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Application of an anatomically-detailed finite element thorax model to investigate pediatric cardiopulmonary resuscitation techniques on hard bed ☆

Binhui Jiang [a], Haojie Mao [b], Libo Cao [a], King H. Yang [b,*]

[a] The State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan, China
[b] Bioengineering Center, Wayne State University, Detroit, MI, USA

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ABSTRACT

Objectives: Improved Cardiopulmonary Resuscitation (CPR) approaches will largely benefit the children in need. The constant peak displacement and constant peak force loading methods were analyzed on hard bed for pediatric CPR by an anatomically-detailed 10 year-old (YO) child thorax finite element (FE) model. The chest compression and rib injury risk were studied for children with various levels of thorax stiffness.
Methods: We created three thorax models with different chest stiffness. Simulated CPR's in the above two conditions were performed. Three different compression rates were considered under the constant peak displacement condition. The model-calculated deflections and forces were analyzed. The rib maximum principle strains (MPS's) were used to predict the potential risk of rib injury.
Results: Under the constant peak force condition, the chest deflection ranged from 34.2 to 42.2 mm. The highest rib MPS was 0.75%, predicted by the compliant thorax model. Under the normal constant peak displacement condition, the highest rib MPS was 0.52%, predicted by the compliant thorax model. The compression rate did not affect the highest rib MPS.
Conclusions: Results revealed that the thoracic stiffness had great effects on the quality of CPR. To maintain CPR quality for various children, the constant peak displacement technique is recommended when the CPR is performed on the hard bed. Furthermore, the outcome of CPR in terms of rib strains and total work are not sensitive to the compression rate. The FE model-predicted high strains were in the ribs, which have been found to be vulnerable to CPR in the literature.

1. Introduction

Cardiopulmonary Resuscitation (CPR) was first introduced in the 1950s. In the past few decades, CPR gradually becomes a key emergency procedure for saving the life of victims with cardiac and respiratory arrest [1,2]. Without guidelines, CPR has been performed on floor, stretcher, ICU soft bed, etc. As can be expected, mechanical properties of the place where CPR performed would influence its patient outcomes. A number of studies have been performed to investigate the effect of beds' properties and back support for the quality of CPR [3–9]. These data show that the quality of CPR is better when CPR is performed on hard bed due to increased chest compression [3,8–10]. Despite these reports, emergency CPRs for children while in-hospital were performed mostly on soft bed [11,12]. In order to improve the quality of CPR on soft bed, a backboard was recommended to be inserted under the patient to decrease the deflection of soft mattress by the 2005 International Consensus on Resuscitation Science [13]. Despite this recommendation, there was still active debate as to what extent the beneficial or detrimental influence of backboards on the effectiveness of CPR [2].

In clinical environment, two conventional loading techniques are available: the constant peak displacement technique and the constant peak force technique. The blood flow during CPR is generally considered to be linearly correlated with the depth of chest compression [14] and the CPR guideline has clearly prescribed the chest compression depth for patients of different ages [13]. As a result, the constant peak displacement technique was mostly used since it offered a direct approach to control the chest compression.

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* Corresponding author. Tel.: +1 313 577 0252; fax: +1 313 577 8333.
E-mail address: aa0007@wayne.edu (K.H. Yang).

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However, when the CPR was performed by a Thumper mechanical resuscitator (Michigan Instruments, Grand Rapids, MI) or by a smaller adult rescuer, who likely used his/her torso weight, the constant peak force technique was inevitably adopted [7]. Boe and Babbs [7] stated that for a fixed sternal depression distance, which is presented under the constant peak displacement condition, the actual chest deflection would decrease with increasing bed deflection. While the constant peak force technique could ensure enough depth of sternum-to-spine compression on all but the softest bed, at the expense of greatly increased work by the rescuer [7]. Dellimore and Scheffer [15–16] used the theoretical model developed by Boe and Babbs [7] to further study these two loading techniques and concluded that the constant peak force techniques provides reasonable prediction of chest compression mechanics over a range of clinically relevant chest compression rates during CPR. To date, no comprehensive comparison study of these two loading techniques when the CPR is performing on the hard bed for children has been reported.

Mechanical factors of victims also affect the quality of CPR. Nishisaki et al. [3] considered the effects of victims' mass for chest compressions and found that a lighter torso weight was associated with a larger mattress displacement thus resulting in a smaller chest compression for CPR performed on soft ICU bed without backboard. Dellimore and Scheffer [15] reported that the optimal chest compression performance strongly depended on back support stiffness, chest compression rate, and the thoracic stiffness of the patient being resuscitate. To the best of the authors' knowledge, most studies were based on resuscitation manikin or simplistic mathematical model without considerations of varying chest stiffness of the victim. Additionally, these surrogates did not include the complex anatomical structures of the thorax to allow the measurement of rib strain, which is an explicit indicator of the risk of rib fracture. Consequently, the global chest compression is used as the standard to judge the CPR quality. Unfortunately, while deeper chest compression CPR has a higher probability of saving lives, it may also has a higher probability of causing injuries, such as skeletal fractures, upper airway complications, pulmonary barotraumas, hemothorax, and lacerations of internal organs [1]. More studies are recommended to optimize CPR technique to maintain high life-saving probability while minimizing injury risk. Therefore, the potential injuries of victims need to be considered as a complementary standard for determining the quality of a CPR. The FE anatomically-detailed thorax model can be used to predict the exact rib strains and compare the strain predictions to the literature data on rib damage [17]. As such, the FE anatomically-detailed thorax model is needed and can be used as an important tool to study CPR.

To study how variations of the pediatric victim chest affect CPR quality and evaluate potential risks of injury due to pediatric CPR, a detailed biomechanical pediatric thorax surrogate is needed. Traditionally, adult cadaver subjects were used to evaluate safety countermeasures or to study how external impacts affect internal body responses [18–21]. However, due to regulatory and ethical concerns, pediatric cadavers are rarely used for biomechanical experiments. To the best of our knowledge, only a handful of experiments have used pediatric cadaveric specimens [22–24]. Furthermore, postmortem examination on pediatric subjects was also rarely performed to investigate patterns of injuries [25]. In recent years, FE models with detailed representation of complex anatomical features have been used to calculate regional responses, such as the tissue-level strain and stress, and to associate with the risk of injury upon impact [17,26,27]. These works proved that FE models could be used to study biomechanical injury and reduce the dependence on cadaveric studies. Therefore, some child FE models were developed and validated to study the biomechanics of injury in children. For example, a plurality of child head FE models were developed and validated against accident reconstruction or experimental data [27–30]; the other whole 3YO child FE model was also developed by Mizuno et al. [31] and validated against scaling responses data from that of adults. As such, the child FE models are very useful and important tools to study the biomechanics of injury in children. In this study, a 10 year-old (YO) child thorax FE model with detailed rib structures and internal organs was used to evaluate two different CPR loading techniques (constant peak displacement technique and constant peak force technique) with victims laying on a simulated hard bed. The rib responses during CPR were investigated and considered as a complementary standard for CPR quality aside from chest compression and work consumed during CPR. Lastly, the effect of chest stiffness was studied by introducing a softer chest and a stiffer chest in additional to a normal chest.

2. Methods

A 10 YO child thorax model, which was originally developed by Jiang et al. [32], was adopted in this study. This model was chosen because it had been validated against clinical CPR data using the explicit simulation code: LS-DYNA (LSTC, Livermore, CA). Detailed developmental procedures of the model could be seen from Jiang et al. [32]. Briefly, the geometric data of this model was taken from clinical CT and MRI scans of children (10 years $\pm$ 6 months) treated at Children's Hospital of Michigan (CHM). A series of procedures were adopted to reconstructed 10 YO child geometry based on anthropometric external dimensions data reported by Snyder et al. [33]. The cartilage/rib length ratio and rib angle of the final reconstructed 10 YO child model were also match the literature values. The cartilage/rib length ratios of rib level 1–7 were 0.37, 0.19, 0.20, 0.23, 0.29, and 0.36 respectively in the FE model which fell within costal index function of rib level for the age group (8–11YO children) reported by Sandoz et al. [34]. The ANSYS ICEM CFD/HEXA (ANSYS, Canonsburg, Pennsylvania, USA) was used to mesh solid elements for the bony skeleton and organs. Hypermesh (10.0, Altair, Troy, MI, USA) was used to generate the shell/membrane elements for the cortical bones and skins. In total, 242,266 hexahedral, 1524 pentahedral and 188,318 shell and membrane elements were used. The CONTACT_AUTOMATIC_SURFACE_TO_ SURFACE and CONTACT_AUTOMATIC_SINGLE_SURFACE were used to handle the interaction amongst the skeleton, internal organs, and flesh.

In our pervious study [32], the ranges of material parameters for the 10 YO child were scaled from the adults' data [35–44]. Readers are referred to Jiang et al. [32] for details of the scaling methods. Despite the limitation of the scaling between child and adult, the similar scaling methods were also used by Mizuno et al. [31]. According to the 10 YO child average chest stiffness, the final material parameters for this 10 YO child thorax FE model which was shown in Table 1 was chosen by a material property sensitivity study in the scaled material parameters ranges [32]. The 10 YO child average chest stiffness was calculated from the clinical CPR data which were collected from six children (10.5 $\pm$ 1.75 YO) as reported by Maltese et al. [45], and the value was 7363.5 $\pm$ 1985.5 N/m. The chest stiffness of the final 10 YO thorax FE model was 7359.2 N/m, which was only 0.1% lower than the 10 YO child average chest stiffness. As such, the final FE model from Jiang et al. [32] was used as the baseline model with normal chest stiffness in this study. By altering the material parameters of the flesh, rib, coastal cartilage, and internal organs, the other two FE thorax models representing stiff and compliant pediatric chests were developed. Based on the normal stiffness model, the material parameters of the flesh, rib cortical, rib spongy, and internal organs were increased or decreased by 30% to obtain the stiff or compliant pediatric thorax models, respectively.