Cardiopulmonary Resuscitation Training for Healthcare Professionals

A Scoping Review

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Summary Statement: The optimal strategy for training cardiopulmonary resuscitation (CPR) for healthcare professionals remains to be determined. This scoping review aimed to describe the emerging evidence for CPR training for healthcare professionals.
We screened 7605 abstracts and included 110 studies in this scoping review on CPR training for healthcare professionals. We assessed the included articles for evidence for the following topics: training duration, retraining intervals, e-learning, virtual reality/augmented reality/gamified learning, instructor-learner ratio, equipment and manikins, other aspects of contextual learning content, feedback devices, and feedback/debriefing. We found emerging evidence supporting the use of low-dose, high-frequency training with e-learning to achieve knowledge, feedback devices to perform high-quality chest compressions, and in situ team simulations with debriefings to improve the performance of provider teams.
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In-hospital cardiac arrest (IHCA) occurs in approximately 1 to 10 per 1000 hospital admissions, with risk-adjusted survival outcomes being highly variable between hospitals, suggesting possible differences in cardiopulmonary resuscitation (CPR) quality.[1–8] Studies have demonstrated that CPR quality during IHCA is often substandard, with chest compression (CC) rate, CC depth, and ventilation rates deviating from international guideline recommendations, and defibrillation is being delayed.[9–12] Therefore, the International Liaison Committee of Resuscitation (ILCOR) and the American Heart Association (AHA) have suggested that CPR training be a primary area of interest to improve survival outcomes after IHCA.[13,14]

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Several aspects make IHCA more complex than out-of-hospital cardiac arrest as the in-hospital resuscitation team may not know each other when initiating resuscitation and many providers at the location increases the risk of overcrowding.[15] Moreover, IHCA is unpredictable and can occur anywhere in the hospital. Most cardiac arrests occur outside of the intensive care unit in many European countries, distributed across all hospital departments.[3,16,17] Thus, most healthcare professionals will get exposed to CPR during clinical work. When facing an IHCA, CPR training is recognized to be of utmost importance, and previous research has shown that simulation-based resuscitation training correlates with increased survival after cardiac arrest.[18]

Accordingly, there is a great interest in simulation-based training to improve resuscitation skills. However, knowledge on specific training strategies to enhance CPR quality and patient outcomes after IHCA remains sparse.[19] The ILCOR recently published the 2020 Concensus on Science and Treatment Recommendations statements on Education, Implementation, and Teams based on which the European Resuscitation Council (ERC) and the AHA build their guidelines on resuscitation.[20–23] However, training strategies for healthcare professionals in hospitals specifically are not investigated, and reviews on, for example, retraining, spaced learning, feedback devices, virtual reality (VR), and gamified learning are conducted for healthcare professionals and laypersons combined. Other topics such as course duration, instructor-learner ratio, e-learning for basic life support (BLS) training, and debriefing methods were not reviewed in the 2020 ILCOR Concensus on Science and Treatment Recommendations.

Scoping reviews allow the opportunity to broadly describe evidence within CPR training and discuss nuances on aspects for in-hospital providers that may not be possible for systematic reviews.[24] This scoping review aimed to describe the recent evidence for teaching CPR to healthcare professionals and make suggestions for future directions for CPR training of hospital staff specifically. Moreover, we assessed knowledge gaps and possible opportunities for new systematic reviews to change recommendations for simulation-based resuscitation training for healthcare professionals.

METHODS

This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses statements on scoping reviews.[24] The review was not registered at the International Prospective Registry for Systematic Reviews because they do not accept registrations of scoping reviews. According to Danish law, no approval by an ethical review committee was needed to conduct this study.

We used the PICOST format (Population, Intervention, Comparison, Outcome, Study design, Time frame) to frame the research question: For clinical staff in hospitals (P), does any type of CPR training (I), compared with no CPR training or any other training format (C), change knowledge, CPR skills, or patient outcomes (O). We included all studies in English with a comparator, including randomized controlled trials and nonrandomized studies including interrupted time series, controlled before-and-after studies, case-control studies, and cohort studies. We excluded all editorials, commentaries, opinion papers, letters to the editor, nonpublished studies, and studies in languages other than English.

This scoping review investigates advances in research on CPR training after the 2015 statements by the ERC, AHA, and ILCOR.[21,23,25,26] Thus, we conducted a systematic literature search from January 1, 2014, to December 5, 2020, to ensure that we captured all studies published since the writing process started for the 2015 guidelines. The literature search was conducted by one of the authors (K.G.L.) with an information specialist's support. We searched PubMed, Embase, and Cochrane databases of controlled trials and systematic reviews. The search strategy is provided in Supplemental Digital Content 1 (see text, Supplemental Digital Content 1, description of search strategy, http://links.lww.com/SIH/A738). We did not contact any authors in case of missing data or incomplete study description. Two authors independently reviewed all titles and abstracts retrieved by the systematic search using Covidence (Covidence, Melbourne, Australia). In case of disagreement, the reviewers discussed the abstract until reaching an agreement. Two authors likewise screened full texts, and any dispute was resolved by consensus.

We conducted a broad search to scope all relevant literature relevant for the training of hospital staff. We identified the following training topics for hospital staff that would be used as specific categories: (A) training duration, (B) retraining intervals, and the following topics relating to contextual learning: (1) e-learning; (2) VR, augmented reality, and gamified learning; (3) instructor-learner ratio; (4) equipment and manikins; and (5) other aspects of contextual learning content. Moreover, we wanted to assess studies on feedback devices and feedback/debriefing methods during training.

Inclusion Criteria

When searching the literature, we categorized healthcare professionals as clinical providers who were enrolled in an education or having completed an education, for example, emergency medical technician, paramedic, nurse, physiotherapist, or physician. We chose to include healthcare students as their learning curriculums generally reflect the skills needed for clinicians and because their training is the foundation for subsequent provider training. Studies on laypersons, military personnel, neonatal resuscitation, clinical studies on out-of-hospital cardiac arrest, and participants training other skills than CPR were excluded. We included studies related to adult BLS and advanced life support (ALS) and pediatric life support training involving CPR.

Instead of using strict definitions on the educational topics as often used in systematic reviews, we chose to include broad definitions to describe the educational topics' overall evidence. Accordingly, retraining intervals covered both regular training intervals, booster training (low-dose retraining for skill retention), and spaced learning (distributing the course curriculum over several weeks or months as opposed to massed learning with the whole course conducted in, for example, 1 day), acknowledging that these concepts are related but not identical. In the feedback/debriefing category, we assessed both instructor debriefing and feedback methods (including aspects of mastery learning/rapid cycle deliberate practice, feedback devices, and use of instructor feedback vs. peer feedback).

Extraction and Selection of Studies

All articles were extracted on an excel spreadsheet specifying the study design, population, type of intervention, comparison, and most important results. The design was adapted from the method used for scoping reviews conducted by the ILCOR.[27] Moreover, we used prespecified deductive categorization of the type of intervention according to the previously mentioned prespecified categories for educational interventions of interest. The first 10 articles were extracted and discussed jointly among 3 authors to ensure standardization of the remaining articles' extraction process.

Because this is a scoping review, no bias assessment was performed. We categorized articles using deductive thematic analysis in accordance with the prospectively defined training aspects as described previously.

RESULTS

We identified 7605 studies, of which 506 studies were selected for full-text screening, and 110 studies were finally included (Fig. 1). Separate flow charts for screening the initial (see figure, Supplemental Digital Content 2, flow chart for initial screening, http://links.lww.com/SIH/A739) and updated search (see figure, Supplemental Digital Content 3, flow chart for updated search, http://links.lww.com/SIH/A740) are provided in the Supplemental Digital Content. We identified 86 studies relating to the 9 prespecified topics,[28–113] and the remaining 24 studies did not relate to our prespecified topics of interest (see table, Supplemental Digital Content 4, description of studies not relating to the specified topics, http://links.lww.com/SIH/A741).[114–137] We summarized all existing recommendations by the ERC, AHA, and ILCOR on the CPR training topics covered in this review (Table 1).[20–23]

Course Duration

Current guidelines do not recommend any specific course durations for BLS or ALS training (Table 1). We did not identify any studies comparing different durations of traditional courses. We only identified 1 study comparing 1, 2, or 3

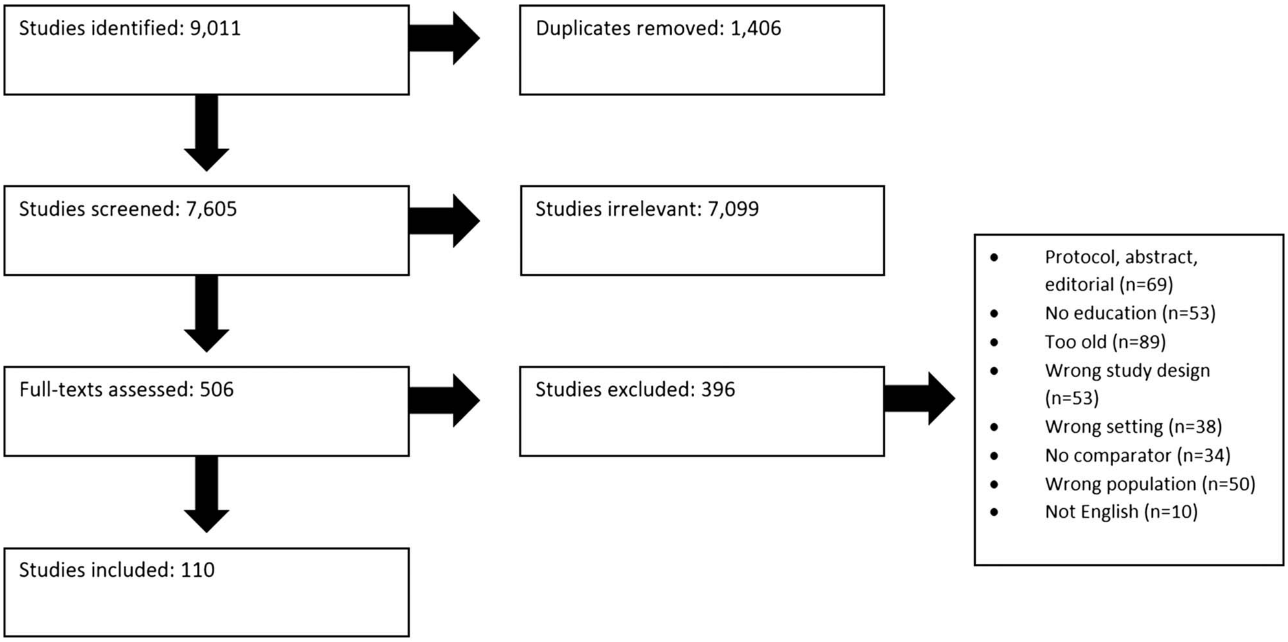

FIGURE 1. Flow chart of inclusion of articles.

repetitions of watching a self-instruction BLS video, finding no difference in CC skill acquisition.[101] We found several studies on different durations of face-to-face training with the use of e-learning and self-training, which are presented hereinafter (see table, Supplemental Digital Content 5, studies on e-learning, http://links.lww.com/SIH/A742).

Retraining Intervals and Spaced Learning

The 2020 guidelines acknowledge the benefit of low-dose, high-frequency training without having any specific recommendations on retraining intervals. Still, the AHA and ILCOR suggest using spaced learning as opposed to massed learning (Table 1). We identified 11 studies on different retraining intervals (n = 8) and/or use of spaced learning (n = 3), including 7 randomized simulation studies and 3 observational studies (see table, Supplemental Digital Content 6, studies on retraining intervals and spaced learning, http://links.lww.com/SIH/A743).[29,40,62,73,84,92,98,100,102,106,112] In general, the studies suggest that CPR skills rapidly decay after training, repeating training is associated with better skill acquisition,[92,102] and brief but frequent retraining (every 1–6 months) is better compared with less frequent retraining.[62,73,84,92] Two randomized trials and 1 observational study comparing spaced learning versus massed learning for BLS and pediatric ALS found no significant difference in CC skills between groups. One study found better overall skill acquisition in the spaced learning group,[98] and bag-mask ventilation generally tended to be better in the spaced learning groups.[98,100,106]

E-Learning

Current guidelines recommend that precourse preparation with e-learning may be used for ALS training (Table 1). We identified 17 studies on e-learning (see table, Supplemental Digital Content 5, studies on e-learning, http://links.lww.com/SIH/A742) showing conflicting results, although generally suggesting that e-learning may be efficient when combined with simulation training.[32,34,35,45,46,49] Use of e-learning only may be inferior to traditional ALS training,[99] whereas adding e-learning to conventional BLS or ALS training may positively affect skill acquisition[41] or result in no significant improvements compared with conventional training.[42,44] Studies on e-learning with or without self-training on manikins as compared with conventional training showed diverging results for both BLS training and ALS training.[33,35,45,46] One study found a positive effect of e-learning and practice on manikins using automated feedback as compared with instructor-led training without objective feedback.[46] Overall, 4 studies found diverging results when comparing flipped classroom approaches with e-learning and team-based learning versus traditional courses for BLS[30,47] and ALS.[32,38] Two observational studies showed that 1 or 1.5 days of ALS training + e-learning is associated with comparable knowledge and skill acquisition when compared with traditional 2-day ALS training.[34,49]

Virtual Reality, Augmented Reality, and Gamified Learning

The 2020 AHA guidelines suggest that VR, augmented reality, and gamified learning may be considered for BLS and ALS training (Table 1). We identified 5 studies on this topic (see table, Supplemental Digital Content 7, studies on VR, AR, and gamified learning, http://links.lww.com/SIH/A744).[31,43,48,99,110] One study found no difference between conventional ALS training and VR based ALS training with extensive feedback components.[99] Studies comparing pretraining with VR versus serious gaming and video versus serious gaming found no differences in skill acquisition.[48,110] In comparison, 2 studies found that adding pretraining of serious gaming was superior compared with no pretraining for BLS and ALS training, respectively.[31,43]

Instructor-Learner Ratio

Current guidelines have no recommendations on instructor-learner ratio (Table 1). We identified 2 studies comparing different instructor-learner ratios for BLS training.[50,52] One cluster-randomized study compared different group sizes of 3 to 5 participants per instructor and 7 to 10 participants per instructor in

TABLE 1. Recommendations by Resuscitation Bodies on Retraining, Training Duration, Differentiated/Contextual Learning, Devices (1A), and Trainer-Learner Ratio, E-Learning, Augmented Reality/VR/and Feedback/Debriefing (1B)

A: Existing Recommendations by the ERC, AHA, and ILCOR

	Course Duration	Retraining	Differentiated/Contextual Learning	Devices/Manikins
ERC 2015 guidelines	The optimal duration of instructor-led BLS and AED training courses has not been determined and is likely to vary according to the characteristics of the participants.	Retraining should take place at least every 12–24 mo. High-frequency, low-dose retraining may be considered. It is recommended that individuals more likely to encounter cardiac arrest consider more frequent retraining.	Training should be tailored to the needs of different types of learners.	In centers that have the resources for high-fidelity manikins, we recommend their use. The use of lower-fidelity manikins however is appropriate for all levels of training on ERC courses.
AHA 2020 guidelines	No recommendations	It is recommended to implement booster sessions when using a massed learning approach for CPR training, and it should be considered implementing spaced learning courses in place of massed learning.	The best instructional designs are tailored to specific learning objectives, learner type, and context of learning. It is reasonable to conduct in situ simulation training in addition to, or in place of, traditional training.	Use of higher-fidelity manikins for ALS training can be beneficial at centers with available infrastructure. Alternatively, lower-fidelity manikins may be considered, and it is reasonable to align manikin features with learning objectives.
ILCOR 2020 statements	No recommendations	Skills decay within 3–12 mo after BLS training. Suggest that individuals likely to encounter cardiac arrest consider more frequent retraining and suggest spaced learning instead of massed learning.	No recommendations	Suggest high-fidelity manikins for ALS training when centers have the resources for that; otherwise, low-fidelity manikins are acceptable (weak recommendations).
*AHA evidence statement	No recommendation	The current massed approach to CPR training should be replaced or supplemented with a spaced practice. Debriefing after real resuscitation events and in situ simulation can be used to provide spaced training experiences. No specific interval is recommended.	Instructors should consider optimizing learning context for healthcare professionals (eg, team composition, in situ setting).	Manikins or task trainers should be selected on the basis of the availability of physical features that align with relevant learning objectives.

B: Existing Recommendations by the ERC, AHA, and ILCOR Continued

	Instructor-Learner Ratio	E-Learning	AR, VR, and Gamified Learning	Feedback Devices	Feedback/Debriefing
ERC 2015 guidelines	No recommendation	Self-instruction programmes with hands on practice (eg, video, DVD, online training, computer giving feedback) seem to be an effective alternative to instructor-led courses for laypeople and healthcare professionals learning BLS.	No recommendation	Directive CPR feedback devices are useful for improving compression rate, depth, release, and hand position.	The ideal format of debriefing has yet to be determined. The standard ERC feedback format is the learning conversation.
AHA 2020 guidelines	No recommendation	It may be reasonable to incorporate precourse e-learning into existing ALS courses. A combination of self-instruction and instructor-led teaching is recommended as an alternative to instructor-led courses for lay rescuers.	Gamified learning or VR may be considered for BLS or ALS training for lay rescuers and/or healthcare professionals.	Use of feedback devices during training can be effective in improving CPR performance.	Deliberate practice and mastery learning model may be considered for improving skill acquisition and performance in BLS and ALS courses.
ILCOR 2020 statements	No recommendation	E-learning for BLS not reviewed. Recommends providing the option of precourse e-learning as part of a blended learning approach for participants of ALS courses (strong recommendation, very low to moderate certainty of evidence).	No recommendation	Suggest the use of feedback devices that provide directive feedback on compressions (weak recommendation, low-certainty evidence).	No recommendations.
*AHA evidence statement	No recommendation	No recommendation	Studied and applied game attributes that are refreshed and changed regularly should be used.	Quantitative data should come from several sources, including instructors, CPR devices, and data from simulators.	Feedback and debriefing should be part of a curriculum design and should not occur in isolation. Feedback should be data driven. The debriefings should prepare participants for debriefings after actual clinical events.

*The AHA evidence statements include suggestions and not recommendations per se as it is not a systematic review with evidence grading.

BLS training, finding that groups with 3 to 5 participants per instructor had more time for feedback and discussion compared with larger groups and participants generally preferred group sizes of less than 6 participants per instructor. However, there was no difference in skill acquisition.[52] Another randomized study found no difference in skill acquisition between group sizes of 3, 5, or 8 medical students per instructor in BLS training that was time adjusted (ie, larger group size equals longer course duration), so the hands-on time per participant was equivalent.[50]

Equipment and Manikins

Current guidelines recommend using high-fidelity manikins for ALS training if the resources are available, but low-fidelity manikins may be used instead (Table 1). We identified 6 studies investigating fidelity of manikins[53–57] or Automated External Defibrillators (AEDs) (see table, Supplemental Digital Content 8, studies on equipment and manikins, http://links.lww.com/SIH/A745)[58] of which 4 studies were randomized.[53–55,57] Overall, 1 randomized trial showed improved skill performance after training with high-fidelity manikins compared with low-fidelity manikins for BLS.[53] In contrast, 2 randomized trials found no difference between groups for ALS training.[54,57] Two studies compared bundled interventions with problem-based learning plus high-fidelity manikin training or both low- and high-fidelity training compared with low-fidelity manikin training finding superior results for the bundled interventions.[55,56] An observational study on a tablet-based AED trainer compared with a standard AED trainer for BLS training showed no difference between groups.[58]

Contextual Learning Content

Current guidelines recommend that CPR training be performed to reflect real-world needs (Table 1). We identified 10 studies on contextual learning content: 6 randomized trials[59–61,63,72,103] and 4 observational studies (see table, Supplemental Digital Content 9, studies on contextual learning content, http://links.lww.com/SIH/A746).[64–66,108] The studies suggested that blood-pressure directed CC quality targets reflecting clinical practice in hospitals is effective for training CCs and contextualized curriculums reflecting the clinical setting (including actual time intervals) and shared mental models may be superior to conventional BLS training.[59,60,63,64,72,103] Moreover, simulation-based learning may result in superior skill acquisition when compared with lecture- or video-based learning for BLS and ALS training.[61,65] One before-after study found that implementation of key resuscitation quality targets in hospital ALS training was associated with an increased chance of return of spontaneous circulation and survival to hospital discharge.[66]

Feedback Devices

Current guidelines recommend the use of feedback devices for CPR training (Table 1). We identified 17 studies on feedback devices for CPR training (see table, Supplemental Digital Content 10, studies on feedback devices, http://links.lww.com/SIH/A747).[46,67,74,77,79,81–83,86,89,92,93,96,105,109,138,139] Most studies were on BLS training and generally showed a significant benefit of objective and real-time feedback from feedback devices when compared with no feedback (from device or instructor) or instructor-feedback only (without a feedback device).[67,74,92] Most studies assessed CPR quality immediately after training, but 1 study suggested that real-time audiovisual feedback may improve skill retention at 3 months.[96]

Feedback and Debriefing

Although current guidelines acknowledge feedback and debriefing as an important part of CPR training, they do not recommend any specific method (Table 1). We identified 17 studies on feedback strategies for BLS and ALS training (see table, Supplementary Digital Content 11, studies on feedback and debriefing, http://links.lww.com/SIH/A747).[51,55,60,68–72,75,76,78,80,87,88,90,97] The methods of feedback used for training were context specific and depended on learners' level, experience, learning objectives, and the instructor. Mastery learning[60,69,104] and self-directed learning[46,70,72] with or without an online/e-learning component showed contradicting results when compared with traditional training (instructor-led training). However, instructor-led feedback/debriefing had a higher quality[75] measured using the Debriefing Assessment for Simulation in Healthcare instrument.[140,141] Overall, the addition of objective feedback data improved CPR skills.

Many studies did not describe the feedback methods. However, those described are learning conversation for feedback,[90] the sandwich technique,[78,90] rapid cycle deliberate practice,[60,68] gather-analyze-summarize model,[69] and stop-and-go debriefing.[78] Techniques for debriefing included advocacy with inquiry[70,78] and debriefing with crisis resource management focus.[87] The feedback conversation focus was in all studies related to learning objectives, most often including measures on CPR skills. Although the importance of recognizing the deteriorating patient and initiating CPR is of utmost importance, most BLS courses did not provide feedback in this area. However, those that did had better results in this phase of the cardiac arrest scenario.[60,70,107]

DISCUSSION

This scoping review identified 110 studies relating to 9 prespecified categories considered important when designing CPR training for healthcare professionals. Moreover, we found that several knowledge gaps persist relating to each of the categories.

Course Duration

There were no recommendations on the duration of BLS courses in recent guidelines, and we did not find any evidence to suggest any specific course duration. In comparison, studies on laypersons found contradicting results when comparing different durations of CPR training,[28,142] thus supporting not to suggest any particular course duration for clinicians. Of note, the ERC BLS course and the AHA BLS course for healthcare professionals both have a duration of approximately 3.5 hours, and the ALS courses in both organizations are performed over 2 days.

Notably, several factors may affect the optimal course duration, thus making it difficult to identify a single optimal course duration. Some studies suggested that the ALS course duration may be shortened using e-learning as precourse preparation (see under e-learning). Although precourse preparation may shorten the face-to-face time with an instructor, it may not affect, or even prolong, the time spend for the learner. Even so, precourse preparation has its advantages. Given that the learner may complete the content whenever possible, the learner-time and the instructor-time, should both be considered. Moreover, other factors affecting the course duration may include the specific skill, the learner experience, the context, and the teaching methods including the use of spaced learning formats and mastery learning. Importantly, future research should consider all of these factors when investigating any optimal course duration.

Retraining Strategies

We found a growing body of evidence supporting that retraining may be conducted as low-dose, high-frequency training in line with the 2020 guideline recommendations.[143,144] Notably, the AHA has recently promoted the Resuscitation Quality Improvement program, where healthcare professionals train CCs on a manikin with automated feedback a few minutes every 3 months as an alternative to traditional annual retraining.[145] This approach may be ideal for achieving high-quality CC quality.[146] However, considering the need for learning the BLS algorithm with correct identification of a cardiac arrest, immediate cardiac arrest call with knowledge of the local procedure,[147] use of both compressions and ventilations, and collaboration among hospital providers in a realistic setting, this approach may not stand alone. Frequent and brief in situ simulations (eg, 15 minutes every 3 months) with teams of healthcare professionals, including debriefings, may be a solution for retaining and improving both technical and nontechnical skills for IHCA.[84]

Importantly, the effect of retraining may be modified by using spaced learning (distributing the course curriculum over several weeks or months). Recent guidelines suggest using spaced learning for CPR training,[25] which is a new suggestion based on studies on pediatric providers[62,98,100,106] and knowledge on spaced learning from other research fields.[148] Importantly, studies on spaced learning and retraining intervals mostly assess certain skills, such as compressions and ventilations. However, it remains unknown whether certain skills, such as communication skills, need different retraining strategies compared with CC skills. Finally, the ERC and the AHA courses are currently conducted in a massed learning format, and more studies should address how accredited courses, such as the ERC and AHA courses, could be transformed into a spaced training format to improve skill retention.[98]

E-Learning, Gamified Learning, and VR

Although recent guidelines recognize the benefit of e-learning for laypersons' BLS training, less is known for healthcare professionals. This scoping review suggests that flipped classroom approaches may be used instead of traditional course designs for both BLS and ALS training of clinicians,[34,38,47,49] and e-learning may be used in addition to traditional training with beneficial effect.[41,42,44,149] Moreover, 2 observational studies suggested that ALS training may be conducted with a face-to-face course over 1 or 1.5 days compared with 2 days if using e-learning.[34,49] One may be concerned that self-training and e-learning only will not ensure practical training of critical contextual skills, including nontechnical skills. Although some studies support the use of e-learning and self-training, other studies reported inferior skills when using e-learning only.[33,35,39,45,46,99] This may owe to e-learning being beneficial for knowledge acquisition and knowledge retention without ensuring acquisition of psychomotor skills. Moreover, it is questionable whether nontechnical skills can be learned, or tested, using e-learning or VR as opposed to actual team scenarios. Accordingly, e-learning and self-training should be used in combination with instructor-led simulation but may not be used in isolation.

Contextual Learning: Group Sizes, Equipment, and Content

Contextual learning is widely accepted as an important aspect of training as it increases learner motivation, learning, and transferability of acquired skills.[23] Contextual learning covers all aspects relating to how the training applies to the learners' real-world practice. Thus, this scoping review does not cover all aspects of contextual learning but specifically focuses on 3 parts being relevant to instructors organizing CPR training for healthcare professionals: number of learners per instructor, equipment being used in training, and content of the training. Notably, the international guidelines do not provide any recommendations on the instructor-learner ratio when training.[21,23,25,26] We found very limited new evidence to support any new recommendations on a specific instructor-learner ratio. Finding any ideal instructor-learner ratio may also be challenging as it may depend on the topic and context of teaching. In some cases, instructors may not be needed at all (eg, booster training of CC quality using a manikin with objective feedback), whereas a high instructor-learner ratio may be required in other cases to ensure that there is enough time for feedback when the learner is acquiring a new skill.[50,52] Furthermore, the group composition may be more important than the group size when considering training that reflects clinical practice. Guidelines emphasize the importance of simulation in teams with a group size and setting mimicking real IHCA.[20,22,23] Thus, the instructor-learner ratio may be guided by the appropriate team size when training CPR.[23,150] Of note, the ERC and the AHA use an instructor-learner ratio of at least 1:6 for training BLS and ALS.

Notably, the randomized studies we found on high-fidelity manikins found no difference in learning outcomes.[54,57] In contrast, some observational studies with bundled interventions found large positive effects of high-fidelity manikins, although likely to carry a high risk of bias.[55,56]

We identified some very heterogeneous studies on contextual learning content. We did not identify compelling new evidence to prompt a new systematic review on contextual learning content. However, all studies support contextualization of training, thus supporting current recommendations.[21,23,25,26] Overall, the studies showed that simulation-based training in teams may be superior to lecture-based training and that using a contextual curriculum for in-hospital CPR is superior compared with a curriculum that is not contextualized for the environment.[60] Notably, contextualizing the learning content includes both familiarization with hospital beds and other equipment being used in the clinical setting.[59,60] We did not identify relevant studies on in situ simulation compared with training in, for example, a simulation center. However, previous studies have demonstrated the importance of in situ simulations. It may enable providers and leadership to identify problems with, for example, equipment and train CPR skills in the setting where they will be used.[151–155] Moreover, frequent use of in situ simulations in teams is reported to be associated with higher survival outcomes,[18] thereby supporting the notion of in situ simulations as an important training method.

Feedback Devices and Debriefing

We found increasing evidence supporting the benefit of feedback devices,[46,51,55,60,67–72,74–83,85–93,96,97,104,105,107] which is already recommended in current guidelines.[21,23,25,26] Feedback devices can be used for real-time feedback during training or as a component of data-driven feedback after simulation scenarios or clinical resuscitation attempts. Self-training with automated feedback may be sufficient for the maintenance of technical CPR skills during retraining. However, it is questionable if instructor-less training is sufficient for initial training or acquisition of new skills. Moreover, instructor-less training may not be used to train or retrain nontechnical skills, which are an important part of in-hospital CPR.[128,156–159] In either scenario, mastery learning and a degree of deliberate practice are needed with data-driven feedback from a device and/or an instructor. For the latter, there is no one feedback/debriefing method that seems to be superior to another. However, there is no doubt that rapid cycle deliberate practice has proven effective and may be considered as part of the training strategy.[60,68,104,160]

In IHCA, the recognition of the deteriorating patient is context specific and often determined by local conditions, patient demographics, culture, staff, and skills. Therefore, it would seem relevant to combine the basic CPR skills with a team-based approached and adapt the feedback/debriefing approach to learner groups and context depending on learners' needs.[161–165]

Direction for In-hospital CPR Training

We have focused on CPR training for hospital providers based on the literature on CPR training for healthcare professionals in general. When considering the optimal organization for CPR training for hospital providers, one must consider optimal learning outcomes, learner preferences, patient outcomes, and practical implementation, including financial costs. A recent systematic review found only a few studies investigating the impact of CPR training on survival outcomes.[166] However, most studies do suggest that simulation-based training may increase survival outcomes.[18,66,166] We did not identify any studies on the impact of different CPR training designs on financial costs, neither any studies were investigating practical implementation. Factors believed to be associated with additional costs for training would be increased course duration (removing providers from the floors and instructor salaries) as well as recommendations of using expensive equipment. We did not identify any studies investigating the costs associated with low-dose high-frequency training. However, gray literature and user experiences suggest that low-dose high-frequency training may reduce costs because of lower course expenses and staff spending less time away from clinical work.[167,168] Cost-effectiveness of training depends on not only costs for training but also skill acquisition related to costs and costs per life saved or quality-of-life gained. Thus, future research should ideally investigate costs of training methods as well as the impact on clinical outcomes.

We have summarized considerations on incorporating different learning formats into a low-dose high-frequency CPR training program for hospital staff in Figure 2, which should be considered as a hypothetical model only, and time durations are examples as the optimal time duration is unknown. Notably, this scoping review did not assess the impact of debriefings of real IHCAs. However, other studies suggest that debriefings of real-life events may be used as a supplement to CPR training.[21,23,25,26,169–171]

Knowledge Gaps and Research Priorities

This scoping review identified several important knowledge gaps. Firstly, most identified studies were conducted on healthcare students. Moreover, many of the studies on hospital

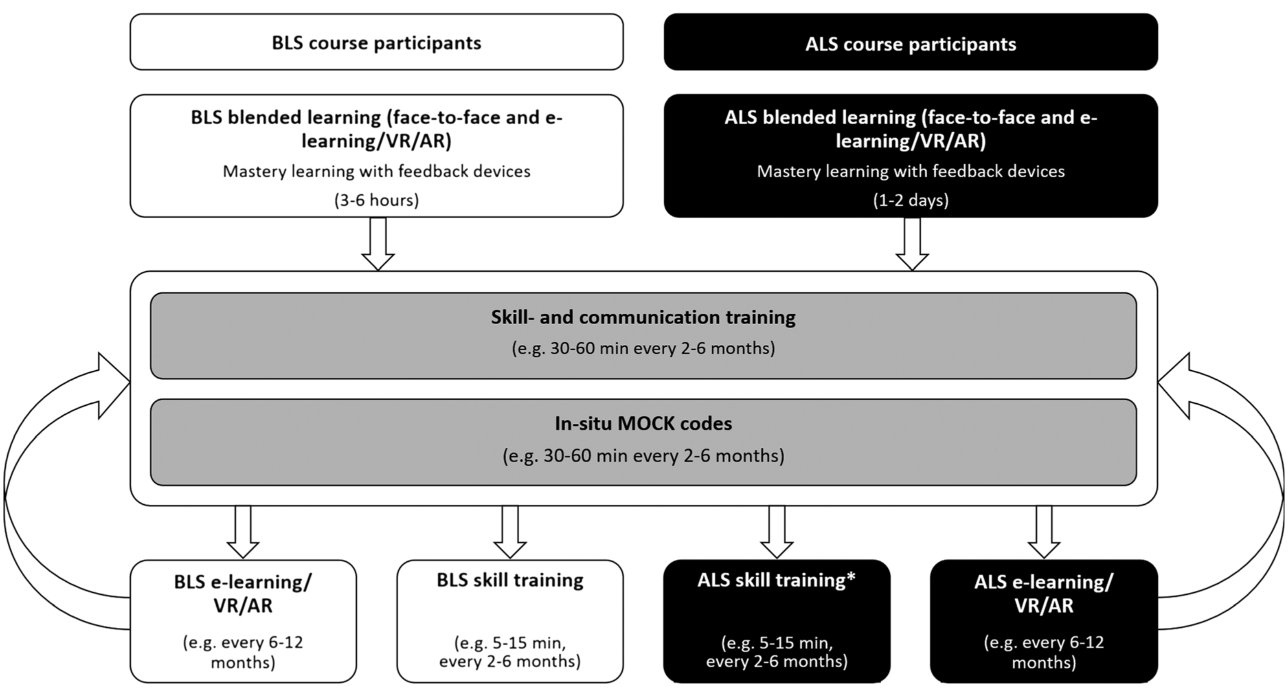

FIGURE 2. Considerations for low-dose, high-frequency CPR training of hospital staff. *ALS may include BLS skills.

providers were based on pediatric providers only. Accordingly, resuscitation education research on clinicians in the adult setting is warranted. In addition, studies should focus on context and content-specific training for the various teams of healthcare professionals. Secondly, the administrative costs and benefits for alternative training methods remain unknown, which is an obvious barrier to implement a contextual training scheme across an organization. Thirdly, most studies assessed skill acquisition immediately after training without assessing skill retention, actual skill performance, and impact on survival outcomes. Thus, most studies correspond to Kirkpatrick level 2, and studies addressing level 3 and 4 are warranted.[172] Fourthly, most studies on technical skill acquisition after CPR training were evaluated in simulation and did not incorporate the complexity of CPR in an advanced life support setting. Many of the included studies examined CC skills only, and only a few studies considered how to train nontechnical skills and how CPR training affects nontechnical skill acquisition. Notably, the optimal training strategy may depend on the skill being trained according to the context to where it should be used. Future studies should address how nontechnical skill training can be acquired and retained in, for example, low-dose, high-frequency CPR training.

Limitations

As this is a scoping review, no formal bias assessment was conducted. Thus, we do not provide recommendations but suggestions, and our findings should be interpreted with caution given the design of this review and the included studies. We included studies on CPR training for healthcare professionals and healthcare students as we believe that training of laypersons and other kinds of training for healthcare professionals will not be relevant to the clinical context of this review although aspects of learning may be transferable across disciplines. Many studies included in this scoping review were based on healthcare students or prehospital healthcare professionals, and one should be careful when applying the results to in-hospital healthcare professionals. Moreover, several studies were not randomized and cannot infer on any causal effect. Importantly, we based our study upon ILCOR statements, ERC and AHA guidelines on education, and the AHA statement on resuscitation education science. Thus, we did not include studies before 2014, and we did not include studies without the full text in English.

CONCLUSIONS

This scoping review identified a growing body of evidence on CPR training methods for healthcare professionals. Based on the available evidence, we suggest using low-dose, high-frequency training with e-learning to achieve knowledge, feedback devices to achieve high-quality CCs, and in situ team simulations with debriefings to improve the performance of provider teams.

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Video Review of Simulated Pediatric Cardiac Arrest to Identify Errors/Latent Safety Threats: A Mixed Methods Study

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Introduction: Outcomes from pediatric in-hospital cardiac arrest depend on the treatment provided as well as resuscitation team performance. Our study aimed to identify errors occurring in this clinical context and develop an analytical framework to classify them. This analytical framework provided a better understanding of team performance, leading to improved patient outcomes.
Methods: We analyzed 25 video recordings of pediatric cardiac arrest simulations from the pediatric intensive care unit at the Alberta Children's Hospital. We conducted a qualitative-dominant crossover mixed method analysis to produce a broad understanding of the etiology of errors. Using qualitative framework analysis, we identified and qualitatively described errors and transformed the data coded into quantitative data to determine the frequency of errors.
Results: We identified 546 errors/error-related actions and behaviors and 25 near misses. The errors were coded into 21 codes that were organized into 5 main themes. Clinical task–related errors accounted for most errors (41.9%), followed by planning, and executing task-related errors (22.3%), distraction-related errors (18.7%), communication-related errors (10.1%), and knowledge/training-related errors (7%).
Conclusions: This novel analytical framework can robustly identify, classify, and describe the root causes of errors within this complex clinical context. Future validation of this classification of errors and error-related actions and behaviors on larger samples of resuscitations from various contexts will allow for a better understanding of how errors can be mitigated to improve patient outcomes.
(*Sim Healthcare* 00:00–00, 2022)

Key Words: Simulation, pediatrics, cardiopulmonary resuscitation, errors, mixed methods, framework analysis.

While better treatments have resulted in improved outcomes from pediatric in-hospital cardiac arrest over time, these outcomes are still unacceptably poor with survival of only 50%,[1] a high rate of permanent disabilities, and poor quality of life in survivors.[2,3] Analysis of a US national registry found that almost 30% of resuscitations included at least one reported error and that there was a significant negative association between survival and presence of error.[4] Of all clinical teams, resuscitation teams are particularly vulnerable to error[5,6] due to the nature of its complex and stressful environment.[7] We need a better understanding of barriers to providing timely and optimal care to children experiencing cardiac arrest.

Team training for resuscitation teams has been associated with improvements in patient outcome at an institutional level[8–11] and is now recommended for all resuscitation team members.[12] However, this training was not developed to address specific errors observed during crisis situations, but rather from what is generally known about teamwork in other high-stakes industries, such as aviation.[13–15] To optimize team training, we need to better understand how resuscitation teams perform, to better teach them how to apply their knowledge and skills.[16]

In this study, we aimed to (1) identify errors in simulated pediatric cardiac arrest in the context that they occur to produce a broad understanding of their etiology and (2) develop an analytical framework to classify and quantify errors in this clinical context.

METHODS

Study Design and Setting

Our organization research ethics board approved this prospective, observational study, and all participants provided informed consent. A cardiopulmonary resuscitation (CPR) quality educational bundle was implemented in the pediatric intensive care unit (PICU) at the Alberta Children's Hospital, Calgary, Canada, from September 3, 2015, to November 22, 2016. We previously reported suboptimal compliance with resuscitation guidelines from analysis of video-recorded simulated pediatric cardiac arrest events that were captured as part of this project.[17] In this study, we report a secondary analysis of these video-recorded simulated events (Table 1).

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TABLE 1. Simulated Events

Clinical Scenarios	No. Events
Shockable events with advance airway/intubated patients	
Tricyclic antidepressant overdose	1
Ventricular tachycardia: myocarditis	3
Ventricular fibrillation: severe hypothermia	3
Ventricular fibrillation: electrocution injury	3
Ventricular tachycardia: hyperkalemia with hemolytic uremic syndrome	3
Shockable events with nonintubated patients	
Myocardial Infarction: Kawasaki patient	2
Ventricular tachycardia: Torsades de Pointes	1
Non-shockable events with advance airway/intubated patients	
Pulseless electrical activity: trauma brain injury, high intracranial pressure, and herniation	3
Pulseless electrical activity: trauma tension pneumothorax	2
Non-shockable events with nonintubated patients	
Severe bradycardia with pulse: postcardiac surgery complete heart block	2
Pulseless electrical activity: cardiac tamponade postcardiac surgery	2

This study was a qualitative-dominant crossover mixed-method analysis,[18,19] using a mono strand conversion design.[20] With the aim of developing an analytical framework to classify errors in simulated pediatric cardiac arrest, we first used framework analysis to identify and classify errors. Framework analysis allowed us to comprehensively describe and understand errors, error-related actions, and behaviors seen in the simulated events to create an interpretive framework, meaningful and useful for educators aiming to improve the quality of care provided during pediatric resuscitations. In addition to framework analysis, we applied a mono strand conversion design to add value to the qualitative data.[21] The frequency analysis of themes helped us draw conclusion regarding frequency of errors, error-related actions, and behaviors seen in the simulated events (Fig. 1).

We followed the recommendations for conducting and reporting simulation-based research, using the extension for observational studies (strengthening the reporting of observational studies in epidemiology).[22] We also followed the standards for reporting qualitative research.[23]

Researchers' Reflexivity

Researchers who performed the video review (first and second authors) were not involved in the events. The first author was unknown to participants, while the second had an ongoing research relationship with some of the participants but had no clinical interaction with them. While reviewing the videos, this author disregarded previous experiences with these participants when observing their actions. Senior author was an attending physician in the unit at the time of video recording and facilitated many of the simulations. While this author acknowledges that she had an ongoing professional relationship with most of the participants during the study, when she reviewed the videos, she reflected on other prior experiences she had witnessed and experienced herself that may help explain the behaviors that she observed. She made a specific attempt to disregard her previous experiences with the specific individuals involved. The author has extensive knowledge of both pediatric resuscitation guidelines (as a member of the International Liaison Committee on Resuscitation)[12,24] but also how they are routinely applied in the real world of pediatric critical care. The guidelines do not account for all clinical scenarios and must be considered in context. This knowledge is essential to identifying what is an actual error as well as attempting to understand why that error may have occurred. The senior author understandings and knowledge about resuscitation and participants in the study become a resource rather than a potential threat to knowledge production.[25]

We used an audit trail with detailed accounts of decisions made throughout the analysis to guarantee rigor and consistency in identifying and classifying the incidents under study.

Data Collection and Analysis

Figure 2 summarizes the steps used to develop our analytical framework and matrix, including familiarization, coding, developing a working analytical framework, applying the framework, and charting following the model by Gale et al.[26] Data collection and analysis were concomitant in this study. To develop a preliminary set of codes, the first author, who was familiar with all the videos and the tasks and procedures that frequently occur or are expected to occur in cardiac arrest resuscitation events, identified relevant segments or incidents that included actions, interactions, and behaviors that were either prone to error, prompted an error, or became the error itself, using a subgroup of the events. These segments constituted our unit of analysis and were depicted using a succinct

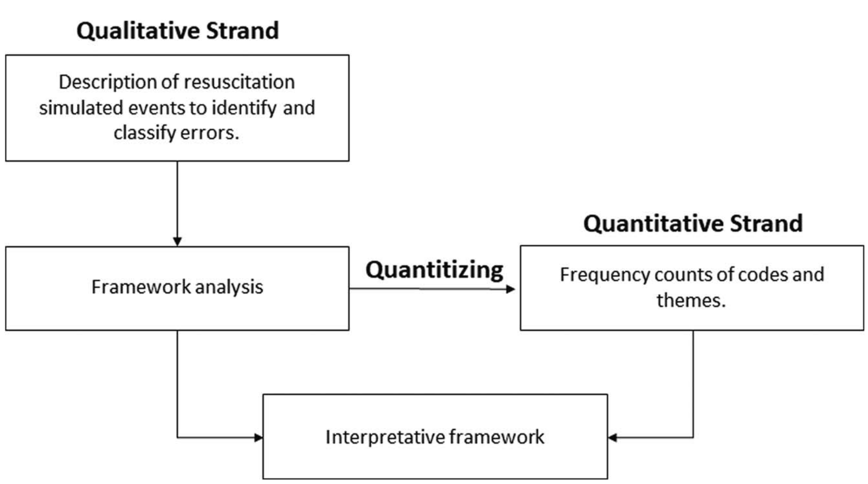

FIGURE 1. Qualitative-dominant crossover mixed-methods design.

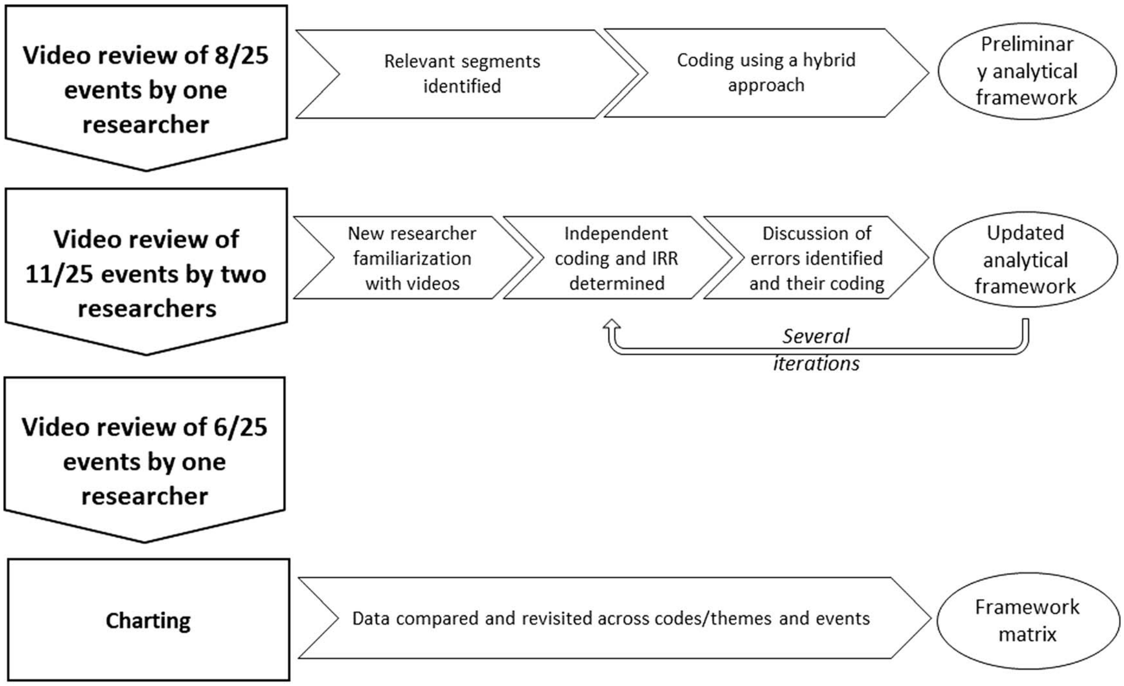

FIGURE 2. Steps taken to develop the analytical framework.

descriptive narrative of the fragment of interest including its timeframe. This analysis was informed by the 2015 American Heart Association guidelines,[27,28] the Clinical Performance Tool a validated pediatric resuscitation guideline-adherence tool,[29] and considered team members' attitudes and behaviors.

To identify and classify errors and/or actions that led to an error, we used a hybrid approach, combining inductive and deductive coding. The same segment was multiple coded if several actions or behaviors were evident and determined the occurrence or likelihood of errors, to appropriately describe the scope and nature of the error happening. Codes were grouped into overarching themes and entered into the framework matrix. We coded near misses using the definition provided by the US Institute of Medicine, as "an act of commission or omission, that could have harmed the patient, but did not cause harm as a result of chance, prevention, or mitigation."[30]

The set of codes identified was discussed with the senior author in several meetings and upon agreement in their definitions, descriptions, and scope, a second researcher was trained in identifying segments with errors and classifying them using the set of codes. Most of the remaining videos were independently coded by the 2 authors and interrater reliability was determined using the Cohen κ coefficient. After independently reviewing and coding each simulation, both authors watched the video recordings together and discussed the incidents identified and their coding. Disagreements in coding were discussed and solved between coders. When agreement was not reached, the senior author made the final decision on the coding. The analytical framework was iteratively revisited and updated at each meeting. The updated framework was then applied to code a subsequent simulation and to review and recode all the previously coded ones if the coding, definitions, or descriptions changed. During this phase, the coding was mostly deductive, but inductive coding was considered, and new codes added if new errors or incidents with errors or prone to errors arose that were not covered in the current set of codes. This process stopped when interrater reliability was consistently 0.6 or higher between coders. One of the 2 researchers coded the remaining video recordings. The senior author, as the medical expert, reviewed all segments with potential clinical implications regardless of agreement or not between coders.

When all video recordings were analyzed, the team met to review the framework matrix. Developing a matrix (charting) is a distinctive step in framework analysis[26,31] that allowed us to revisit codes, merge, or expand them if needed after exhaustively comparing the data across codes, within and between simulations.

Once the final analytical framework was agreed upon, we converted the coded qualitative data into quantitative data (quantitizing). Quantitizing is the process of assigning numerical values (nominal or ordinal) to data conceived as not numerical[21] or transforming qualitative data into numerical formats.[32] We used the frequency count of all codes for quantitizing our data to summarize and interpret the patterns found.[21,33,34]

RESULTS

A total of 104 PICU staff (PICU attending physicians, nurse practitioners, registered nurses, respiratory therapists, and rotating medical residents) participated in 25 in situ pediatric cardiac arrest simulations, all of which were included for video review and analysis. Number of participants, their professional characteristics, and demographics are published elsewhere.[17] See the Supplemental Digital Content 1 (see document, Supplementary Digital Content 1, http://links.lww.com/SIH/A865, diagram of the room) for a diagram of the room where the simulations took place showing the position of the equipment and video recording setup.

We identified 339 relevant segments of interest for analysis in 25 simulated events that were classified into 546 errors or error-related actions and behaviors and 25 near misses. The errors were organized into 5 main areas (themes): (1) clinical task-related errors; (2) planning and executing task-related; (3) communication-related errors; (4) distraction-related errors; and (5) knowledge/training-related errors. Table 2 summarizes

TABLE 2. Frequency of Themes and Codes/Error or Error-Related Actions and Behaviors

Definition	Examples	Error/Codes	Frequency (Percentage of Total Errors, %)
Theme 1: Clinical task–related errors		**Subtotal**	**229 (41.9)**
Errors or behaviors related to medications, time-sensitive clinical tasks, and treatment decisions.	The first shock to be given in PICU is set at 2 J/kg. A first shock was given in ED. This is the second shock and should be given at a double dosage (4 J/kg).	Poor management of a medical condition	23 (4.2)
		Dosage error or medication error	11 (2)
		Delaying an expected task	75 (13.7)
		Fail to act upon a fact or prioritize a proper action	34 (6.2)
		Omissions	86 (15.8)
Theme 2: Planning and executing task-related errors		**Subtotal**	**122 (22.3)**
Failure to project a proper plan or to properly coordinate tasks and resources. Failure to comply with a task or plan and/or poorly executing a task.	Leader plans for a pulse check when switching compressors. Compressors coordinate to follow the leader's plan but switch fast and do not check for pulses. The nurse who becomes compressor starts compressions without leaving time for a pulse check.	Fail to execute a plan/task	19 (3.5)
		Incorrect planning of task	10 (1.8)
		Poor coordination of tasks, time management, and allocation of human resources	41 (7.5)
		Poor execution	28 (5.1)
		Lack of urgency	15 (2.7)
		Performing an unnecessary task	9 (1.6)
Theme 3: Communication-related errors		**Subtotal**	**52 (10.1)**
Failures in properly communicating orders or closing the loop (by team leaders), limitations to perform (by providers). Failure to discuss an unreasonable or unexpected order/recommendation either by the leader or another team member.	Leader asks compressors to switch. The compressors rotated 41 s ago. There is hesitation between compressors, they do not understand the need for switching but do not speak out or mentioned to the leader that they just switched out.	Lack of communication	25 (4.6)
		Miscommunication	26 (4.8)
		Submissive behavior	4 (0.7)
Theme 4: Distraction-related errors		**Subtotal**	**102 (18.7)**
Behaviors that distract or could potentially distract themselves or others from their main tasks.	The RT is hyperventilating the patient. While bagging, the RT is also coaching compressors following Zoll's feedback for CPR quality.	Generating a distraction	2 (0.4)
		Being distracted of main role/task	19 (3.5)
		Lack of or inadequate situational awareness	62 (11.4)
		Leaders' hands-on	19 (3.5)
Theme 5: Knowledge- and training-related errors		**Subtotal**	**38 (7)**
Behaviors that show a lack of knowledge or training, including lack of confidence and failure to express the limitations to perform a task.	Leader confirms with RT that the patient is being ventilated at a rate from 10 to 15/min	Lack of knowledge/training	19 (3.5)
		Uncertainty/Lack of confidence	11 (2)
		Poor or inefficient use of devices' features—Zoll's features	8 (1.5)

themes, definitions and examples, their codes, and frequencies. All codes' definitions and examples are included in the Supplemental Digital Content 2 (see document, Supplementary Digital Content 2, http://links.lww.com/SIH/A866, analytical framework to identify and classify errors and actions that could lead to an error: codes' definition and examples).

Common and Impactful Errors

A subset of errors/codes, along with examples, are further described hereinafter as they were found to be the most common and we believe could have the most potential impact on patient safety.

Omissions

We identified and classified omissions as tasks or actions expected to be done during the event based on rules (American Heart Association guidelines or internal PICU rules) that either did not happen or were expected to happen regularly and were only done occasionally. Examples of tasks not done were leaders failing to indicate proper ventilation rate, length of compressing cycles, CPR quality targets, and missing assigning roles or tasks. Examples of tasks not done frequently enough were performing pulse and/or rhythm checks every 2 minutes in coordination with rotating compressions and following CPR quality.

Delaying an Expected Task

We coded delaying an expected task when we found teams performing tasks that were expected according to guidelines within a certain timeframe but happened later. Examples of these delays were: delivering a first shock after 2 minutes of pulselessness and delivering subsequent shocks longer than 2 minutes when still in a shockable rhythm, delaying compressions more than 30 seconds after recognizing pulselessness, and delaying administering epinephrine in greater than 5 minutes. We found that delaying starting compressions was commonly linked to another error/code, failing to prioritize a proper action.

Lack of or Inadequate Situational Awareness

We used this code when we found that providers disregarded or did not notice important elements of the physical environment or their performance. Examples included: team members failed to recognize poorly performed tasks by themselves or other providers, failed to recognize new information or follow required parameters on monitors, and uncomfortably performed tasks due to the position of equipment, other providers, or uncomfortable clothing and accessories. In general, it was evident how little awareness providers had about the impact of space during resuscitation. Providers commonly failed to communicate whether the space was appropriate for them to work or not and, if necessary, propose new layouts for the room. This lack of situational awareness translated into low-quality chest compressions, wrong ventilation rates, and second and subsequent shocks given at a low energy dose, all of which may impact patient outcome in the real world.

Lack of Knowledge/Training

At times, team members were noted to lack required knowledge or training to properly perform specific tasks, recognize, and verbalize new information (eg, identify a new rhythm on the monitor). This code was applied when we observed team members expressing their lack of knowledge of skills for a task they were assigned and were taught how to perform a task after the leader or other team member recognized incorrect technique or based their performance on wrong knowledge. However, we did not code situations where we could not identify the basis of the wrongdoing, or the poor performance could have been the result either of lack of knowledge or because of a distraction. Therefore, we may have underidentified this code in this study.

Uncertainty and Lack of Confidence

Related to lack of knowledge, we observed providers who appeared hesitant when observing changes in patient status and how to act under these circumstances. These behaviors were evident through vague communications regarding findings or requests for assistance in assessing patients' status, suggesting that team members were afraid of saying the wrong thing or misinterpreting a change. Instead of acting accordingly, providers preferred to share their decision-making process. In general, these situations caused delays and impacted the quality of the resuscitation that may have led to poor patient outcomes, highlighting the need to empower bedside providers to share their knowledge.

Fail to Act Upon a Fact or Prioritize a Proper Action

During some events, a clinical condition was clearly identified and stated by bedside providers (eg, pulselessness) but instead of taking the right action, providers failed to act on it. Examples include calling for help when detecting pulselessness, attaching patient to defibrillator, and placing backboard and/or stools instead of starting CPR immediately. In these situations, providers were clearly aware of the clinical condition and the right course of actions as they worked toward it.

In some cases, bedside providers waited for an order of an attending physician or another senior provider. Like uncertainty and lack of confidence as described previously, these behaviors caused delays in time-sensitive tasks and reinforce the need for empowering bedside providers. In other examples, attending physicians were present and leading the event but vaguely indicated the proper course of actions. For example, during a scenario of ventricular fibrillation associated with severe hypothermia, the leader mentioned several times that "the child is cold and that is likely to be limiting the resuscitative efforts," but other than ordering warmed fluids, the leader does not order any task directed at warming the patient.

Near Misses

We identified 25 near misses in 17 of the 25 events. In all cases, we could identify the root error that was fixed by chance, prevention, or mitigation. Most of the near misses were coupled to an observed error (Table 3), and three were multiply coded, to a total of 29 codes.

TABLE 3. Summary of Near Misses Identified in Relation to Original (Root) Errors Coded

Themes	Codes	Frequency (%)
Clinical task related	Omission	10/25 (40%)
	Delaying an expected task	2/25 (8%)
	Dosage/medication error	1/25 (4%)
Planning and executing task related	Poor coordination of tasks	2/25 (8%)
	Poor execution	2/25 (8%)
	Incorrect planning of tasks	1/25 (4%)
Communication related	Miscommunication	5/25 (20%)
	Lack of communication	1/25 (4%)
Knowledge and training related	Lack of knowledge	1/25 (4%)

Omissions accounted for 40% of the near misses associated root errors. The most common instances coded included situations where goals, target, or tasks were not stated but the tasks were properly done. These omissions seemed to be fixed by individual team member's knowledge or skills (eg, proper ventilation rate, times for rotating compressors, coaching CPR quality). Other code commonly coded with the near misses was miscommunication (20%).

DISCUSSION

We report a unique methodological approach to comprehensively describing the types and source of errors seen within simulated pediatric cardiac arrest events. Applying both qualitative and quantitative methods allowed us to both describe what errors existed, their relative frequency, as well as gaining a better understanding of possible explanations for why these errors occurred. We identified that errors are both common (more than 20 errors per event) and broad in scope (5 unique themes and 21 codes) within this clinical context. The error rate we found is substantially higher than what others have reported. Ornato et al[4] analyzed a large database of real cardiac arrest events and reported a very low rate of resuscitation team error, with greater than 70% of events reporting no errors at all. Given that the source of these data was self-report within a retrospective registry, however, it is likely that reporting bias may have significantly underestimated the true error rate.[35–37] Furthermore, most studies in this field classify and identify what events occurred but do not include what should have happened, so omissions are not frequently reported. Similar to our approach, Yamada et al[38] described error rate and type during neonatal resuscitation, including omissions, and reported a relatively high error rate of approximately 6 errors per event. Finally, our comprehensive approach allowed us to identify and understand near misses. We can learn just as much about the challenges of the resuscitation environment from studying what errors were mitigated. Reason[39] described a "Swiss cheese model" to explain why errors sometimes reach the patient and why sometimes they do not. Studying actual error as well as near misses allows us to identify the "holes" in our health care system so that they can be closed.

Different resuscitation researchers have developed and applied different error identification methods and classification systems. Yamada et al[38] classified neonatal resuscitation errors as either errors of omission or commission but did not code errors related to behavior and rather focused on cognitive and technical skills only. Webman et al[40] used a similar scheme in classifying errors during pediatric trauma resuscitation, with the addition of errors of selection. However, they only analyzed a subset of resuscitations, as they focused solely on events where "nonroutine events" were previously identified.[40] Others focused on identifying and classifying "latent safety threats" (LST), that is, potential system failures, rather than emphasizing behaviors of individuals and the team as a whole.[41,42] Having said that, there is overlap between the themes we identified using our error definitions with latent safety threats identified elsewhere.[42] We believe that this provides validity evidence to our results. It has not yet been determined which approach is ideal; however, we believe that our approach allows for a more comprehensive assessment of errors, as we included errors of omission, commission (which we called performing an unnecessary task), and selection (which overlaps with our identification of delays, planning and executing failures, among others). Furthermore, we identified errors related to cognitive (eg, inadequate situational awareness, lack of urgency), behavioral (eg, lack of communication, delaying an expected task) and technical outcomes (eg, poor execution, poor use of device's features). Finally, our methods included double coding of certain tasks/events to capture multiple error classifications to better explain the root causes of a single error. Coupled with an assessment of near misses, we believe that we are confident that no errors were missed and that we have a full understanding of how they related to each other and how team performance was impacted overall.

It is imperative that whatever the approach and classification system are used, that work in this field continue. There is mounting evidence that errors and delays in providing key therapies during resuscitation are associated with poor outcomes.[43–47] For example, Valenzuela et al[43] reported a decrease in survival rate of 10% for every minute that defibrillation is delayed. Resuscitation team members know that providing prompt defibrillation to a patient in a shockable rhythm is a priority, so we need to understand why these delays and errors happen so that they can be mitigated. Our proposed error framework both identifies the error and attempts to explain why it occurred. It is no longer sufficient to provide resuscitation courses to team members and hope that they will execute the required tasks in an organized and efficient manner. They clearly do not at times, so it is imperative that we have methods to identify when they do not and to understand why.

Moving forward, we will conduct more detailed quantitative testing and integrate it to the qualitative findings to identify types and parts of pediatric resuscitation events that are at higher risk for error, as well as what errors commonly occur together and what errors have more of an impact on patient outcomes. Specifically, statistical analyses will be used to compare frequency of codes between types of simulation scenarios (eg, shockable vs. nonshockable events) and possible associations between codes. Integration of the quantitative analysis will further enrich the interpretative framework and inform recommendations regarding (1) system changes with safety approaches such as force functions, mandatory double checks, checklists, room maps, among others and/or (2) human factors by training empowerment, clarity in communication, improving summaries, and checkpoints to improve situational awareness, etc. The effectiveness of implementing any of these safety approaches can be rigorously studied now that we have a way of clearly measuring their impact.

There are several limitations to this study. First, this framework was developed from a set of simulated pediatric resuscitation events from a single center. We need to further refine and validate this framework with data from other centers and from non-ICU environments (such as the emergency department), as organizational culture, local practices, and resource availability will likely alter the type and relative frequency of resuscitation-related errors. Similarly, our framework needs to be applied to neonatal and adult resuscitation events, as there may be important differences that need to be described for future research in this area to potentially benefit an older patient population.

Second, this framework was developed from simulation-based data. As some centers are now beginning to record and analyze real-life pediatric resuscitation events,[37,48] we will have the opportunity to comprehensively study and describe errors where it really counts—with real patients. Given how hard real-world data are to collect, however,[49–51] simulation-based research will always play a role in this field. It will also allow us to manipulate the resuscitation environment in specific ways with future studies to better understand specific challenges that these teams face in this very complex clinical environment.

Third, some resuscitation-related events, such as medication preparation, were not adequately captured on the videos. Other research has shown that these tasks are also prone to error,[52] so these must be similarly analyzed. In the future, we need to adequately capture the entire team to ensure completeness of our observations.

Fourth, certain elements of human behavior, such as distraction, cognitive load, and situational awareness, are difficult to observe and draw conclusions from, given our inability to read the minds of the participants. However, in the present study, we only coded these when we were able to see the entire sequence of events, actions, and facial expressions. We did not code the events where the expressions were too subtle. In addition, we discussed discrepancies between coders, and if discrepancies persisted, the senior author made the final decision. In future studies, supplementing event analysis with analysis of postevent debriefs and surveys of participants can improve our understanding of these more cognitive processes, so that we can be more confident we are properly inferring from observable behavior.

In conclusion, we have developed a framework that can be applied within future resuscitation research to robustly identify, classify, and describe the root causes of errors within this complex clinical environment. This will allow us, and other researchers, to study how errors can be mitigated to improve patient outcomes in the future.

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