# Evaluation of the Neonatal Resuscitation Program's Recommended Chest Compression Depth Using Computerized Tomography Imaging.

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# Evaluation of the Neonatal Resuscitation Program's recommended chest compression depth using computerized tomography imaging☆

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ABSTRACT

*Background:* Neonatal Resuscitation Program (NRP) guidelines recommend chest compression depths of 1/3 the anterior–posterior (AP) chest depth. Appropriateness of this recommendation has not been rigorously assessed.
*Objective:* To compare the efficacy and safety of neonatal chest compression depths of 1/4, 1/3, and 1/2 AP chest depth during cardiopulmonary resuscitation.
*Design/methods:* Anterior–posterior internal and external chest depth, heart dimensions, and non-cardiac thoracic tissue depth were measured from neonatal chest CTs. Using these measurements, residual internal chest depth, the remaining depth of the chest between the sternum and spine after external compression, was calculated for compression depths of 1/4, 1/3 and 1/2 anterior–posterior chest depth. Compression sufficient to compress the chest to <10 mm of residual internal chest depth was defined as over-compression. Using a mathematic model, an estimated ejection fraction (EF) was calculated for each chest compression depth. Compression inadequate to obtain a predicted 50% EF was defined as under-compression. Descriptive statistics, Fisher's exact test and Student's *t*-test were used to analyze data, where appropriate.
*Results:* Fifty-four neonatal chest CT scans were evaluated. Estimated chest compression induced EF increased incrementally with increasing chest compression depth (EF was 51 ± 3% with 1/4 AP chest depth vs 69 ± 3% with 1/3 AP chest depth, and 106% with 1/2 AP chest depth, $p < 0.001$). Under-compression was predicted in 29/54 patients with 1/4 AP compression depth, but none of the patients with 1/3 or 1/2 AP compression depth, $p < 0.001$. Over-compression, or lack of adequate residual chest depth, was predicted in 49/54 patients with 1/2 AP compression depth, but none of the patients with 1/4 or 1/3 AP compression depth, $p < 0.001$.
*Conclusions:* Mathematical modeling based upon neonatal chest CT scan dimensions suggests that current NRP chest compression recommendations of 1/3 AP chest depth should be more effective than 1/4 compression depth, and safer than 1/2 AP compression depth.


## 1. Introduction

The American Heart Association (AHA) and Neonatal Resuscitation Program (NRP) recommend performing chest compressions during neonatal cardiopulmonary resuscitation (CPR) by approximately 1/3 the anterior– posterior chest depth.[1,2] Chest compressions are provided to maintain blood flow during an extensive resuscitation. Studies in animals and humans show positive correlation between receiving adequate compressions and improved outcomes.[3–6] Although adequate chest compressions are important to achieve adequate cardiac output, over-compressing the chest,

*Abbreviations:* AHA, American Heart Association; AP, anterior–posterior; CPR, cardiopulmonary resuscitation; CT, computerized tomography; EF, ejection fraction; NRP, Neonatal Resuscitation Program; PALS, pediatric advanced life support.

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and therefore leaving inadequate residual chest depth during CPR, has its own potential risks. Some of these risks may include rib fractures, cardiac contusion, and other thoracic injuries. Despite the importance of delivering appropriate chest compressions, the NRP and AHA AP chest compression depth guidelines have not been rigorously evaluated in neonates.

Because of practical difficulties and ethical challenges involved in evaluating chest compressions during human CPR, investigators have used radiographic images and mathematical modeling to evaluate chest compression recommendations. We do not feel that there is an animal model that adequately replicates the anatomy of the neonatal chest in order to estimate the effects of chest compressions. In a descriptive study in adults, Pickard used chest radiographs to show that AHA guidelines for chest compression depth (1.5–2 inches) would correspond to 20% anterior–posterior chest depth,[7] less than 1/4 the AP chest depth. In children, Braga used computed tomography (CT) scans to estimate that chest compressions to an anterior–posterior (AP) chest compression depth of 1/2 external AP depth is not ideal and may not be safe.[10] In neonates, two chest radiographic studies demonstrated that the center of the cardiac silhouette typically lies underneath the lower third of the sternum.[8,9] These findings were extrapolated and incorporated into AHA and AAP Neonatal Resuscitation Program guidelines. Because no clinical or imaging data address chest compression depth for neonatal CPR, we evaluated neonatal CT scans and used computer modeling to simulate chest compressions and assess the effects of different chest compression depths. We hypothesized that current NRP chest compression recommendations of 1/3 AP chest depth would be more effective than 1/4 AP compression depths and safer than 1/2 AP compression depth.

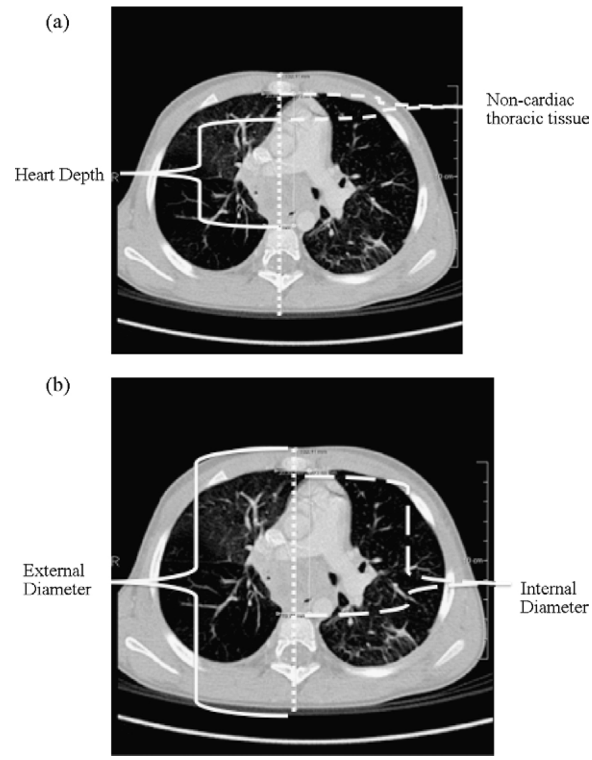


**Fig. 1.** Axial chest CT showing the measurements used for this study (a and b).

## 2. Methods

### 2.1. General schema of study design

This retrospective study was approved by the Institutional Review Board at the Children's Hospital of Philadelphia and was granted a waiver of informed consent.

### 2.2. Subject enrollment

One hundred and nineteen consecutive chest CT scans performed by the Department of Radiology at the Children's Hospital of Philadelphia were screened for study inclusion, and 59 of these scans were of neonates (<28 days of age). Fifty-four of these subjects met criteria for inclusion in this study. Subjects were excluded from this study if major (visually obvious) chest wall deformities such as a pectus excavatum, or chest/lung hypoplasia were present. Also excluded from this study were those subjects with large thoracic lesions, such as a large congenital cystic adenomatoid malformation or a congenital diaphragmatic hernia.

### 2.3. Analysis

The measurements used in this study were derived from axial cuts of previously obtained neonatal CT scans. As exemplified in Fig. 1, all measurements were calculated along a line drawn through the mid-line of the chest at the level of the lower 1/3 of the sternum. The lower third of the sternum was identified by scrolling through axial cuts of the CT scan, and using the distinct landmarks of the sternal notch and xiphisternal joint to orient to a consistent location to compare CT measurements. The external chest depth was calculated by measuring a line drawn perpendicularly from the skin anteriorly (surface of sternum) to the skin posteriorly (surface of vertebrae touching stretcher bed). Additionally, the internal depth was calculated by measuring a line drawn perpendicularly from the posterior sternum to the anterior vertebral body. Any non-cardiac thoracic tissue in the chest mid-line, such as lung tissue, which would not directly translate the force of the chest compression to the heart, was also measured. The depth of a proposed chest compression was calculated for 1/4, 1/3, and 1/2 the measured external chest depth. *A priori*, we assumed that the full depth of the chest compression is transmitted to the internal structures. Residual internal chest depth after simulated chest compression was calculated as the internal chest depth minus the depth of the proposed chest compression. Prospectively selected and empirically designated values for under-compression and over-compression were defined, based upon consensus and prior publications of this research group.[10] Under-compression of the heart was prospectively defined as chest compressions estimated to result in <50% of normal ejection fraction (EF) for age. Over-compression of the heart was prospectively defined as chest compressions estimated to result in <10 mm residual depth. For face validity, predicted over-compression was additionally confirmed by a chest compression that would be predicted to result in >90% normal EF for age. If calculated EF was greater than 100%, then the reported value was truncated to 100%. Fig. 2 illustrates two representations of axial chest CTs that show the simulated effects of chest compression on the anatomic dimensions of the chest structures.

The measurements obtained from the neonatal CT scans were also incorporated into mathematical models created to estimate the EF obtained by simulated chest compression depths of 1/4, 1/3, or 1/2 of anterior–posterior external chest depth. These models assumed a cardiac compression model for generation of blood flow during CPR as described subsequently in Eqs. (1)–(3).

Variables in the initial state before compression are defined as follows: $x_0$, external chest depth; $h_0$, heart depth; $d_0$, non-cardiac thoracic tissue. Variables in the initial state after compression are defined as follows: $x$, external chest depth; $h$, heart depth.

The chest compression depth is $\Delta x = x_0 - x$. If $\Delta x$ is less than the non-cardiac thoracic tissue $d_0$, we assumed that the ventricles are

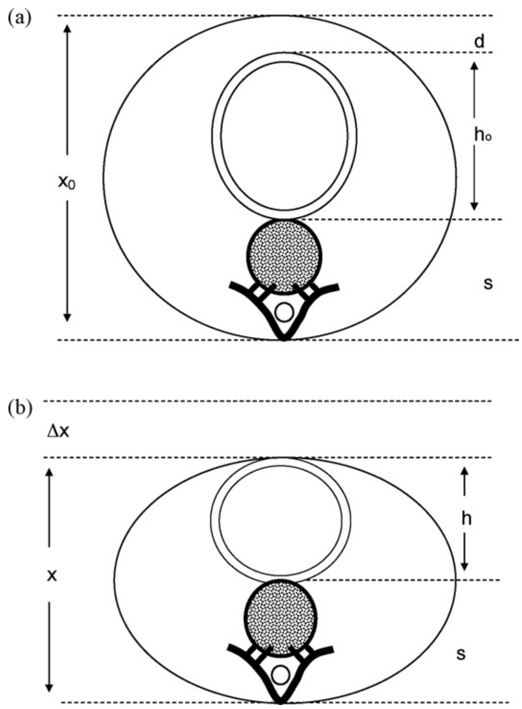


**Fig. 2.** Measured dimensions in axial chest CT cuts of neonates prior to (a) and after a compression. *x*, external chest depth; Δ*x*, chest compression depth; *h*, heart depth; s, spine.

not compressed and the ventricular EF equals 0. The linear relationship between EF and chest compressions has been previously documented in the literature.[11] Therefore, if $\Delta x$ is greater than the non-cardiac thoracic tissue, then the ventricular EF is

$$EF = \frac{\Delta x \Delta d_0}{h_0} \quad (1)$$

Summary statistics were described with mean and standard deviation for parametric variables and median with interquartile range for non-parametric variables. The overall association between proportion of patients meeting criteria for over-compression or under-compression as a function of AP chest compression depth category (1/4, 1/3, 1/2 AP chest depth) was analyzed by two-tailed 2 × 3 Fisher's exact test analysis. To compare the proportion of patients with predicted under-compression or over-compression at 1/4 vs 1/3, 1/4 vs 1/2, and 1/3 vs 1/2 AP chest compression depth, a two-tailed 2 × 2 Fisher's exact test was applied. A one-sample *t*-test was used to compare the calculated values for EF with standard normal values. A two-sample *t*-test was used to compare EF at 1/4 vs 1/3, and 1/4 vs 1/2, and 1/3 vs 1/2 chest compression depth.

## 3. Results

Chest CT scans from 54 neonates performed between 2002 and 2006 met inclusion criteria and were analyzed. Of these subjects, 29 were male, and 25 were female. The age range was 0–28 days of age with a mean age of 14 ± 19.8 days. The reasons for obtaining the CT scans can be seen in Table 1. The measurements of the dimensions taken from the 54 CT scans can be seen in Table 2.

## 4. Data from CT scan calculations

Table 3 displays the number of patients in each age group with predicted over-compression (<10 mm of residual internal chest depth) at each prospectively designated chest compression depth. The overall association between proportion of patients meeting criteria for over-compression or under-compression as a function of AP chest compression depth category (1/4, 1/3, 1/2 AP chest depth) was analyzed by two-tailed 2 × 3 Fisher's exact test analysis. To compare the proportion of patients with predicted under-compression or over-compression at 1/4 vs 1/3, 1/4 vs 1/2, and 1/3 vs 1/2 AP chest compression depth, a two-tailed 2 × 2 Fisher's exact test was applied.

**Table 1**
Reason for obtaining a chest CT scan for the study subjects.

| Reason for study | Subjects |
|---|---|
| Lung lesion/respiratory distress | 40 |
| Tumor/mass | 5 |
| Congenital anomalies | 5 |
| Cardiac disease/lesion | 2 |
| None | 2 |

Scans in which the thoracic pathology was present were not seen as involving the heart in a way that would in itself compromise flow.

## 5. Results from the mathematical model

The estimated EFs for each compression depth compared to values during normal sinus rhythm are shown in Table 4.[12,13] Using the mathematical model, 29/54 subjects receiving a chest compression of 1/4 anterior–posterior chest depth achieved <50% EF, and were therefore considered to be undercompressed. In contrast, no subjects receiving a 1/3 or 1/2 chest compression depth were undercompressed. The overall association between proportion of patients meeting criteria for over-compression or under-compression as a function of AP chest compression depth category (1/4, 1/3, 1/2 AP chest depth) was analyzed by two-tailed 2 × 3 Fisher's exact test analysis. To compare the proportion of patients with predicted under-compression or over-compression at 1/4 vs 1/3, 1/4 vs 1/2, and 1/3 vs 1/2 AP chest compression depth, a two-tailed 2 × 2 Fisher's exact test was applied. A one-sample *t*-test was used to compare the calculated values for EF with standard normal values. A two-sample *t*-test was used to compare EF at 1/4 vs 1/3, and 1/4 vs 1/2, and 1/3 vs 1/2 chest compression depth. Table 5 displays the number with under-compression (i.e. <50% estimated EF).

## 6. Discussion

To our knowledge, this is the first study that utilizes data from recorded chest CT scan images from human neonates to inform mathematical models to evaluate recommended neonatal chest compression depth. The data derived from these CT scans, as well as the mathematical modeling of the EF based on this data, suggest that the current NRP chest compression recommendation of approximately 1/3 anterior–posterior chest compression depth is a safe and sufficient recommendation. The 1/3 AP compression depth resulted in better EF than 1/4 compression depth. Furthermore, no subjects receiving the 1/3 AP chest compression depth were undercompressed (i.e. had a predicted EF <50%), whereas 54% were predicted to be undercompressed at the 1/4 compression depth. The 1/3 AP compression depth was much less likely to meet criteria for predicted over-compression than 1/2 compression depth.

An important consideration, when formulating neonatal chest compression depth guidelines, is to achieve adequate EF while minimizing the risk of over-compression of the neonatal heart. Although reported complications from neonatal chest compressions are rare, rib fractures and cardiac contusion can occur.[14,15] In this study, 88% of subjects receiving a 1/2 AP chest compression depth would be at high risk for over-compression of the heart. In

**Table 2**
Analysis of the basic anatomic measurements compiled from the 54 neonatal CT scans.

| | Minimum (mm) | Maximum (mm) | Mean (mm) | Standard deviation (mm) |
|---|---|---|---|---|
| Internal depth | 40.3 | 90.6 | 49.9 | 6.9 |
| External depth | 70.6 | 113.4 | 90.5 | 7.7 |
| Heart depth | 21.6 | 51.1 | 41.6 | 4.7 |
| Non-cardiac thoracic tissue | 1.1 | 9.3 | 1.5 | 0.6 |

**Table 3**
Number of neonatal patients with overcompressed 1/4, 1/3 and 1/2 anterior–posterior chest compression depths.

| | 1/4 compression depth | 1/3 compression depth | 1/2 compression depth |
|---|---|---|---|
| Number of patients with <10 mm residual internal chest depth | 0 | 0 | 49* |

* $p < 0.001$ two-tailed Fisher's exact test.

**Table 4**
Predicted ejection fraction using mathematical modeling informed by CT scan data for varying depths of chest compression in 54 neonates.

| | 1/4 AP chest depth | 1/3 AP chest depth | 1/2 AP chest depth | Normal values |
|---|---|---|---|---|
| Ejection fraction[a] | 51.1 ± 2.8%<br>$p < 0.001$ | 69.3 ± 3.2%<br>$p = 0.65$ | 105.6 ± 4.3%<br>$p < 0.001$ | 69.1 ± 5% |
| Number of subjects with EF > 90%* | 0 | 1 | 51* | |

[a] Analysis by two-tailed, two-sample *t*-test to compare calculated values with standard normal values for age.
* $p < 0.001$ two-tailed Fisher's exact test.

**Table 5**
Number of neonatal patients with undercompressed 1/4, 1/3 and 1/2 anterior–posterior chest compression depths.

| | 1/4 compression depth | 1/3 compression depth | 1/2 compression depth |
|---|---|---|---|
| Number of patients with EF <50% normal value* | 29* | 0 | 0 |

* $p < 0.001$ two-tailed Fisher's exact test.

contrast, no subjects receiving either 1/4 or 1/3 compression depth ratio would be at risk for over-compression of the heart.

Estimated EF, derived by our mathematical model based on CT scan measured dimensions, also suggests that 1/3 anterior–posterior compression depth is the most appropriate choice. Using the confirmatory definition of over-compression as predicted EF >90%, only 1/54 patient at 1/3 AP chest depth vs 51/54 at 1/2 AP chest depth were estimated as overcompressed.

## 7. Study limitations

This study has several limitations. It is a retrospective, observational study based on measurements taken from neonatal chest CT scans. However, we used prospective conservative definitions of under- and over-compression of the heart. This neonatal study sample was from a large tertiary care center and excludes patients with chest abnormalities; therefore, it may not be representative of the neonatal population-at-large who may receive chest compressions. In addition, the mathematical model based on our CT scan measurements has several assumptions. This model assumes that compression frequency is slow enough and relaxation time long enough so there is nearly complete recoil of the chest between compressions, and that the heart does not shift position significantly during chest compression. Further, the estimation of EF using this mathematical model is higher than cited in adult human CPR literature.[16,17] Nevertheless, such assumptions are consistent with previous mathematical modeling of pediatric and adult CPR, which have correlated with physiologic performance in patients.[18,19]

## 8. Conclusions

Based upon mathematical modeling and neonatal chest CT scan reconstruction dimensions, chest compressions to 1/3 anterior–posterior chest depth recommended by the Neonatal Resuscitation Program appear more appropriate than alternative 1/4 or 1/2 anterior–posterior compression depths. Though it may be difficult for a resuscitator to discern the difference between these three chest compression depths, we feel that targeting the chest compression depth recommended by the AAP should be a resuscitator's goal. A 1/3 AP compression depth was estimated to generate a greater EF than 1/4 AP compression depth, with minimal risk for under-compression of the heart. A 1/3 AP compression depth was estimated to generate less risk for over-compression than 1/2 AP compression depth. Our findings support the 2005 American Heart Association and American Academy of Pediatrics Neonatal Resuscitation Program recommendations for chest compression depth target.

## Conflict of interest statement

None of the authors of this study has any conflicts of interest to disclose.

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