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Chest Compression Quality in a Newborn Manikin: A Randomized Crossover Trial (August 2016)

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ABSTRACT The objective of this paper was to examine the changes in applied force and rate of chest compression (CC) during 5 min of CC with a target CC rate of 90/min (CC90) or 120/min (CC120) with and without metronome guidance during simulated neonatal cardiopulmonary resuscitation (CPR). We performed a randomized controlled manikin trial. Fourteen neonatal resuscitation program providers performed CC90 and CC120 with or without a metronome in a randomized order. Peak and residual leaning force and CC rate each minute of CPR were analyzed with Friedman's analysis of variance (ANOVA) (within interventions) and two-way repeated measures ANOVA (between interventions). There was a large variability in force application, with no difference between groups. Peak and residual leaning forces in CC90 and CC120 did not change with time with or without a metronome. The CC rate increased with time in all groups except CC90 without a metronome. In conclusion, neither the target CC rate nor using a metronome influenced the peak and residual leaning forces during simulated neonatal CPR.

INDEX TERMS Cardiopulmonary resuscitation, chest compression, fatigue, force, neonatology.

I. INTRODUCTION

The short- and long-term outcomes after prolonged cardiopulmonary resuscitation (CPR) in newborn infants are poor [1]. Even though chest compressions (CC) are performed in <0.1% of term and near-term infants [2], studies have shown a positive correlation between receiving adequate CC and improved outcomes [3]. Thus, it is important to investigate how efficacy of delivery room CC can be improved to limit mortality and morbidity in the affected infants. Current neonatal resuscitation guidelines recommend a 3:1 compression to ventilation (C:V) ratio with 90 CC and 30 inflations to achieve approximately 120 events per minute to maximize oxygen delivery [4]. However, the optimal CC rate during neonatal CPR remains unclear. A recent mathematical study suggests that higher CC rates than the currently recommended 90 CC/min could optimize systemic perfusion and improve survival [5]. However, using higher CC rates might increase rescuer fatigue [6], [7]. Li *et al.* [7] reported that fatigue during simulated CC as measured by a 20% reduction in peak CC pressure in a neonatal manikin occurred after 72 s during continuous CC with asynchronous ventilation (CCaV) at a rate of 120/min, after 96 s during CCaV at a rate of 90/min, and after 156 s during 3:1 C:V CPR [7]. In comparison, the current guidelines for pediatric and adult resuscitation recommend that providers should switch every 2 minutes to avoid significant rescuer fatigue [8]. Despite the importance of delivering appropriate CC, fatigue during CC has not been rigorously evaluated during neonatal CPR. In addition, whether using the correct rate and avoidance of either over- or under-compressing the chest, and leaving residual chest depth during CPR influence CC quality has not been examined.

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The aim of this study was to assess CC quality by measuring CC force and rate during simulated neonatal CC. Two different rates (90/min vs. 120/min) were compared. Both CC rates were performed both with and without a metronome for rate guidance. We hypothesized that CC at 120/min would be more fatiguing compared to CC at 90/min measured by i) decay in applied force, ii) increased residual leaning, and iii) decreased CC rate over time; and iv) that metronome rate guidance would result in a more consistent CC rate and force application over time.

II. MATERIALS AND METHODS

A. ENVIRONMENT AND SUBJECTS

This study was carried out at the Royal Alexandra Hospital, Edmonton, a tertiary perinatal center admitting approximately 1,500 infants to the Neonatal Intensive Care Unit (NICU) annually. The Northern Alberta Neonatal Program Research Committee and Health Ethics Research Board, University of Alberta approved the study. All study subjects were recruited by using Health Ethics Research Board approved study posters, which were displayed throughout the NICU at the Royal Alexandra Hospital over a period of four weeks. Fourteen registered Neonatal Resuscitation Program (NRP) healthcare professionals (neonatal–perinatal fellows ($n = 3$), respiratory therapists ($n = 9$) and registered nurses ($n = 2$)) were included. No participants were recruited from NRP classes. Exclusion criteria were expired NRP registration or any medical condition contraindicating the exertion required for CPR. Written informed consent was obtained from the participants in the study.

B. CHEST COMPRESSIONS

We used the neonatal manikin Neonatal Resuscitation Baby® (Laerdal Medical, Stavanger, Norway). According to the manufacturer, this manikin exhibits realistic resistance for CC that allows for learning the appropriate amount of pressure needed to perform effective CC in a real-life situation. The manikin was placed on an adjustable resuscitation incubator (Giraffe Incubator, General Electric Healthcare, Burnaby, Canada) to allow for height adjustments for each participant corresponding to their own comfort level. The NRP providers all performed CC on the manikin using the two-thumb method and focusing their thumb pressure on a 2 mm-thin sensor (FingerTPS™, Pressure Profile Systems, Los Angeles, CA), measuring one inch (2.5cm) in diameter (surface area 4.9cm^2), placed on the manikin's chest (Fig. 1). The utility of this sensor for measuring CC force has been evaluated previously [9]. All participants performed CC standing on the manikin's right side facing towards the head of the manikin.

C. RANDOMIZATION

All participants performed 5 min CC with each of the four CC methods: 1) CC 90/min with a metronome, 2) CC 90/min without a metronome, 3) CC 120/min with a metronome and 4) CC 120/min without a metronome. The sequence of the CC methods was determined for each participant using an online tool (http://www.randomizer.org) and a code list.

D. DATA COLLECTION

The FingerTPS™ system has a set of force sensors that can be put on the fingers and in the palm. For the purpose of this study we used the recordings from the palm sensor strapped around the manikin's chest, with the sensor pad placed over the lower third of the sternum (Fig. 1). This is where the participants were asked to focus their thumb force during CPR. The force was measured continuously in pounds (lbs.) and recorded using the Chameleon software (PPS, Los Angeles, CA). The participants were blinded to the force tracing during the experiments and were allowed to rest for at least four hours between each CC method

FIGURE 1. The placement of the FingerTPS™ palm sensor on the manikin's chest.

E. SAMPLE SIZE DETERMINATION

Because there is currently no knowledge about what comprises a clinically significant difference in the studied outcome parameters, we decided for a convenience sample of 25 participants. After completing ~60% of the experiments, an interim analysis showed that there was no difference in any parameter and even with an increased sample size to 50 participants we would not find a difference. Thus, we stopped inclusion after 14 participants.

F. DATA PROCESSING AND STATISTICAL ANALYSES

The raw data from the FingerTPS™ recordings contain continuous force measurements in lbs. distributed as peaks representing the force exerted by CC, and troughs representing the force applied to the sensor between CC (Fig. 2). The latter represents residual leaning force as a result of incomplete release of the force exerted on the chest wall between CCs.

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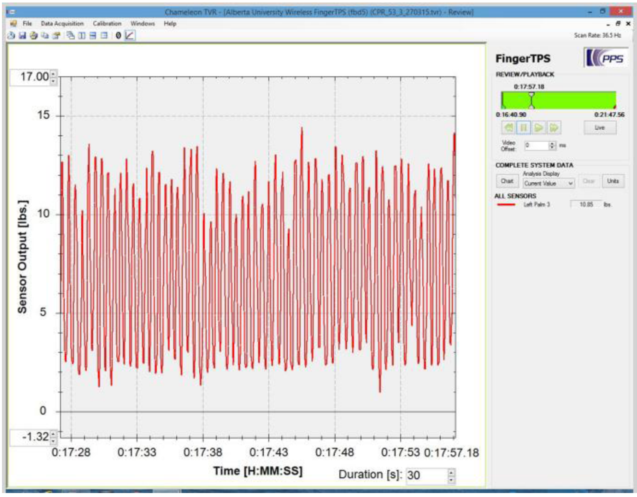

FIGURE 2. The raw data from the FingerTPS™ force measurements. The peaks represent the force exerted by chest compressions (CC), and the troughs represent the force applied to the sensor due to incomplete release between CC.

The main outcomes of study were: 1) The median of each participant's mean peak and residual force in lbs. during the 5 min of CC for each protocol. 2) The median of the mean CC rate during the 5 min of CC in each protocol. 3) The median of the mean peak and residual leaning force over each of the 5 min in each protocol. 4) The median of the mean CC rate over each of the 5 min in each protocol. The median peak and residual leaning force, and CC rate were compared between interventions (target CC rate and without/with a metronome) with the Mann-Whitney *U* test. We used Friedman's analysis of variance (ANOVA) to determine if the CC force and rate within each intervention changed significantly during the experiment. We used a two-way repeated measures ANOVA to compare the temporal changes in CC force and rate between interventions. These results are reported as the main study results. However, as the intra-class correlation coefficient (ICC) in our data was 0.43 ($p < 0.01$) we also performed a linear and non-linear mixed model analysis after log and sqr transformation of the skewed data. Statistical analyses were performed in IBM SPSS Statistics 22 (IBM Corporation, Armonk, NY), and SAS software (SAS Institute Inc., Cary, NC).

III. RESULTS

The participants had a median (interquartile range (IQR)) neonatal work experience of 1 (1-6) years with a range 1 to 34 years. The median (IQR) time since NRP course or upgrade was 8 (3-15) months.

A. THE MEDIAN OF EACH PARTICIPANT'S MEAN FORCE IN LBS. DURING THE 5 MIN OF CHEST COMPRESSIONS

Median (IQR) of the mean peak force in each experiment, irrespective of CC method was 16 (9-35) lbs., indicating a large variability in force application in the individual experiments. Using a metronome resulted in a similar applied force compared to no metronome during CC at a rate of 90/min ($p = 0.75$) and 120/min ($p = 0.64$) (Table 1) (Mann-Whitney *U* test).

TABLE 1. Median (interquartile range) peak CC force and rate in the different intervention groups (n = 14).

	CC 90/min with metronome	CC 90/min without metronome	P-value	CC 120/min with metronome	CC 120/min without metronome	P-value
Peak force (lbs.)	18 (6-43)	22 (9-35)	0.75	21 (11-48)	16 (12-35)	0.64
CC rate (min^{-1})	90 (90-91)	93 (88-103)	0.04	121 (120-122)	124 (116-130)	0.24

CC – chest compression

B. MEDIAN OF THE MEAN CC RATE DURING THE 5 MIN of CHEST COMPRESSIONS

The median CC rate was close to target in all intervention groups (Table 1). The CC rate was more consistent across individuals when using a metronome. When CC were performed at a rate of 90/min, CC rate was significantly higher without the use of a metronome ($p = 0.04$) (Mann-Whitney *U* test). During CC at a rate of 120/min, median CC rate was also slightly higher without metronome compared to using a metronome ($p = 0.24$) (Mann-Whitney *U* test).

C. CHANGES OVER EACH OF THE 5 MIN OF CHEST COMPRESSIONS

1) PEAK FORCE

When continuous CC were performed at a rate of 90/min and 120/min, the peak force did not change with time with ($p = 0.56$ and $p = 0.59$, respectively) or without a metronome ($p = 0.15$ and $p = 0.61$, respectively) (Table 2) (Friedman's ANOVA). There was no difference in the temporal changes in CC force between continuous CC with and without a metronome at 90/min and 120/min ($p = 0.41$ and $p = 0.76$, respectively) (two-way repeated measures ANOVA).

TABLE 2. Median (interquartile range) peak CC force and rate each of the 5 min of CC in the different intervention groups (n = 14).

	CC 90/min with metronome		CC 90/min without metronome		CC 120/min with metronome		CC 120/min without metronome	
Minute	CC force (lbs.)	CC rate (min^{-1})	CC force (lbs.)	CC rate (min^{-1})	CC force (lbs.)	CC rate (min^{-1})	CC force (lbs.)	CC rate (min^{-1})
1	17 (10-46)	89 (89-90)	33 (16-46)	91 (87-98)	32 (14-61)	118 (118-119)	24 (17-38)	122 (116-126)
2	14 (10-45)	90 (90-90)	31 (15-48)	93 (87-101)	27 (13-47)	120 (120-120)	24 (16-44)	125 (117-129)
3	14 (10-54)	90 (90-90)	31 (15-43)	92 (86-101)	22 (16-49)	120 (120-120)	22 (17-38)	125 (117-129)
4	16 (10-53)	90 (90-90)	29 (15-45)	93 (86-103)	21 (15-51)	120 (120-121)	23 (18-37)	124 (115-130)
5	19 (10-50)	90 (90-91)	29 (16-46)	94 (86-106)	24 (15-48)	120 (120-121)	24 (17-50)	127 (118-132)

CC – chest compression

2) RESIDUAL LEANING FORCE

When continuous CC were performed at a rate of 90/min, the residual leaning force tended to be lower when using a metronome (Table 3). The residual leaning force did not change with time neither with nor without a metronome ($p = 0.06$ and 0.32, respectively) (Table 3) (Friedman's ANOVA).

There was no difference in the temporal changes in residual leaning force between continuous CC 90/min with and without a metronome ($p = 0.26$) (two-way repeated measures ANOVA).

TABLE 3. Median (interquartile range) residual leaning force (lbs.) each of the 5 min of chest compression for the different interventions (n = 14).

Minute	CC 90/min with metronome	CC 90/min without metronome	CC 120/min with metronome	CC 120/min without metronome
1	3 (1-7)	8 (3-21)	7 (3-12)	4 (3-9)
2	5 (2-10)	8 (2-19)	7 (3-14)	6 (4-9)
3	4 (1-9)	9 (4-15)	7 (3-15)	6 (3-10)
4	4 (2-8)	8 (4-16)	5 (3-9)	7 (5-10)
5	5 (3-7)	10 (4-19)	4 (2-8)	7 (4-9)

CC – chest compression

When continuous CC were performed at a rate of 120/min, the residual leaning force was similar without and with a metronome (Table 3). The residual leaning force did not change with time neither with nor without a metronome ($p = 0.68$ and 0.97, respectively) (Table 3) (Friedman's ANOVA).There was no difference in the temporal changes in residual leaning force between continuous CC 120/min with and without a metronome ($p = 0.68$) (two-way repeated measures ANOVA).

3) CC RATE

For all time points and intervention groups, not using a metronome resulted in a higher CC rate than with a metronome (Table 2).

When CC were performed with a metronome at a rate of 90/min, the CC rate increased with time with ($p < 0.001$) but not without the use of a metronome ($p = 0.60$) (Friedman's ANOVA). There was no difference in the temporal changes in CC rate between experiments with and without a metronome ($p = 0.12$) (two-way repeated measures ANOVA).

When CC were performed at a rate of 120/min both with ($p < 0.001$) and without ($p = 0.001$) the use of a metronome, the CC rate increased significantly with time (Friedman's ANOVA). There was no difference in the temporal changes in CC rate between experiments with and without a metronome ($p = 0.29$) (two-way repeated measures ANOVA).

For all the endpoints, using the mixed model analysis did not change the conclusions.

IV. DISCUSSION

In this study of simulated neonatal CC we observed large inter-participant variations in applied peak force, residual leaning and CC rate, irrespective of target CC rate or the use of a metronome. Bjorshol *et al.* [10] reported inconsistencies and poor quality CC from the initiation of CC with large inter-individual variation during simulated adult CPR. Our study found similar results with high inter-individual variation in CC force and rate already in the first minute of simulated CPR. To overcome inconsistencies in CC delivery, Andriessen *et al.* [11] used a "Rhythm of life aid" (ROLA) [12] feed forward and feedback device on a manikin during simulated neonatal CPR and reported that 3:1 C:V CPR with the ROLA device resulted in CC with greater pressure and less variability compared to CPR without ROLA. In addition, using the ROLA device resulted in a more consistent CC rhythm.

A recent manikin study reported faster fatigue during CCaV 120/min compared to 3:1 C:V [7]. In the current study the target CC rate (90/min or 120/min) did not influence the peak CC force during the 5 min of simulated CPR. The additional use of a metronome did not affect the changes in CC force over time at any CC rate. This is similar to previously published adult studies [13]. In real-life CPR, CC and ventilations should be performed at a ratio of 3:1 with a total of 120 events per minute. However, use of a metronome to guide the rate is not standard practice. In the current study, the use of a metronome did result in a closer to target CC rate with less inter-individual variability, especially when the target CC rate was 90/min. Surprisingly, we found a slight increase in CC rate over time in all intervention groups, which was not alleviated when a metronome was used. Our results are in contrast to other studies that demonstrated that the CC rate decreases over time, which has been interpreted as an indicator of rescuer fatigue [14]. However, fatigue can both be 'physical' or 'mental'. Physical fatigue is the inability to maintain optimal muscle performance [15], whereas mental fatigue is the inability to maintain optimal cognitive performance [16]. Both physical and mental fatigue are transient and they are interconnected, and mental fatigue has been shown to decrease physical performance [16]. We speculate that an increasing CC rate over time might either be a sign of mental fatigue or a compensating mechanism of the rescuer to counteract their perceived physical feeling of fatigue.

A. LEANING

Successful resuscitation from cardiac arrest requires the delivery of high-quality CC ensuring full recoil between CC. CC leaning (or "incomplete recoil") occurs when a rescuer does not completely release the downward force from the chest wall after a CC, with or without lifting the thumbs off the chest between CC. Laboratory investigations have suggested that leaning during CC negatively affect hemodynamics during CPR [17]. Thus, the current neonatal resuscitation guidelines recommend complete chest wall decompression during CPR [4]. However, CC leaning is very common (up to 91%) during resuscitation and exhibits a wide distribution [18]. Analysis of adult in-hospital CPR showed that leaning decreased over time during continuous CC blocks, suggesting that either fatigue is not a major determinant of leaning, or that increased leaning may have been counteracted by automated feedback provided during CPR [18]. During neonatal CPR this has not been analyzed. In the current study we found only a very slight increase in leaning over time, which was similar in all groups. Our findings support the suggestion by Fried *et al.* [18] that leaning might not be a function of rescuer fatigue.

B. LIMITATIONS

Some participants gave oral feedback that the size and feel of the manikin was not similar to a real-life infant. The most common comment was "that it felt harder to perform proper-depth CC in the manikin than in a baby". This might partly explain the excessive force applied by some participants. Also, the absence of the stress of a real-life resuscitation may have affected the results.

C. FUTURE DIRECTIONS

Even though much research in newborn resuscitation in recent time has aimed to confirm the assumption that fatigue is a primary determinant of CC quality [7], [19], the results of this study suggest that other factors than fatigue should also be considered.

In the manikin used in our study, one-third of the AP diameter of the chest equals about 35 mm, and a force of 14.3 lbs. (6.5 kg) is necessary to achieve a 40 mm deep CC (*Laerdal Medical*, personal communication). The median peak force we measured in our experiments exceeded 14 lbs., irrespective of the target CC rate or the use of a metronome. Thus, studies investigating the optimal force during neonatal CC and how this can be achieved in the clinical situation are warranted. Furthermore, systems with real-time feedback on rate, force and/or depth, and leaning during neonatal CC may be needed. Such devices are already commercially available for adult CPR. The ROLA system, which has been designed for infants, is currently only used in trials.

V. CONCLUSION

In conclusion, expected signs of fatigue including reduced CC force, increased residual leaning force, and lower CC rates during 5 minutes of CC were not consistently present between individuals and interventions. We could not confirm our hypothesis that CC at 120/min was more fatiguing compared to CC at 90/min, and using a metronome did not consistently improve CC force and rate over time. Other factors than the traditional 'physical' fatigue may be of importance in terms of the quality of neonatal CC. As excessive force may be as harmful as too little force, further studies are warranted to assess real-time feedback systems on CC quality during the important first minutes of neonatal CC.

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REFERENCES

[1] D. J. Harrington, C. W. Redman, M. Moulden, and C. E. Greenwood, "The long-term outcome in surviving infants with Apgar zero at 10 minutes: A systematic review of the literature and hospital-based cohort," *Amer. J. Obstetrics Gynecol.*, vol. 196, no. 5, pp. 463.e1–463.e5, 2007.

[2] J. M. Perlman and R. Risser, "Cardiopulmonary resuscitation in the delivery room. Associated clinical events," *Arch. Pediatrics Adolescent Med.*, vol. 149, no. 1, pp. 20–25, 1995.

[3] L. Wik, P. A. Steen, and N. G. Bircher, "Quality of bystander cardiopulmonary resuscitation influences outcome after prehospital cardiac arrest," *Resuscitation*, vol. 28, no. 3, pp. 195–203, 1994.

[4] J. Kattwinkel *et al.*, "Part 15: Neonatal resuscitation: 2010 American heart association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care," *Circulation*, vol. 122, no. 18, pp. S909–S919, Nov. 2010.

[5] C. F. Babbs, A. Meyer, and V. Nadkarni, "Neonatal CPR: Room at the top—A mathematical study of optimal chest compression frequency versus body size," *Resuscitation*, vol. 80, no. 11, pp. 1280–1284, 2009.

[6] A. M. Boldingh, T. H. Jensen, A. T. Bjørbekk, A. L. Solevåg, and B. Nakstad, "Rescuers' physical fatigue with different chest compression to ventilation methods during simulated infant cardiopulmonary resuscitation," *J. Maternal-Fetal Neonatal Med.*, vol. 29, no. 19, pp. 3202–3207, 2015.

[7] E. S. Li, P.-Y. Cheung, M. O'Reilly, K. Aziz, and G. M. Schmölzer, "Rescuer fatigue during simulated neonatal cardiopulmonary resuscitation," *J. Perinatol.*, vol. 35, no. 2, pp. 142–145, Feb. 2015.

[8] M. R. Sayre *et al.*, "Part 5: Adult basic life support: 2010 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations," *Circulation*, vol. 122, no. 16, Suppl 2, p. S298-324, Oct. 19, 2010.

[9] A. L. Solevåg *et al.*, "Quantifying force application to a newborn manikin during simulated cardiopulmonary resuscitation," *J. Maternal-Fetal Neonatal Medicine*, vol. 29, no. 11, pp. 1770–1772, Jul. 2015.

[10] C. A. Bjørshol, K. Sunde, H. Myklebust, J. Assmus, and E. Søreide, "Decay in chest compression quality due to fatigue is rare during prolonged advanced life support in a manikin model," *Scand. J. Trauma, Resuscitation Emergency Med.*, vol. 19, p. 46, Aug. 2011.

[11] P. Andriessen, S. B. Oetomo, W. Chen, and L. M. Feijs, "Efficacy of feed forward and feedback signaling for inflations and chest compression pressure during cardiopulmonary resuscitation in a newborn mannequin," *J. Clin. Med. Res.*, vol. 4, no. 4, pp. 274–278, Aug. 2012.

[12] W. Chen *et al.*, "Rhythm of life aid (ROLA): An integrated sensor system for supporting medical staff during cardiopulmonary resuscitation (CPR) of newborn infants," *IEEE Trans. Inf. Technol. Biomed.*, vol. 14, no. 6, pp. 1468–1474, Nov. 2010.

[13] H. Jäntti, T. Silfvast, A. Turpeinen, V. Kiviniemi, and A. Uusaro, "Influence of chest compression rate guidance on the quality of cardiopulmonary resuscitation performed on manikins," *Resuscitation*, vol. 80, no. 4, pp. 453–457, Apr. 2009.

[14] C. A. Bjørshol, E. Søreide, T. H. Torsteinbø, K. Lexow, O. B. Nilsen, and K. Sunde, "Quality of chest compressions during 10 min of single-rescuer basic life support with different compression: Ventilation ratios in a manikin model," *Resuscitation*, vol. 77, no. 1, pp. 95–100, Apr. 2008.

[15] J. A. Hawley and T. Reilly, "Fatigue revisited," *J. Sports Sci.*, vol. 15, no. 3, pp. 245–246, Jun. 1997.

[16] S. M. Marcora, W. Staiano, and V. Manning, "Mental fatigue impairs physical performance in humans," *J. Appl. Physiol.*, vol. 106, no. 3, pp. 857–864, Mar. 2009.

[17] D. E. Niles *et al.*, "Prevalence and hemodynamic effects of leaning during CPR," *Resuscitation*, vol. 82, no. 2, pp. S23–S26, Dec. 2011.

[18] D. A. Fried *et al.*, "The prevalence of chest compression leaning during in-hospital cardiopulmonary resuscitation," *Resuscitation*, vol. 82, no. 8, pp. 1019–1024, Aug. 2011.

[19] R. J. Hemway, C. Christman, and J. Perlman, "The 3:1 is superior to a 15:2 ratio in a newborn manikin model in terms of quality of chest compressions and number of ventilations," *Arch. Disease Childhood-Fetal Neonatal Ed.*, vol. 98, no. 1, pp. F42–F45, Jan. 2013.