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Evaluation of the proper chest compression depth for neonatal resuscitation using computed tomography
A retrospective study

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Abstract

This study was created to assess whether a 30-mm depth of chest compression (CC) is sufficient and safe for neonatal cardiopulmonary resuscitation.

This retrospective analysis was performed with chest computed tomography scans of neonates in 2 hospitals between 2004 and 2018. We measured several chest parameters and calculated heart compression fraction (HCF) using the ejection fraction formula. We evaluated whether one-third of the external anterior-posterior (AP) diameter and HCF with them are the equivalent to 25-, 30-, 35 mm and HCF with them, respectively, and the number of individuals with over-compression (internal chest AP diameter − compressed depth <10 mm) to estimate a safe CC depth. We divided the patients into term and preterm groups and compared their outcomes.

In total, 63 of the 75 included individuals were analyzed, and one-third of the external lengths was equivalent to 30 ± 3 mm ($P < .001$). When the patients were divided into term (n = 53) and preterm (n = 10) groups, the equivalent depth was 30 ± 3 mm in the term group ($P < .001$) and 25 ± 2.5 mm in the preterm group ($P = .004$). The HCF with 30 mm was equivalent to that for one-third of the external length ($P < .001$). When we simulated CCs with a 30-mm depth, over-compression occurred more frequently in the preterm group (20%) compared to the term group (1.9%) ($P = .014$).

A 30-mm depth could be appropriate for sufficient and safe neonatal resuscitation. Shallower CC should be considered in preterm babies.

Abbreviations: ANCOVA = analysis of covariance, AP = anteroposterior, CC = chest compression, CPR = cardiopulmonary resuscitation, CT = computed tomography, IQR = interquartile ranges, NICU = neonatal intensive care unit, PACS = picture archiving and communication system, SD = standard deviation.

Keywords: basic life support, cardiopulmonary resuscitation, chest compression, neonate

1. Introduction

International guidelines for resuscitation during the neonatal period, which is usually defined as <28 to 30 days after birth, is applied to newly born infants during the first weeks after birth and any infants during initial hospitalization.[1,2] Although extensive resuscitative efforts are required in <1% of newborns,

a significant volume will require cardiopulmonary resuscitation (CPR).[3,4] High-quality CPR maintains vital organ perfusion and is related to the survival rate and favorable neurologic outcomes in cardiac arrest patients.[5,6] Unlike in adult resuscitation where chest compressions (CC) are the most important element, ventilation is the most important element of performance in pediatric and neonatal resuscitation.[7–9] However, circulatory support with CCs is required, and meaningful performance is achieved if the heart rate is <60/min despite effective ventilation.[9]

The present international guidelines recommend neonatal resuscitation with the two-thumb encircling method over the lower third of the sternum with a depth of approximately one-third of the anteroposterior (AP) diameter of the chest wall.[9,10] This recommended depth in neonate cardiac arrest is based on the study by Meyer et al that demonstrated one-third of the external AP chest diameter to be a more effective and safer CC depth for neonatal resuscitation using chest computed tomography (CT) during the neonatal period defined as <28 days after birth.[11] However, there are limited data on the target CC depth required to improve resuscitation during the pediatric period from birth to the onset of puberty, and current evidence suggests that it is approximately 1.5 inches (40 mm) in infants to 2 inches (50 mm) in children.[8]

In addition, there is no qualified target depth in neonatal resuscitation, unlike in adult, pediatric, and infant resuscitation cases. Therefore, the aim of this study was to assess whether a depth of one-third of the external chest AP diameter in neonates was sufficient using chest CTs and whether this was equivalent to the result with 30 mm depth. We hypothesized that a CC depth of approximately 30 mm is safe and appropriate for neonatal CPR.

2. Material and methods

2.1. Study design

We conducted a retrospective study to evaluate the appropriate CC depth for neonate cardiac arrest using chest CT. This study was performed at 2 academic tertiary hospitals with 20 and 40 beds in the neonatal intensive care units (Seoul and Gyeonggi-Do, Republic of Korea) in August 2019. The study was approved by the Institutional Review Board of Hanyang University Hospital (ref. no. HYUH 2019-06-015) and the Institutional Review Board of Seoul National University Bundang Hospital (ref. no. B-1907-555-102), and a waiver of informed consent was granted. All methods were performed in accordance with the relevant guidelines and regulations.

2.2. Study participants

We extracted medical records of individuals who underwent chest CT at the NICU from January 2004 to December 2018. The inclusion criterion was age ≤28 days. Twin or multiple births, extremely-low-weight babies (<1000 g), and individuals with anatomical abnormalities in the chest, such as pectus excavatum or total atelectasis, were excluded. Of the eligible patients, we randomly selected 6 individuals who were not included in this study through the random integer set generator on the website (https//www.random.org) to extract the numbers randomly for a pilot study. The data from the pilot study demonstrated that a mean of 28.03 mm and a standard deviation of 0.80 mm were required. A minimal sample size of 9 was found to achieve 95%

power to detect equivdalence for mean with one standard deviation when the equivalence limits were 3.0 mm (upper) and −3.0 mm (lower) and the mean difference between one-third of the external chest AP diameter and 30 mm was 1.97 mm, with a 0.05 significance level using the PASS 16.0.4 software package power analysis and sample size software (NCSS, LLC; Kaysville, UT).

2.3. Equipment and materials

The CT equipment used in this study were a Brilliance 64 channel or 256 ICT slice multi-detector CT scanner (Philips Healthcare, Best, Netherlands) and a Somatom Definition Flash or Definition Flash scanner (Siemens Health care, Forchheim, Germany). Settings for the examination were as follows: 80 kVp, 40 mAs, 0.99- to 1.15-mm/s table feed, 0.5-second rotation time, 3-mm slice thickness, and 3-mm intervals. All CT images were stored in the picture archiving and communication system (PACS, Centricity, GE Healthcare, Milwaukee, WI).

2.4. Data collection

We collected basic information on age, sex, height, weight, and gestational age, of all included individuals. All CT images for each subject were reconstructed and shown in transverse and sagittal views using PACS. Each image was cross-linked to images with other settings. Two emergency physician authors reconstructed all images of each subject with consensus. We selected the image at which the maximal diameter and left ventricular outflow tract of the heart were shown in the transverse view and then measured parameters as follows: external chest AP diameter (millimeter), perpendicular from the skin anteriorly on the sternum to the skin posteriorly on the back; internal chest AP diameter (millimeter), from the posterior surface on the sternum vertically to the anterior vertebral body; heart AP diameter (millimeter), anterior to posterior diameter of the heart in-line with the external and internal AP diameter; and residual depth diameter (millimeter), internal chest AP diameter (millimeter) − compressed depth (millimeter); we assumed heart diameter as the end-diastolic volume and internal chest AP minus the proposed CC depth as the end-systolic volume. Therefore, the mathematical formula of (heart AP diameter − [internal chest AP diameter − proposed CC depth]) determined stroke volume. We calculated heart compression fraction (HCF), which is the proportion of the heart compressed by chest compression with proper CC depth, using the following ejection fraction formula.[11,12]:

$$\frac{[\text{heart AP diameter} - (\text{internal chest AP diameter} - \text{proposed CC depth})]}{\text{heart AP diameter}} \times 100$$

2.5. Primary and secondary outcomes

The primary outcome was whether one-third of the external chest AP diameter of the individuals was equivalent to 25-, 30-, or 35 mm. The secondary outcomes were whether HCF with one-third of the external chest AP diameter of the individuals was equivalent to those with 25-, 30-, and 35 mm and the number of individuals with <10-mm residual internal chest depth when CC was performed at 25-, 30-, and 35-mm depths. We divided the participants into a term group (gestational age ≥37 weeks and ≥ 2500 g) and a preterm group (gestational age <37 weeks or

<2500g) and compared the parameters and outcomes between the 2 groups.

2.6. Statistics [12]

All data were compiled using a standard spreadsheet application (Excel 2016; Microsoft, Redmond, WA) and analyzed using SAS version 9.4 (SAS Institute Inc., Cary, NC). Kolmogorov–Smirnov tests were performed for normal distribution data, and descriptive statistics were generated and presented as frequencies and percentages for categorical data and as either medians or interquartile ranges (non-normal distribution) or as means and standard deviations (normal distribution) for continuous data. A 1-sample t test for equivalence using 2 one-sided tests between one-third of the external AP diameter and 25-, 30-, and 35 mm and paired t test for equivalence using 2 one-sided tests between HCF with 25-, 30-, and 35 mm and then with one-third of the external AP diameter were used. Participant characteristics, parameters, and outcomes between the 2 groups were compared using either the Mann–Whitney U test (non-normal distribution) or an independent t test (normal distribution) for continuous measurements, and the χ^2 test or Fisher exact test was used to analyze categorical variables. Analysis of covariance (ANCOVA) or ranked-ANCOVA was performed to adjust for influencing factors and to investigate the main factor influencing the outcomes. A value of $P < .05$ was considered significant.

3. Results

3.1. Study population

In total, 75 individuals were recruited for this study, of whom, 7 were excluded for pectus excavatum (n=2) or total atelectasis (n=5). Finally, a total of 63 individuals was analyzed (5 had loss of data) and divided into term (n=53) and preterm (n=10) groups (Fig. 1). Baseline characteristics of the individuals are summarized in Table 1. There were significant differences in age, height, weight, and gestational age but not sex between the groups.

3.2. CT measurement

The CT measurements are summarized in Table 2. The external and internal chest AP diameters and heart height were significantly different (all $P < .001$). We adjusted for factors of age, sex, and height that could affect the results using ANCOVA or ranked-ANCOVA. A significant difference was observed in all results between the 2 groups (all $P < .001$). The equivalence test for total neonates and the two groups regarding one-third of the external chest AP diameter is summarized in Table 3 and Figure 2. In the total neonates, one-third of the external chest AP diameter was equivalent to 30 ± 3 mm ($P < .001$). When the term and preterm groups were analyzed separately, the equivalence of one-third of the external chest AP diameter was 30 ± 3 mm in the term group ($P < .001$) and 25 ± 2.5 mm in the preterm group ($P = .004$). In addition, the equivalence test regarding HCF with one-third of the external chest AP diameter for total neonates and the 2 groups is summarized in Table 4. The HCF with one-third of the external chest AP diameter was equivalent to that with 30 ± 3 mm in total neonates ($P < .001$). The equivalence of HCF with one-third of the external chest AP diameter was 30 ± 3 mm in the term group ($P < .001$) and 25 ± 2.5 mm in the preterm group ($P = .01$). Furthermore, when we simulated the CCs with a 30-mm depth, 1 of 53 individuals (1.9%) in the term group and 2 of the 10 individuals (20.0%) in the preterm group had overcompression ($P = .014$, Table 5). There was no over-compression in the simulation with a 25-mm depth ($P = 1.000$), whereas it was increased to 5 of the 53 patients (9.4%) in the term group and to 5
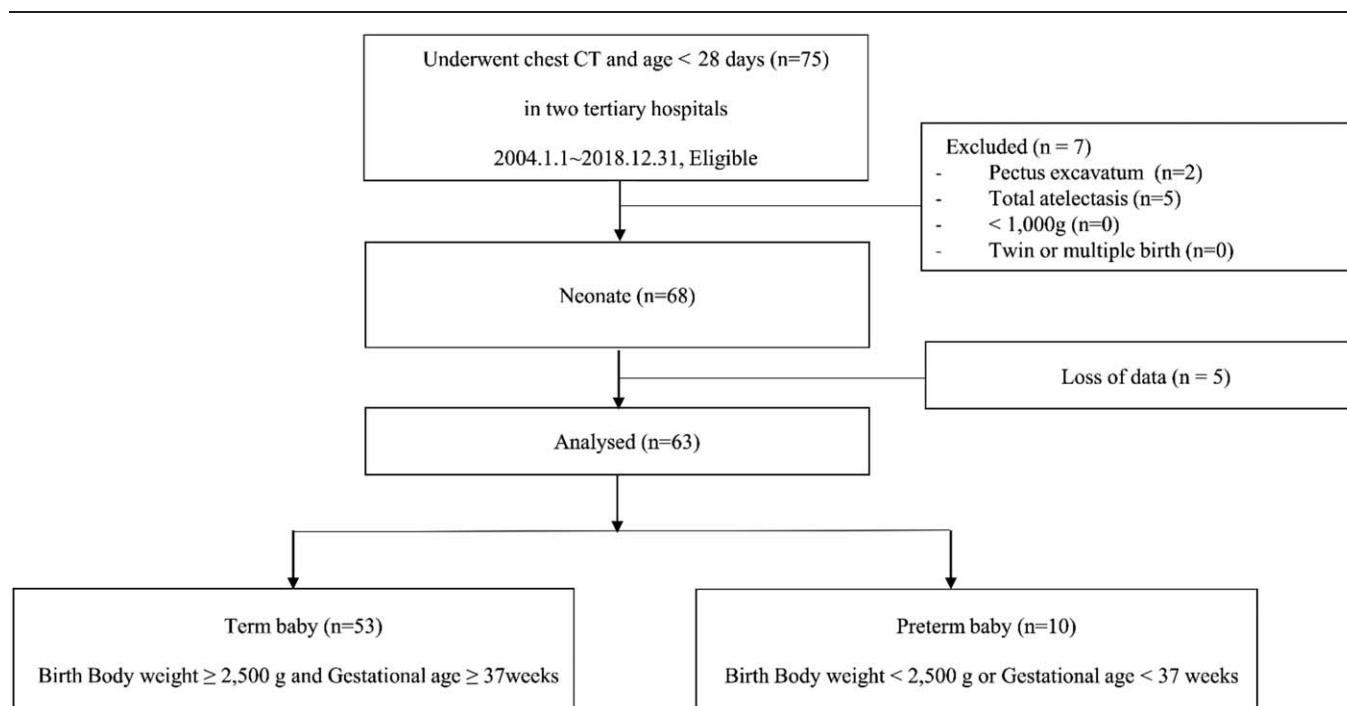

Figure 1. Flowchart of individuals' enrolment in the study.

Table 1

Baseline characteristics of patients.

	Total neonate (n=63)	Term (n=53)	Pre-term (n=10)	P
Age, days	8.70±8.88	7.68±8.33	14.1±10.17	.035*
Sex (male)	33 (52.4%)	28 (52.8%)	5 (50.0%)	1.0000
Height, cm	49.18±4.07	50.05±3.38	44.67±4.56	<.001*
Weight, g	3173.17±620.62	3345.29±437.52	2197.78±620.50	<.001*
Gestational age, days	268.62±13.50	272.08±9.15	250.30±18.12	.004*

The term group represents neonates who were gestational age ≥37 weeks and birth weight ≥2500 g. The preterm group represents neonates who were gestational age <37 weeks or birth weight <2500 g. Continuous variables are presented as mean±SD, and tested using independent t test, whereas categorical variables are presented as N (%), and tested using Fisher exact test.
* $P < .05$ is significant.

Table 2

Comparison of computed tomography measurements between the term and preterm groups.

	Total neonate (n=63)	Term (n=53)	Pre-term (n=10)	P	Adjusted P
External chest AP diameter, mm	88.48±11.85	90.96±10.98	75.34±6.59	<.001*	<.001*
External chest AP diameter/3, mm	29.49±3.95	30.32±3.66	25.11±2.20	<.001*	<.001*
Internal chest AP diameter, mm	49.88±6.33	50.99±6.02	43.98±4.56	<.001*	.001*
Heart AP diameter, mm	39.89±5.73	40.95±5.53	34.28±2.86	<.001*	<.001*

The term group represents neonates who were gestational age ≥37 weeks and birth weight ≥2500 g. The preterm group represents neonates who were gestational age < 37 weeks or birth weight <2500 g. Continuous variables are presented as mean±SD. The 2 groups were compared using the independent t-test or Mann–Whitney test and adjusted for age by ANCOVA or ranked-ANCOVA. AP = anteroposterior.
* $P < .05$ is significant.

Table 3

The equivalence test about one-third of the external chest AP diameter with a 25-, 30-, and 35-mm of proper chest compression depth for total neonates and the 2 groups.

Equivalence hypothesis	Alternative hypothesis		Total neonate (n=63)	Term (n=53)	Pre-term (n=10)
		Mean (s.d.), mm	29.49 (3.95)	30.32 (3.66)	25.11 (2.20)
25−2.5 mm <μ <25 + 2.5 mm	Lower Boundary >22.5 mm	P	<.001*	<.001*	.002*
	Upper Boundary <27.5 mm		1.000	1.000	.004*
	Equivalence		1.000	1.000	.004*
30−3.0 mm < μ <30 + 3.5 mm	Lower Boundary >27 mm		<.001*	<.001*	.99
	Upper Boundary <33 mm		<.001*	<.001*	<.001*
	Equivalence		<.001*	<.001*	.99
35−3.5 mm < μ <35+3.5 mm	Lower Boundary >31.5 mm		1.00	.99	1.00
	Upper Boundary <38.5 mm		<.001*	<.001*	<.001*
	Equivalence		1.00	.99	1.00

The term group represents neonates who were gestational age ≥37 weeks and birth weight ≥2500 g. The preterm group represents neonates who were gestational age <37 weeks or birth weight <2500 g. A 1-sample t test was used to evaluate equivalence using two one-side tests. μ = one-third of external chest AP diameter, AP = anteroposterior.
* $P < .05$ is significant.

of the 10 patients (50.0%) in the preterm group in the simulation with a 35-mm depth ($P = .001$).

4. Discussion

The majority of studies on proper CC depth have used radiographic images and mathematical modeling because there are many restrictions on the ability to solve practical and ethical problems for studies during human CPR. In a cohort study of six infants who underwent cardiac surgery and suffered subsequent cardiac arrest, CC with a depth one-half of the external chest AP diameter increased systolic blood pressure by 62% compared to CC with one-third depth.[13] However, Meyer et al reported that the external chest AP diameter was 90.50±7.7 mm from 54 neonatal chest CT scans, and that one-third depth of the external chest AP diameter was a sufficient CC depth to result in an ejection fraction close to the normal level.[11] Jin et al reported that the external chest AP diameter of 93 infants who were 3.72± 4.08 months old was 85.90±16.30 mm.[14] In the present study, the value was 88.48±11.85 mm from the 63 neonatal chest CT scans. Based on the result that one-third depth of the external chest AP diameter is a sufficient CC depth, the value of the total neonates was 29.49±3.95 mm, which was equivalent to 30 mm. We believe that it is appropriate to compress the chest with a 30-mm depth for neonatal resuscitation guidelines.

CC is performed more frequently in preterm deliveries and infants compared to near-term and term deliveries.[15–17] There have been no previous reports pertaining to CC depth in neonates and infants with a mention of gestational age. In this study, the external chest AP diameter and one-third depth value of the preterm group were 75.34±6.59 mm and 25.11±2.20 mm, respectively, which was not equivalent to 30 mm but was
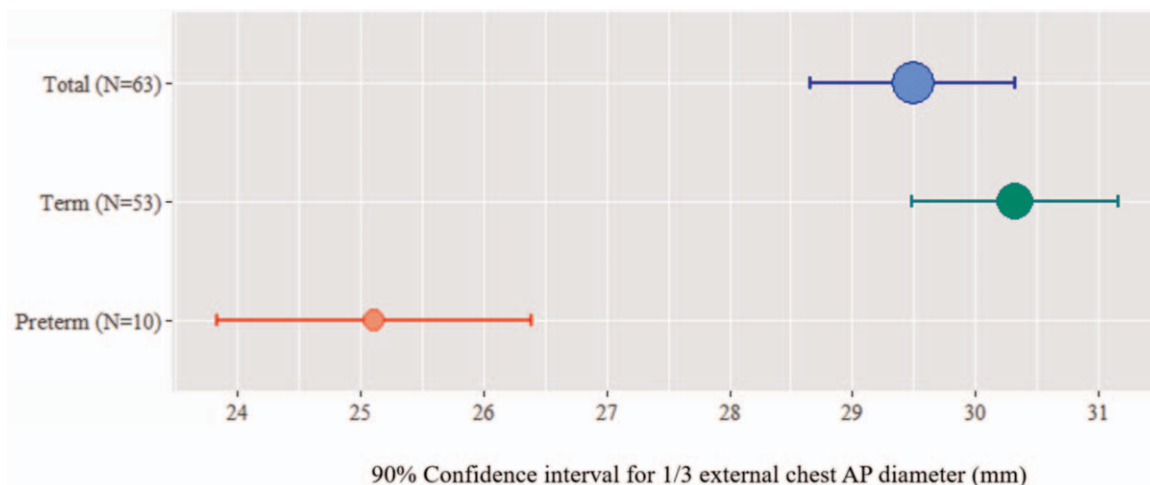
Figure 2. Forest plot of a sufficient chest compression depth (A) x-axis 90% confidence interval for one-third of the external chest AP diameter (millimeter) (B) y-axis Total (n=63), term (n=53), Preterm (n=10). A 30-mm depth in the term group and a 25-mm depth in the preterm group are equivalent to one-third of the external chest AP diameter in total.

Table 4

The equivalence test about HCF of one-third of the external chest AP diameter with a 25-, 30-, and 35 mm of proper chest compression depth for total neonates and the 2 groups.

Equivalence hypothesis		Total neonate (n=63)	Term (n=53)	Pre-term (n=10)
$-7\% < \mu_{25} < 7\%$	Mean (s.d.) of difference	−10.42 (7.41)	−12.36 (5.80)	−0.15 (6.65)
	P	1.000	1.000	.01[*]
$-7\% < \mu_{30} < 7\%$	Mean(s.d.) of difference	2.34 (8.76)	0.04 (6.97)	14.53 (7.23)
	p-value	<.001[*]	<.001[*]	.99
$-7\% < \mu_{35} < 7\%$	Mean(s.d.) of difference	15.10 (10.21)	12.43 (8.22)	29.22 (7.99)
	p-value	1.000	.99	.99

The term group represents neonates who were gestational age ≥37 weeks and birth weight ≥2500 g. The preterm group represents neonates who were gestational age <37 weeks or birth weight <2500 g. A 1-sample t test was used to evaluate equivalence using 2 one-side tests. μ_{depth} = mean of difference of between HCF with depth of 25-, 30-, and 35 mm and with 1/3 of the external chest AP diameter, AP = anteroposterior, HCF = heart compression fraction.

[*] P value <.05 is significant.

Table 5

Number of neonates with overcompression when simulated to compress the chest with a 25-, 30-, and 35-mm depth.

Chest compression depth	Total neonate (n=63)	Term (n=53)	Pre-term (n=10)	P
25 mm	0 (0%)	0 (0%)	0 (0%)	1.000
30 mm	3 (4.8%)	1 (1.9%)	2 (20.0%)	.014[*]
35 mm	10 (15.9%)	5 (9.4%)	5 (50.0%)	.001[*]

Overcompression represents a residual internal chest depth of <10 mm when chest compression was performed.

Categorical variables are presented as N (%) and tested using Fisher exact test.

[*] P<.05 is significant.

equivalent to 25 mm. CC with a 25-mm depth could be sufficient in preterm or low-birth-weight baby CPR. However, 5-mm-deep CC results in a higher survival rate and better neurological outcomes for adult cardiac arrest patients.[18,19] Furthermore, a 30-mm depth would be be an appropriate CC depth in term babies and in those with a birth weight ≥2500 g.

Pediatric injuries from CPR occurred in 15 of 211 cases (7%) in ages ranging from 6 to 140 months, and 7 (3%) had injuries that were considered medically significant, including pneumothorax, epicardial hematoma, and pulmonary interstitial hemorrhage.[20] Iatrogenic injuries from CPR are rarer in children than in adults.[20] In addition, Reyes et al reported that the 2005 American Heart Association guidelines emphasized that rigorous CCs in infant cardiac arrest resulted in a higher rate of rib fractures.[21] In studies evaluating CC depth through CT, overcompression is defined as excess depth resulting in injuries from CPR. The number of over-compressions was measured when the residual depth (internal chest AP diameter − compressed depth) was <10 mm.[11] Braga et al reported that CCs with a depth of half the external chest AP diameter might not be safe in pediatric CPR.[22] Furthermore, Meyer et al reported that CC with a depth one-third of the external chest AP diameter for neonate cardiac arrest was safer than that with a one-half external chest AP compression diameter.[11] In our study, assuming a 30-mm CC

depth, approximately 5% of the total individuals experienced over-compression (1 of 53[1.9%] in the term group and 2 of 10 (20%) in the preterm group; $P = .014$). The proportion of over-compressions with a 35-mm depth increased to approximately 16%, whereas there was no over-compression in either group with a 25-mm depth.

There were several limitations to this study. First, this study excluded extremely-low-birth-weight babies (<1000 g). Furthermore, a proper chest compression depth can be shallower than the results obtained in our preterm group. Second, the CT images were not obtained during real CPR situations, and we did not consider possible relocation of thoracic structures due to CC or positive pressure ventilation during CPR. Third, minor measurement errors could have occurred because all distances were measured using a straight-line on sagittal images without considering the curvature. Fourth, it is essential that studies relating to survival rates and neurologic outcomes are applied to actual cardiac arrest patients. Finally, we could not observe the difference in coronary or cerebral blood flow and survival rate by CC depth for CPR. In addition, we could not reflect changes in chest wall resistance, and we could not determine the difference between the two groups by CC during actual CPR.

5. Conclusions

A proper depth for sufficient and safe CC during CPR in neonates could be determined to be 30 mm, which was one-third of the depth of the external chest AP diameter. This was true for term and normal birth weight babies. When performing CCs in preterm or low-birth-weight babies, a shallower depth should be considered compared to those used for term and normal birth weight babies.

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Writing – review & editing: Juncheol Lee, Dong Keon Lee, Jaehoon Oh.

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