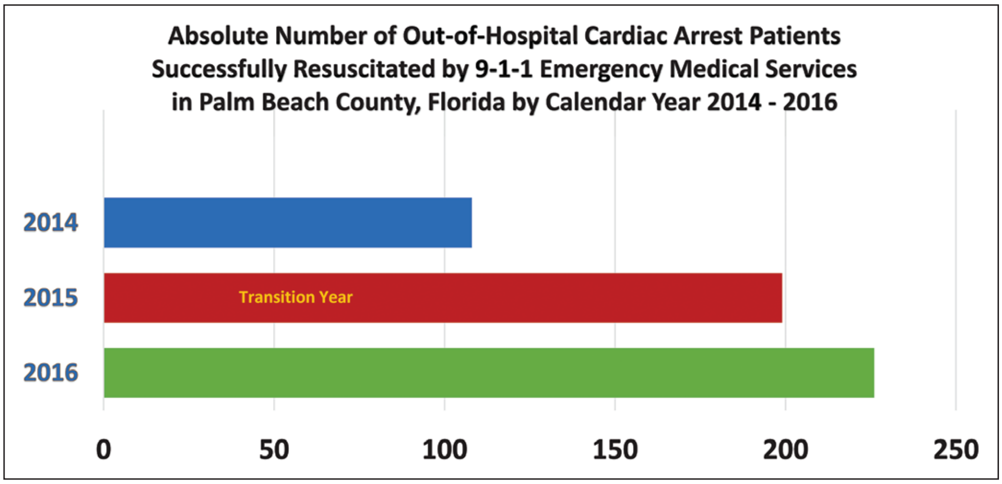

Figure 4. The raw number of patients resuscitated by emergency medical services teams who were successfully delivered to the emergency department alive with sustained circulation for the calendar years 2014, 2015 (the year of transition with inclusion of head-up cardiopulmonary resuscitation), and 2016, respectively.

The usual preclinical translation from swine models to humans may also be a factor. Human beings have much larger lower extremities, and other anatomical differences may alter the physiology of head-up/torso-up CPR. Accordingly, we recently compared the swine model with a cadaver model with this bundled flow augmenting approach and found similar proportional changes in blood flow (32). These findings encourage us to believe that this distinction is less of a concern, but the optimal degree of elevation (e.g., 20° vs 30°) and the actual elevation sequence and timing of elevation for human beings are all important considerations that are currently under evaluation using new technology to support the degree and timing of the head-up/torso-up implementation (33).

Also, the optimal rate and depth of compressions may be altered by this flow augmenting bundle, and recent studies have indicated the dependence of ITD effectiveness on quality CPR (rate, depth, and interruptions) in large clinical studies (6, 7). In addition, during this preliminary feasibility analysis, EMS crews used a full body tilt (Fig. 2). Subsequent work in our laboratory has indicated preliminarily that supine (0°) position for the legs accompanied by a head-up and torso-up position may be the more ideal approach (12, 14, 31).

Likewise, another caveat is that the protocol used here included deferring of positive pressure ventilation several minutes to diminish intrathoracic pressure effects on preload (24, 34–36). However, that consideration was based on traditional CPR procedures, and it may need to be reconsidered recognizing the increased blood flows achieved with this adjunctive bundle. Rescue breaths might best be implemented earlier in the resuscitation efforts using the bundle described here, but we still suggest that they be delivered without interrupting compressions (during a compression upstroke preferably) and provided with a lesser frequency such as one breath every 8–10 seconds (35, 36). The overall consideration is that this particular issue also deserves further investigation and particularly within the context of this bundle.

Finally, our own preliminary laboratory experience (unpublished) indicates that the ResQPump, a manual ACD device, may be more effective than the mechanical LUCAS device (used here) in terms of producing stronger swings in negative thoracic pressure and thus further augmenting venous return. Again, this additional preclinical observation creates another hypothesis-generating consideration for further investigation.

CONCLUSIONS

Although using a historical control design, the immediate, steady rise in resuscitation rates observed during the relatively brief protocol transition phase, and the subsequent sustained doubling of successful delivery of resuscitated patients to area hospitals, makes a very strong case that that this bundled technique can improve OOHCA outcomes significantly. At the very least, this analysis does indicate that quality improvement initiatives involving evidence-based progressive approaches to resuscitation, performed in a methodical, conscientious quality assurance manner, can help EMS significantly improve and sustain improved OOHCA outcomes, even within very large, complex populations and logistically challenged systems of care. Such successes not only immediately benefit the involved community at large, but they can also serve as recommended approaches for other communities seeking ways to effect improved life-saving in their own EMS systems.

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