


Rapid degradation of psychomotor memory causes poor quality chest compressions in frequent cardiopulmonary resuscitation providers and feedback devices can only help to a limited degree

A crossover simulation study

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Abstract

Studies report a decline in the psychomotor memory of cardiopulmonary resuscitation (CPR) providers within months of training, but they are prone to subject bias. We hypothesized that this degradation is faster and more prevalent in real world practice. The aims of our study were to

1. assess the quality of chest compressions (CC) delivered routinely by CPR-certified clinicians who are not primed by study conditions, and
2. investigate if psychomotor memory degrades if feedback devices are removed.

Forty anaesthetists and intensivists participated in a voluntary, half-day, randomized crossover study using case-based simulation. Participants were paired and randomly assigned into 2 groups; each receiving automated feedback either in the first or second cycle of CPR. Two cycles of CC and defibrillation (ACLS protocol) were administered on a manikin. CC parameters including overall quality were measured by a feedback device.

The median proportion of good quality CC was poor at baseline but improved with feedback; 38.2% (IQR 27.7, 58.7) to 57.7% (IQR 38.0, 68.7), $P < .05$. The median proportion of good quality CC fell after feedback withdrawal; 50.5% (IQR 24.5, 67.7) to 25.6% (9, 37.6), $P < .05$. No carryover effect was observed. Treatment effect and period effect were detected.

Baseline quality of CC amongst frequent CPR providers is poor, and can be improved partly by feedback devices. As psychomotor memory of good quality CCs degrades rapidly after removal of feedback, a multimodal approach is required for CPR skill retention. Future research on the optimal frequency of CPR training, including the use of feedback devices in clinical practice should be explored.

Abbreviations: ACLS = advanced cardiac life support, AHA = American Heart Association, BCLS = basic cardiac life support, CC = chest compressions, CPR = cardiopulmonary resuscitation, ECG = Electrocardiogram, FF = feedback first, ILCOR = International Liaison Committee on Resuscitation, IQR = interquartile range, NFF = non-feedback first, SD = standard deviation.

Keywords: cardiopulmonary resuscitation, training, feedback, learning, skills retention

Editor: Phil Phan.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Sing health Institutional Research Board ethics committee (CIRB Ref: 2017/2141).

There is no conflict of interest.

Supplemental Digital Content is available for this article.

The datasets generated during and/or analyzed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

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How to cite this article: Lim W, Ong J, Ong S, Teo L, Fook-Chong S, Ho V. Rapid degradation of psychomotor memory causes poor quality chest compressions in frequent cardiopulmonary resuscitation providers and feedback devices can only help to a limited degree: a crossover simulation study. *Medicine* 2021;100:8(e23927).

Received: 13 May 2020 / Received in final form: 25 November 2020 / Accepted: 27 November 2020

<http://dx.doi.org/10.1097/MD.00000000000023927>

1. Introduction

Effective chest compressions (CC) during cardiac arrest, of adequate depth (5 to 6 cm) and rate (100 to 120 per minute), with minimal interruption improves survival.^[1–3] During cardiopulmonary resuscitation (CPR), trained providers often deliver CC without knowing its effectiveness. Deterioration of CC has been reported to occur within 6 months to a year after training^[4] implying muscle memory loss. This is compounded by the infrequency of in-hospital cardiac arrests (approximately 2 per 1000 admissions^[5]) leading to a potential decline in the quality of CC.

In the last decade, feedback devices have been designed to improve the quality of CC.^[6–9] These devices also allow uninterrupted rhythm analysis during CPR. Two systematic reviews and meta-analyses reported evidence supporting the use of feedback devices during training and CPR.^[9,10] When used during training, these feedback devices promote objective debriefing and longer retention.^[2,11] Although CPR quality is improved, improvement on patient outcome or survival has not been reported.^[8,9] Hence, the International Liaison Committee on Resuscitation (ILCOR) and the American Heart Association (AHA) have made cautious recommendations on the use of feedback devices during resuscitation.^[12–14] In their absence, first responders rely on skills retained from prior CPR training to deliver what they believe to be optimal CC during resuscitation. In our hospital, CPR feedback devices have not been widely adopted due to a lack of familiarity and cost. Additionally, our hospitals code blue team comprises an anaesthesiologist and/or intensivist, a junior doctor and a nurse. We hypothesized that psychomotor memory degrades rapidly even in this group of trained CPR providers and regular code blue responders, affecting their ability to deliver good quality CC.

The primary objectives of our study were to assess

1. the quality of chest compressions (CC) delivered routinely by regular code blue responders who are not primed by study conditions, and
2. the effect of feedback devices on CC quality.

Our secondary objectives were to evaluate the rate of deterioration in CC quality if automated feedback is removed, and to evaluate learner retention from CPR indices.

2. Materials and methods

2.1. Ethics

The study was approved by the Sing health Institutional Research Board ethics committee (CIRB reference 2017/2141). Written informed consent was obtained from participants.

2.2. Study design

A randomized, crossover study was conducted in Singapore General Hospital in November 2016. An email invitation for study participation was sent to all doctors in the department of anaesthesiology and intensive care 1 week prior to the study. A convenience sample of 40 doctors (specialists and junior doctors), with valid certification in Basic Cardiac Life Support (BCLS) and Advanced Cardiac Life Support (ACLS) participated voluntarily. Participant details including gender and designation were collected. (See Table 1 for demographics details). No financial incentives were offered for participation. A Zoll CPR training manikin (AED Plus Demo Manikin) and the ZOLL “R” series Plus (USA) defibrillator (Product code: 252-0005-2013-10053) with an accelerometer, providing real-time audio and visual feedback prompts were used in our study.

Participants were randomly assigned to 1 of 2 groups: Feedback first (group FF) with CPR feedback provided first in period 1, or non-feedback first (group NFF) with feedback provided in period 2. The allocation ratio was 1:1 and the allocation sequence was based on the order of walk-in by the participants, with alternate allocation to either group (FF or NFF). Recruitment was stopped after 40 participants were enrolled. Participants were paired as this mimicked a code blue resuscitation where CC providers change to minimize fatigue. Figure 1 shows the flow of CPR simulation interventions in the 2 randomized groups.

Before performing CC, participants were given a brief 30-second verbal description on the use and information provided by the automated feedback device. The simulation utilized a clinical vignette of an intubated and anaesthetized patient who developed ventricular fibrillation during an orthopaedic surgical procedure. Two defibrillation pads were applied to the chest of the manikin prior to simulation as shown in Supplemental Digital Content (Appendix 1: <http://links.lww.com/MD/F512>). These do not discharge into the manikin, thereby eliminating an accidental shock delivered to the participants. The manikin was placed on a firm, flat table and the study was performed in a quiet, isolated room. Besides a signal used to start and stop the simulation, no other external assistance was provided. Each pair performed 2 cycles of continuous CC and defibrillation (without ventilation attempts) according to the ACLS protocol on the manikin. Each cycle lasted 10 minutes with a 5-minute rest between each cycle.

2.3. Measured outcomes

CC rate, CC depth, the proportion of adequate CC rate, the proportion of adequate CC depth, the proportion of good CC quality, compression fraction, pre-shock pauses, peri-shock pauses,

Table 1
Demographics of participants.

Characteristics	FF group (N=20)	NFF group (N=20)	Both groups (N=40)
Age (years)	28 (27, 33)	31 (28, 35)	29 (27, 34)
Gender	Female	16 (80%)	6 (30%)
	Male	4 (20%)	14 (70%)
Designation	Non-residents	8 (40%)	8 (40%)
	Junior Resident	7 (35%)	4 (20%)
	Senior Resident	2 (10%)	3 (15%)
	Consultant Specialist	3 (15%)	5 (25%)
			22 (55%)
			18 (45%)
			16 (40%)
			11 (27.5%)
			5 (12.5%)
			8 (20%)

Data are presented as median (IQR) for continuous data and count (%) for categorical data.

$P = .001$ for chi-square test.

FF group = feedback first group, NFF group = non-feedback first group, IQR = interquartile range.

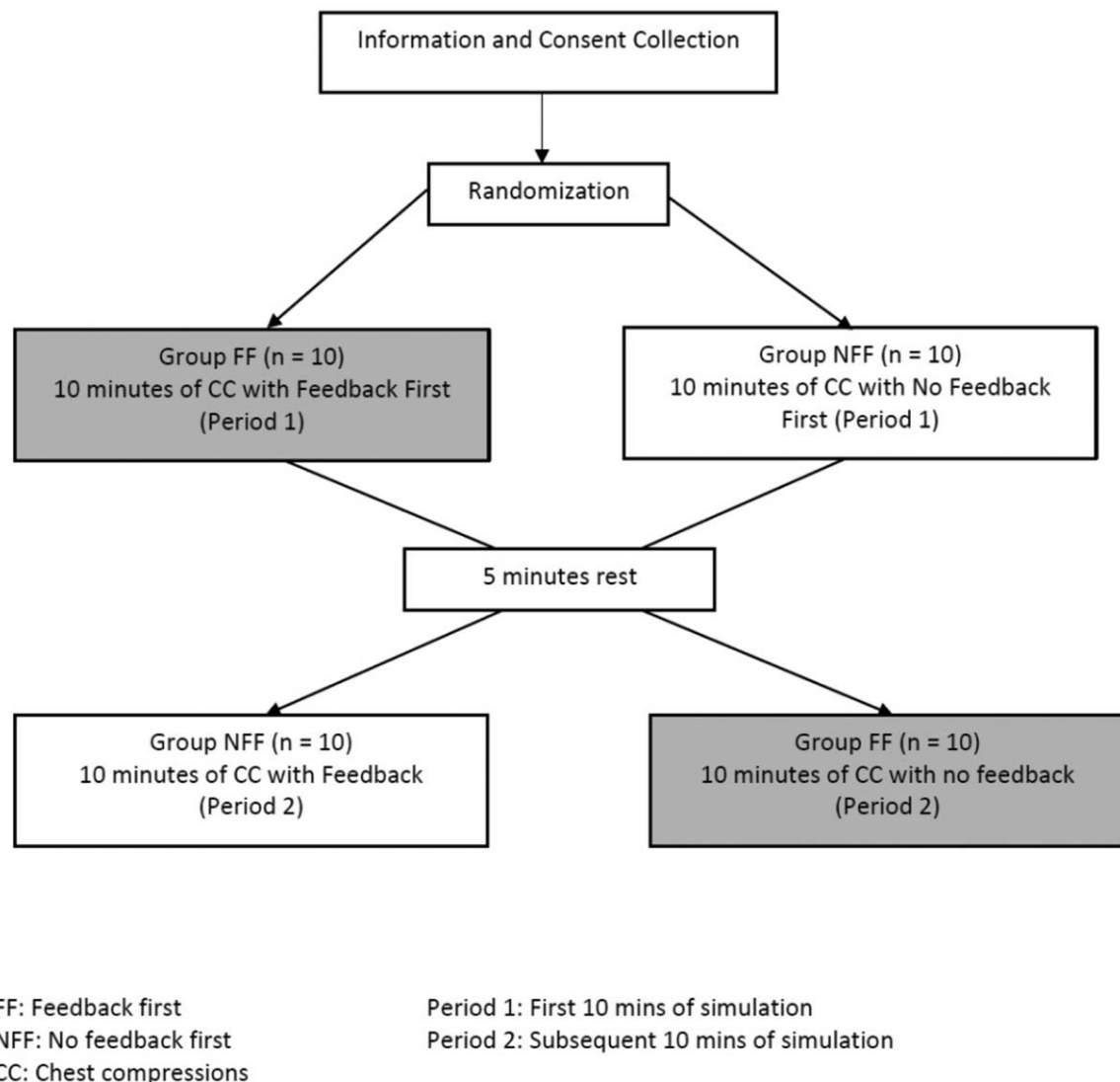


Figure 1. Flowchart of allocation and sequence.

and post-shock pauses were measured as outcome variables. Compression fraction is defined as the proportion of time spent delivering CC during CPR. Peri-shock pause is defined as the duration of interruption interval during defibrillation. Good quality CC was defined in accordance with AHA 2015 guidelines by adequate rate (100 to 120 per minute), adequate depth (5 to 6 cm), adequate CC compression fraction >80% and short peri-shock pauses; that were measured by the ZOLL “R” series plus defibrillator with feedback device. Verbal instructions advising correction action were provided by the feedback device when the quality of CPR deviated beyond set parameters. Real-time visual feedback on CC rate and depth were also displayed on the defibrillator monitor. The data recorded and stored in the defibrillator device was extracted using the manufacturers software (©Rescue Net Code Review). There was no corrupt or missing data.

2.4. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 23. Chi-Squared test was used to test for associations

between categorical variables such as participants gender and designation. The Shapiro–Wilk test was used to test continuous CC variables for normality. The average CC depth and average CC rate were found to follow a parametric distribution and these values were presented as mean \pm 1 standard deviation (SD). Other measured variables (chest compression fraction, percentage of good chest compression quality, percentage of adequate chest compression depth, percentage of correct chest compression rate, pre-shock pauses, peri-shock pauses, and post-shock pauses) were non-parametric and these were presented as median and interquartile range (IQR).

Paired comparisons of parametric CC variables within the same group between period 1 and period 2 were performed using paired *t*-tests. For dichotomous readings (i.e. adequate compression fraction >80%), Mc Nemar test was conducted. Comparisons of parametric CC variables between the FF group and the NFF group within the same period, were performed using independent *t*-tests. Non-parametric CC variables in period 1 and period 2 were tested by Wilcoxon Signed Rank test within each group. The Mann–Whitney *U* test was used to compare

nonparametric variables between the FF group and the NFF group. All tests were two-tailed with a 5% significance.

The carryover effect was tested by comparing combined CC variables from both periods between each group i.e., CC variable in FF group (Feedback + No Feedback) vs NFF group (No Feedback + Feedback). The treatment effect was tested by comparing the difference in period-specific “treatments” in both groups i.e., CC variable in FF group (Feedback - No Feedback) vs NFF group (No Feedback - Feedback). The period effect^[5,15] was tested by comparing differences in CC variables irrespective of period i.e., CC variable in FF group (Feedback - No Feedback) vs NFF group (Feedback - No Feedback). If period effect was detected, data from period 1 was analyzed and compared against CPR, with and without feedback to confirm the validity of our results.

3. Results

3.1. Participant demographics

The majority of the participants that enrolled in our study were trainee doctors (80.0%), however, trainee doctors attend cardiac arrest situations most frequently in our institution (Table 1). The gender distribution in the sub-groups were also unequal and was likely due to chance during the randomization process.

3.2. The baseline quality of CC was generally very poor without a feedback device

CC quality was measured by number of chest compressions delivered within the recommended targets in comparison to the total number of chest compressions delivered. The median

proportion of good quality CC delivered without a feedback device was 38.2% (IQR: 25.6, 58.7) in both groups (Fig. 2). In clinicians that had not been conditioned by the feedback device at the start of the study (NFF group), the median proportion of good quality CC was 4.7% (IQR: 2.1, 19.0). The proportion of adequate CC rate and the proportion of adequate CC depth were the 2 parameters with the worst performance (Table 2). For clinicians that initially performed CPR with a feedback device (FF group), the median proportion of good quality CC was only 25.6% (IQR: 9.1, 37.6) after feedback was removed.

3.3. The use of a feedback device improved the quality of CC

Statistically significant carry-over effects were excluded in feedback and no-feedback CC variables in both groups; *P* values ranged from .31 to .88 (Table 3). A “treatment” effect was observed in both groups (Table 3). With feedback, the median proportion of good CC was observed to be higher compared to without feedback in both groups; 57.7% (IQR 38.0, 68.7) vs 38.2% (IQR 27.7, 58.7) respectively, *P* < .05 (Fig. 3). For clinicians who began CPR without a feedback device (NFF group), the median proportion of good quality CC improved from 4.7% (IQR 2.1, 19.0) to 58.7% (IQR 47.3, 70.2) after a feedback device was introduced. This difference was statistically significant; *P* < .01 (Fig. 4). Clinicians who began CPR with a feedback device at the start of the study (FF group) delivered a similar proportion of good quality CC (median 50.5%, IQR 24.5, 67.7) while feedback was provided. There was no statistical difference between the proportion of good quality CC delivered by both groups in the presence of a feedback device (*P* = .25).

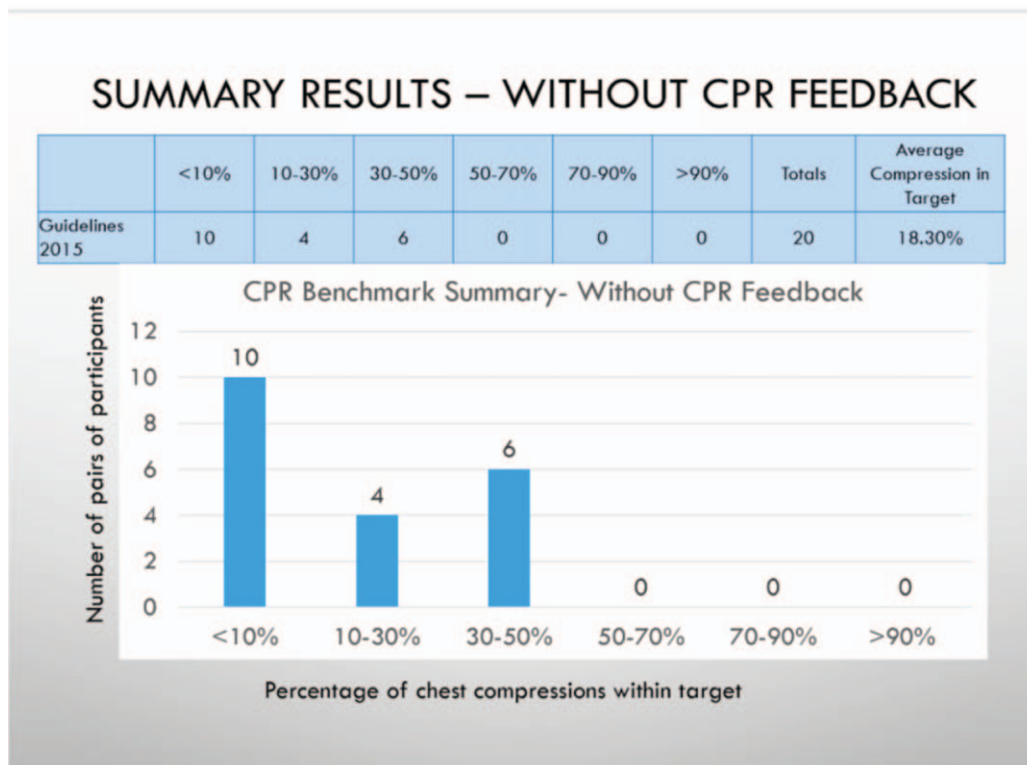


Figure 2. Chest compression quality without use of a feedback device.

Table 2
Summary of CPR indices for both groups, FF and NFF.

End-point	FF group (N=10 pairs)			NFF group (N=10 pairs)			Both groups (N=20 pairs)		
	Period 1: With Feedback (A)	Period 2: No Feedback (B)	(A) vs (B) P value	Period 1: No feedback (C)	Period 2: With Feedback (D)	(C) vs (D) P value	No Feedback (E)	With Feedback (F)	(E) vs (F) P value
Rate (/min)	116±7	108±7	<.01	112±14	113±7	.81	114±7	111±7	.10
Adequate rate (%)	74 (64, 82)	70 (43, 75)	.17	41 (25, 49)	87 (62, 94)	<.01	46 (33, 73)	79 (63, 90)	<.01
Depth (cm)	5.7±0.4	5.4±0.5	.07	5.6±0.7	5.6±0.2	.89	5.5±0.4	5.6±0.3	.32
Adequate depth (%)	70 (46, 75)	52 (26, 62)	.14	32 (16, 38)	71 (68, 73)	<.01	38 (21, 52)	71 (67, 74)	<.01
Compression fraction (%)	82 (79, 89)	87 (85, 91)	<.05	85 (76, 90)	90 (89, 93)	<.01	87 (84, 90)	89 (82, 91)	<.01
Adequate compression fraction >80%	6 (60%)	9 (90%)	.25	7 (70%)	10 (100%)	NA	16 (80%)	16 (80%)	1.00
Peri-shock pauses (s)	15.1 (10.2, 28.6)	15.2 (9.3, 18.3)	.11	14.8 (8.6, 22.4)	12.3 (6.9, 15.6)	<.01	15.2 (8.8, 21.0)	13.6 (9.1, 18.2)	.62

*Both groups = data from both randomized groups merged based on whether feedback was received, irrespective of the period when feedback was received. Data in the table are represented as mean ± 1 S.D. for continuous parametric data, median ± IQR for non-parametric continuous data, and count (%) for categorical data. FF group = Randomization group with Feedback in First Period. NFF group = Randomization group with No Feedback in First Period. NA = cannot be computed as the tabulation for Mc Nemar test had all of the cases (i.e., 100%) with compression fraction >80% in period 2. CPR = cardiopulmonary resuscitation; FF = feedback first; NFF = non-feedback first; IQR = interquartile range; NA = not applicable; S.D = standard deviation.

Overall in all participants, automated feedback exerted its greatest impact by improving the proportion of adequate CC rate, the proportion of adequate CC depth, and the compression fraction (Table 2). Compression fraction is defined as the total time spent on chest compressions (numerator) during the CPR cycle (denominator). Nonetheless, the overall proportion of good quality CC was still low despite feedback in both groups (50.5%–58.7%) and this suggests automated feedback devices alone are inadequate measures to achieve the recommended target of >90% good CC quality.

3.4. CC quality deteriorated after feedback removal and indicated rapid psychomotor memory degradation

A low proportion of good quality CC was observed before feedback was provided (median 4.7%, IQR 2.1, 19.0); this indicated a high degree of psychomotor memory degradation had occurred in these frequent CPR providers since their last CPR recertification assessment (>90% good quality CC required for recertification). Furthermore, the median proportion of good quality CC in the FF group decreased from 50.5% (IQR 24.5, 67.7) with feedback to 25.6% (IQR 9.1, 37.6) after feedback was removed, *P* < .05 (Fig. 4). This suggests that even after 1 cycle of CPR with feedback, psychomotor retention degraded rapidly after 5 minutes of rest, and re-learning was suboptimal.

Table 3
Test for carryover effect, treatment effect, and period effect of automated feedback.

Variables	Carryover effect, P value	Treatment effect, P value	Period effect, P value
Mean depth	.62	.23	.17
% Correct depth (5–6cm)	.55	<.01	<.05
Mean rate	.89	.11	<.05
% Correct rate (100–120 bpm)	.31	.20	<.05
% Good compression quality	.87	<.01	<.05
Compression fraction (>80%)	.17	.62	<.01
Pre-shock pause	1.00	.37	.11
Post-shock pause	.55	.85	.11
Peri-shock pause	.69	.41	.06

3.5. Period effects were observed in both groups of participants

Statistically significant period effects were observed (Table 3). Overall, the mean difference in the CC rate was higher in the NFF group than the FF group; 0.87 ± 5.8 vs -7.3 ± 10.8 , *P* < .05. The mean difference in the proportion of adequate CC rate and the proportion of adequate CC depth were higher in the NFF group compared to the FF group; $38.0\% \pm 27.1\%$ vs $12.1\% \pm 26.6\%$, *P* < .05 and $42.4\% \pm 15.4\%$ vs $15.8\% \pm 28.9\%$, *P* < .05 respectively. The mean difference in the proportion of good quality CPR was notably higher in the NFF group; 46.3% vs 22.3% , *P* < .05. The compression fraction was higher in both groups in Period 2 than Period 1; 89.4% (IQR 87.1%, 91.4%) vs 80.1% (IQR 65.4%, 89.8%) respectively, *P* < .01. These differences may be explained by some degree of learned behavior during Period 1 and the demographic composition of the groups.

4. Discussion

Our study shows that the quality of CC delivered routinely by clinicians without feedback devices are largely suboptimal. Importantly, significant deterioration in the quality of CC after a 5-minute rest period occurred, even in regular code blue responders are expected to have better psychomotor memory. Furthermore, psychomotor retention after automated feedback provision was observed to degrade very rapidly once feedback was removed. This was in contrast to several studies reporting CPR skill decay ranging from 3 to 6 months after training sessions of varied duration (1 to 4 hours) and interval (3 to 6 months^[2,4]).

Our study did not include a training session because our primary objective was to evaluate the quality of CC delivered by regular code blue responders in real world practice (i.e., how CPR-certified clinicians deliver CC routinely without being primed by study protocols). We performed a brief cross-sectional study to minimize the “Hawthorne effect”.^[16] This is an important distinction because the observations reported in current literature were made from longitudinal studies. Participants in longitudinal studies were undoubtedly primed by training at the beginning of study and made aware that they would be reassessed at regular intervals, thus influencing their behavior and the study outcome. In contrast, our participants were not primed and were aware that they would not be assessed

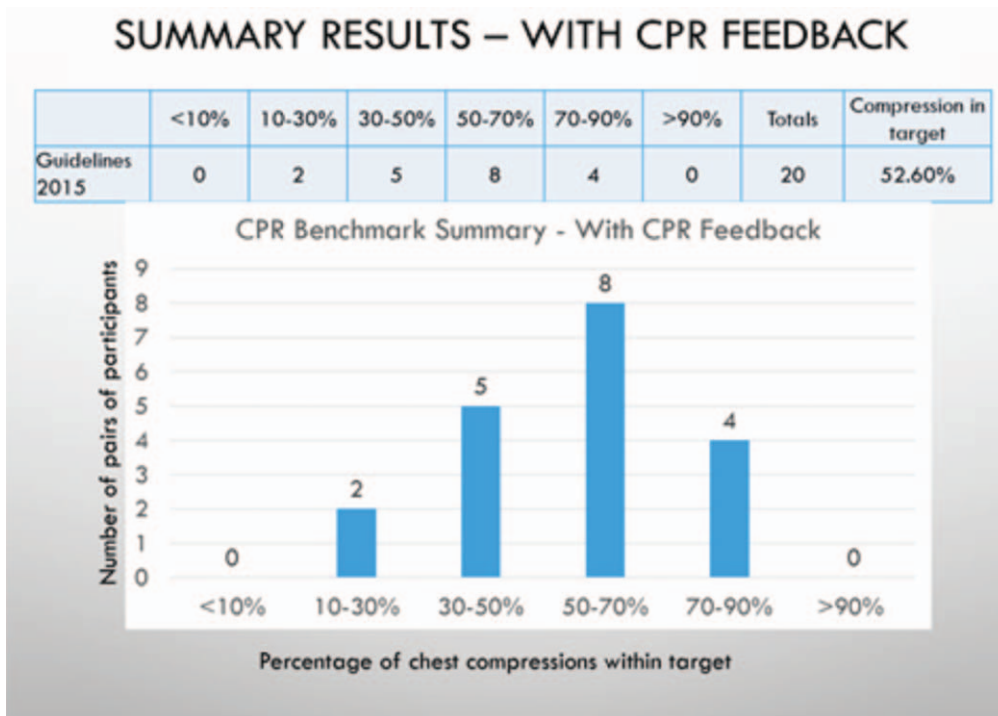


Figure 3. The effect of a feedback device on chest compression quality.

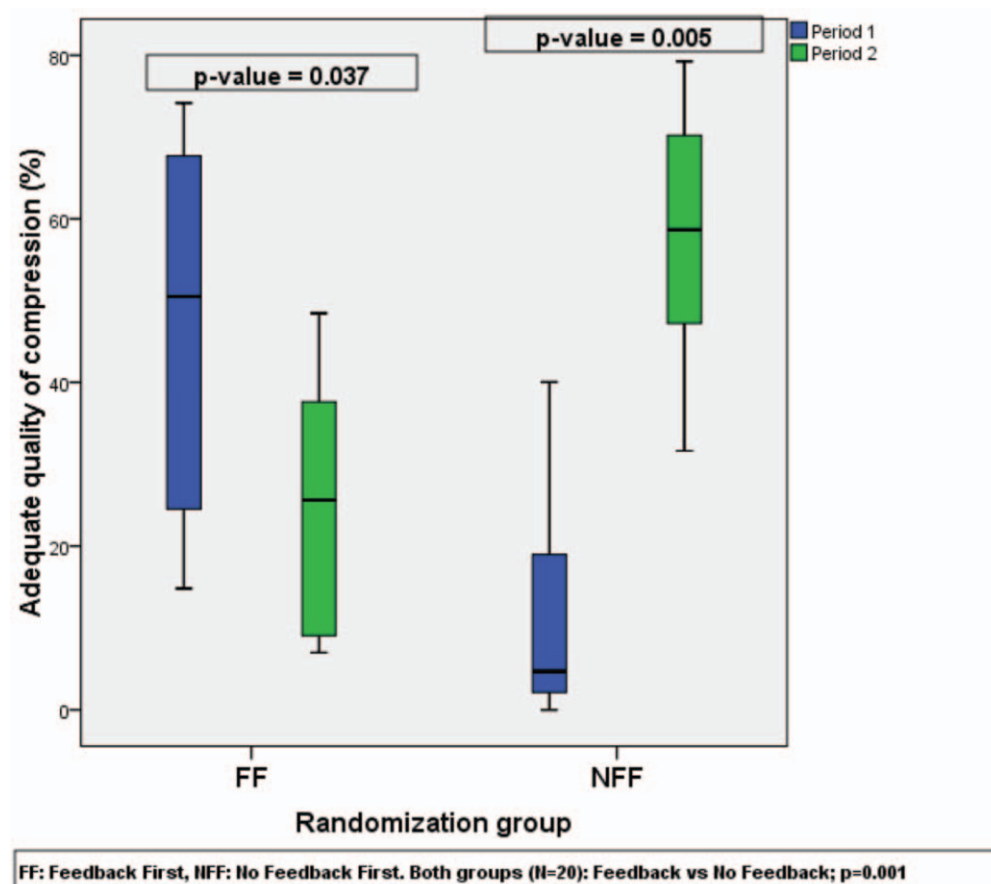


Figure 4. The effect of removing automated feedback on chest compression quality.

regularly thereafter. These could account for some of the differences observed in this study (reflecting actual clinical practice), when compared to other studies.

Psychomotor skills acquisition, including CPR training have evolved over the years.^[17] Sawyer et al proposed an evidence-based pedagogical framework for procedural skill training using simulation^[18] with 6 steps of Learn, See, Practice, Prove, Do, and Maintain. The initial “Learn” step involves both a cognitive and psychomotor phase. The sixth step “Maintain” necessitates continued and consistent training to ensure retention. We postulated that the brief 10-minute simulation in our study with the feedback device in the FF group, was insufficient to address the “Learn” step that enables psychomotor retention.^[19] Additionally, the poor baseline quality of CC amongst regular code blue responders in our study reflected a lack of the “Maintain” step. Shorter training intervals (i.e., daily compared to monthly or quarterly), followed by distributed practice reduces skill decay. This was reported by Oermann et al. who observed significant improvement in CPR performance and skill retention with spaced training sessions among nursing students.^[20] Zhou et al also reported that CC quality was maintained at 3 months after high frequency, low dose training (3 45-minute sessions, weekly), despite a significant decline at 12 months.^[11] Refresher training sessions undertaken every 3 to 6 months may also boost self-confidence and improve CC performance.^[21] Practically however, frequency of training is limited by cost and manpower. Nevertheless, regular practice is recommended over a massed approach to resuscitation training in the most recent AHA guideline in 2018.^[9] Overall, we observed an improvement in CC quality with the use of a feedback device, consistent with those previously reported.^[4–9,23] This was also supported by systematic reviews which demonstrated that CPR feedback devices used during training improved CPR skill acquisition and retention.^[9,21] However, in our study, both groups achieved only 50.5% to 58.7% (medians) of good quality CC, despite the use of a feedback device, which was far from the recommended target of >90%. This was consistent with earlier studies where good quality CC ranged from 42%^[8] to 78%,^[22] demonstrating that feedback devices alone are inadequate. The inability to perform consistent, good quality CC during resuscitation despite the use of feedback devices may account for the lack of better patient outcomes as reported in literature.^[8,9] Hence, it appears that a multi-modal approach to CPR skill retention is required which combines knowledge-based testing,^[4] regular training sessions^[22] and debriefing.^[23]

In addition to providing feedback on CPR indices, the automated feedback device also allows for rhythm analysis during defibrillation charging, thereby minimizing interruption to continuous CC, particularly before defibrillation, which has been associated with greater resuscitation^[1] and cardioversion failure.^[3,8] In our study, the average pre-shock pause was further reduced to 9.42 seconds with feedback, which was within the recommended target of 10 seconds by the AHA guidelines.

Our study has several limitations. Firstly, our sample size was small although representation encompassed all staff grades, ranging from junior doctors to senior specialists. Secondly, there was unequal gender representation in the different groups as a result of randomization. Thirdly, we did not evaluate the interval from the participants prior BCLS or ACLS certification to the current simulation session to estimate the degree of retention present. Fourthly, we did not conduct a code sequence to mirror

an actual code blue event as our primary objective was to determine the degradation of the quality of CC.

5. Conclusion

In summary, the baseline quality of CC amongst frequent CPR providers is poor. Psychomotor memory of delivering good quality CCs degrades rapidly (within minutes) after a feedback device is removed. Although feedback devices improve the quality of CC, this was still insufficient for the recommended target of >90%. A multi-modal approach may be required for CPR skill retention; one which combines knowledge-based testing,^[4] debriefing,^[23] together with the use of an automated feedback device. Further research on the optimal frequency and duration of CPR training with a feedback device, including its utility in routine clinical practice should be explored.

Author contributions

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Writing – original draft: Wan Yen Lim, John Ong, Li-Ming Teo.

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References

- Neumar RW, Shuster M, Callaway CW, et al. Part 1: executive summary: 2015 American Heart Association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation* 2015;132:S315–67.
- Allan KS, Wong N, Aves T, et al. The benefits of a simplified method for CPR training of medical professionals: a randomized controlled study. *Resuscitation* 2013;84:1119–24.
- Valenzuela TD, Kern KB, Clark LL, et al. Interruptions of chest compressions during emergency medical systems resuscitation. *Circulation* 2005;112:1259–65.
- Yang C-W, Yen Z-S, McGowan JE, et al. A systematic review of retention of adult advanced life support knowledge and skills in healthcare providers. *Resuscitation* 2012;83:1055–60.
- Nolan JP, Soar J, Smith GB, et al. Incidence and outcome of in-hospital cardiac arrest in the United Kingdom National Cardiac Arrest Audit. *Resuscitation* 2014;85:987–92.
- Vahedian-Azimi A, Hajjesmaeli M, Amiravadvkouhi A, et al. Effect of the Cardio First Angel™ device on CPR indices: a randomized controlled clinical trial. *Crit Care* 2016;20:147.
- Gruber J, Stumpf D, Zapletal B, et al. Real-time feedback systems in CPR. *Trends Anaesth Critical Care* 2012;2:287–94.
- Bul on C, Delaunay J, Parienti J-J, et al. Impact of a feedback device on chest compression quality during extended manikin CPR: a randomized crossover study. *Am J Emerg Med* 2016;34:1754–60.
- Yeung J, Meeks R, Edelson D, et al. The use of CPR feedback/prompt devices during training and CPR performance: a systematic review. *Resuscitation* 2009;80:743–51.
- Kirkbright S, Finn J, Tohira H, et al. Audiovisual feedback device use by health care professionals during CPR: a systematic review and meta-analysis of randomised and non-randomised trials. *Resuscitation* 2014;85:460–71.
- Zhou X-L, Wang J, Jin X-Q, et al. Quality retention of chest compression after repetitive practices with or without feedback devices: a randomized manikin study. *Am J Emerg Med* 2020;38:73–8.

- [12] Goharani R, Vahedian-Azimi A, Farzanegan B, et al. Real-time compression feedback for patients with in-hospital cardiac arrest: a multi-center randomized controlled clinical trial. *J Intensive Care Med* 2019;7:5.
- [13] Bhanji F, Finn JC, Lockey A, et al. Part 8: education, implementation, and teams: 2015 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. *Circulation* 2015;132:S242–68.
- [14] Soar J, Mancini ME, Bhanji F, et al. Education, Implementation, and Teams Chapter Collaborators Part 12: Education, implementation, and teams: 2010 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations. *Resuscitation* 2010;81:e288–330. doi: 10.1016/j.resuscitation.2010.08.030.
- [15] Pocock SJ. *Clinical Trials: A Practical Approach*. New York.: John Wiley & Sons; 2013.
- [16] McCambridge J, Witton J, Elbourne DR. Systematic review of the Hawthorne effect: new concepts are needed to study research participation effects. *J Clin Epidemiol* 2014;67:267–77.
- [17] Nestel D. The science of teaching of psychomotor skills – and a little bit of art too. *Ultrasound Med Biol* 2019;45:S30.
- [18] Sawyer T, White M, Zaveri P, et al. Learn, see, practice, prove, do, maintain: an evidence-based pedagogical framework for procedural skill training in medicine. *Acad Med* 2015;90:1025–33.
- [19] Cheng A, Nadkarni VM, Mancini MB, et al. Resuscitation education science: educational strategies to improve outcomes from cardiac arrest: a scientific statement from the American Heart Association. *Circulation* 2018;138:e82–122.
- [20] Oermann MH, Krusmark MA, Kardong-Edgren S, et al. Training interval in cardiopulmonary resuscitation. *PLoS One* 2020;15:e0226786.
- [21] Riggs M, Franklin R, Saylany L. Associations between cardiopulmonary resuscitation (CPR) knowledge, self-efficacy, training history and willingness to perform CPR and CPR psychomotor skills: a systematic review. *Resuscitation* 2019;138:259–72.
- [22] Peberdy MA, Silver A, Ornato JP. Effect of caregiver gender, age, and feedback prompts on chest compression rate and depth. *Resuscitation* 2009;80:1169–74.
- [23] Dine CJ, Gersh RE, Leary M, et al. Improving cardiopulmonary resuscitation quality and resuscitation training by combining audiovisual feedback and debriefing. *Crit Care Med* 2008;36:2817–22.