An Objective Index to Estimate the Survival Rate of Primary Blast Lung Injury

Kihyuck Lee, Jungmin Yoon, Kyeongran Min, Jungchang Lee, Shinil Kang, Sung Jun Hong, Sung Hoon Yoon, Jong-Shill Lee, Kyoung Won Nam, Seok Hyun Cho, Hoonki Park, Kim In Young*

Abstract— **To supply proper treatments to the primary blast lung injury (PBLI) patients, it is important to estimate the severity of the primary blast lung injury in accordance with the blast conditions. In this study, a blast-induced mechanical parameter (first principal stress) of lung was calculated using a finite element thorax model and the correlation between the survival rate of the subjects with blast-induced lung damage and an objective index that was related to the first principal stress of the lung model. This study propose the objective index for the estimation of the degree of PBLI. The results have a potential clinical application to improve the efficacy of treatment for blast injury patients.**

I. INTRODUCTION

The blast overpressure (BOP) that is caused by an explosion can induce excessive deformations and damages to the human body. Injuries that caused by the explosion are categorized by four types and the injury caused by the BOP is called a primary blast injury (PBI). The cause of the PBI is the steep and excessive pressure difference between the interior and exterior of the organs. Therefore, it mostly occurs in the organs, such as ears and lungs, which contain air [1]. The mechanism of primary blast lung injury (PBLI) has not been clearly explained; however, in a previous article, Phillips *et al.* [2] reported that the major reason of the PBLI is the BOP that is transmitted to the lung through the chest wall directly rather than through the respiratory tract. There have been several reports suggesting objective parameters that are related to the severity of the PBLI. For example, Bowen *et al.* [3] analyzed the relationships between the survivability and two blast conditions that are peak overpressure (POP) and positive phase duration (PPD). Josephson *et al.* [4] and Stuhmiller *et al.* [5] suggested threshold values of pulmonary inner pressure that can cause the PBLI by analyzing the correlation between the BOP-induced pulmonary inner pressure and PBLI.

In this study, we analyzed the correlation between the survival rates of subjects with BOP-induced lung injury and the first principal stress (FPSS), using computer simulations and proposed an index to estimate the survival rates of PBLI subjects.

II. METHODS

A. Finite Elements Thorax Model

The simplified three-dimensional finite elements thorax model was constructed using a computer tomography (CT) image which includes the connection point of the fourth rib and the sternum of 20-year-old man. The CT image was loaded using a CAD software (Solidworks Version 2012; Dassault Systems, Waltham, USA), and organs of the thorax was segmented into seven parts; chest muscles, sternum, costal cartilages, ribs, backbone, lung, and heart. Then, each of the seven segments was equally extruded to 1 cm. The constructed 3D thorax CAD model was imported to the finite element analysis (FEA) software (COMSOL Multiphysics Version 4.3b; COMSOL Inc., Burlington, USA), and the mechanical properties and kinetic equations for each of the seven segments of the thorax model that were required for the FEA were established utilizing the solid mechanics module and the time-dependent study solver of COMSOL. The implemented thorax model was composed of 25,708 tetrahedral elements, and the numerical problems were calculated using generalized alpha method. The specific values for the mechanical properties of the human organs in the thorax model are listed in Table I and were set by referring to the previous reports [6, 7]. We assumed that, among the seven segments of the thoracic model, the materials comprising the chest muscles, sternum, costal cartilages, ribs, backbone, and heart were linear-elastic materials, and the materials comprising the lungs were hyper-elastic material [8]. We also assumed that mechanical properties of the chest muscles and heart same as mechanical properties of muscles and mechanical properties of the sternum, ribs and backbone same as mechanical properties of bones.

TABLE I. THE VALUES OF THE MECHANICAL PROPERTIES APPLIED TO THE THORAX MODEL. MUSCLES, BONES, CARTILAGE, LUNG

Organ	Mechanical Properties			
	Young's modulus (E) [MPa]	***Poisson's ratio (ν)***	***Density [kg/m^3]***	***Sound velocity [m/s]***
Muscle	3	0.4	1000	1500
Bone	5000	0.3	2000	3100
Cartilage	49	0.4	1281	286
Lung	X	X	320	35

Kihyuck Lee, Jungmin Yoon, Kyeongran Min, Jungchang Lee, Shinil Kang, Sung Jun Hong Sung Hoon Yoon are with the Department of Biomedical Engineering, Hanyang University, Seoul, Korea

Jong-Shill Lee is with the Department of Biomedical Engineering, Hanyang University, Seoul, Korea (e-mail: netlee@hanyang.ac.kr)

Kyoung Won Nam is with the Department of Biomedical Engineering, Hanyang University, Seoul, Korea (e-mail: kwnam@hanyang.ac.kr).

Seok Hyun Cho is with the Department of Otorhinolaryngology, Hanyang University College of Medicine, Seoul KS013 Korea

Hoonki Park is with the Department of Family Medicine, Hanyang University Hospital, Seoul KS013 Korea

In Young Kim is with the Department of Biomedical Engineering, Hanyang University, Seoul, Korea (corresponding author to provide phone: +82-2-2291-1713; fax: +82-2-2220-4949; e-mail: iykim@hanyang.ac.kr).

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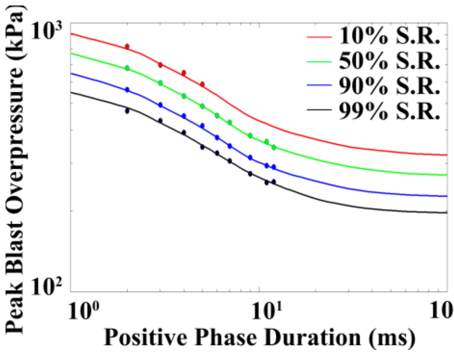

Figure 1. Selected blast test conditions for the modified Bowen's curves proposed by Bass et al. [13]. Lines: modified Bowen's curves for 10 (red), 50 (green), 90 (blue), and 99% (black) survival rates; dots: selected blast conditions that represent 2- to 5-ms PPDs for the 10% survival rate and 2- to 11-ms PPDs for the 50, 90, and 99% survival rates; S.R.: survival rate

The kinetic relationship to simulate the deformation of the thorax model in accordance with the BOP described by (1) was applied to the thorax model [9]:

$$\rho \cdot \frac{\partial^2 u}{\partial t^2} - \nabla \cdot \sigma = \mathrm{F}_V \tag{1}$$

where u represents the displacement, ρ is the density, $\sigma = J^{-1}FSF^T$ is the Cauchy stress tensor, $F = (I + \nabla u)$ is the deformation gradient, I is the identity matrix, ∇u is the gradient of displacement, S is the second Piola-Kirchhoff stress tensor, $J = \det(F)$ is the volume ratio, and F_V is the volume force vector. Than the stress tensor (S_{HEM}) of the hyper-elastic material representing the lung in three orthogonal directions were calculated as below [9]:

$$S_{HEM} = \frac{\partial W_S}{\partial \varepsilon} \tag{2}$$

where W_s represents the elastic strain-energy density function, which is calculated as follows:

$$W_s(\overline{I_1}, J) = c_{quad}(\overline{I_1} - 3)^2 + c_{cub}(\overline{I_1} - 3)^3 + \frac{\kappa}{\beta^2}(-2\ln J + J^2 - 1). \tag{3}$$

where $\overline{I_1}$ represents the first invariant of the isochoric elastic right Cauchy-Green tensor, and the values of c_{quad}, c_{cub}, κ, and β were set to 4.1 kPa, 20.7 kPa, 16.5 kPa, and -2, respectively [8].

After calculating the stress tensors of the lung model in the thorax model, the eigenvectors of the stress tensor was then calculated. Among the calculated eigenvectors, the magnitude of the stress tensor whose eigenvalue was maximum among the three stress eigenvectors was set as the FPSS [9].

B. BOP Model

To calculate the strain and stress tensors of the implemented thorax model in accordance with the variations of the external blast conditions, it was assumed that 1) the BOP calculated from the applied blast condition was applied to the overall side boundaries of the thorax model as static pressure, 2) the BOP was not directly applied to the upper and under boundaries of the thorax model, and 3) the upper and lower boundaries of the thorax model were symmetrically deformed by the BOP propagated to the side boundaries of the thorax model. These assumptions were applied to the simulation using the load condition function and symmetric boundary function of COMSOL. In addition, we also assumed that the source of the blast was placed in front of the thorax model with at a distance R in meters, that the power of the blast was W in kilograms, and that the space was the free-air-blast environment. The values of BOP on the side boundaries of the thorax model in accordance with the variations in the blast conditions (R and W) were calculated based on the Friedlander wave equation [10-12] as below:

$$\begin{cases} BOP(t) = P_0 & \left(t - \frac{R}{U} \le 0\right) \\ BOP(t) = P_0 + P_{so}\left(1 - \frac{\left(t - \frac{R}{U}\right)}{T_s}\right)\exp\left(-\frac{b\left(t - \frac{R}{U}\right)}{T_s}\right) & \left(t - \frac{R}{U} > 0\right) \end{cases} \tag{4}$$

Where P_0 is the atmospheric pressure, P_{SO} is the POP, T_s is the PPD, U is the velocity of the POP, and b is the decay ratio of the exponential term. The mathematical equations and values of those parameters were set as follows:

$$\begin{aligned} Z &= \frac{R}{W^{1/3}}\,[\mathrm{m} \cdot \mathrm{kg}^{-1/3}] \\ P_{so} &= \frac{1772}{Z^3} - \frac{144}{Z^2} + \frac{108}{Z}\ \ [\mathrm{kPa}] \\ T_s &= 10^{-2.75} W^{1/3} Z^{0.27}\ [\mathrm{s}] \\ U &= \sqrt{\frac{6P_{so} + 7P_0}{7P_0}}\,a_0\ \ [\mathrm{m/s}] \\ b &= Z^2 - 3.7Z + 4.2 \end{aligned} \tag{5}$$

Where Z represents the scaled distance, P_0 was fixed at 101.325 kPa and a_0 was fixed at 343 m/s [11, 12].

C. BOP Simulation with FE Thorax Model

To calculate the correlations between the FPSS and the survival rate (which represents the probability of survival at the given blast conditions), we utilized four survival rate curves from an article by Bass *et al.* [13] (modified Bowen's curve [6]), which represent the 10, 50, 90, and 99% survival rates (Figure 1).

The values of R and W for the determined mean PPD and mean POP were calculated by (5) so that the values of the mean PPD and mean POP for the simulation became the same as the PPD and POP on the modified Bowen's curve. Finally, utilizing the four calculated values of the mean POP, mean PPD, R, and W, the degrees of deformation of the thorax model in accordance with the variations of blast condition were simulated, and the values of the FPSS for each blast condition were calculated. The simulation was performed for a duration of 12 ms right after the BOP arrived at the thorax model (Figure 2), and the values of the FPSS at each mesh constituting the thorax model were calculated every microsecond (10,000 values per index).

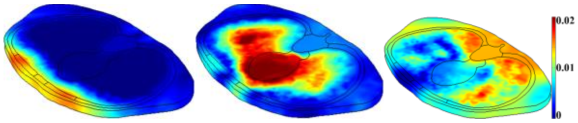

Figure 2. Total displacements [m] from the simulation results of the BOP propagation through the thorax model after blast generation
(a) 1 ms, (b) 5 ms, and (c) 8 ms.

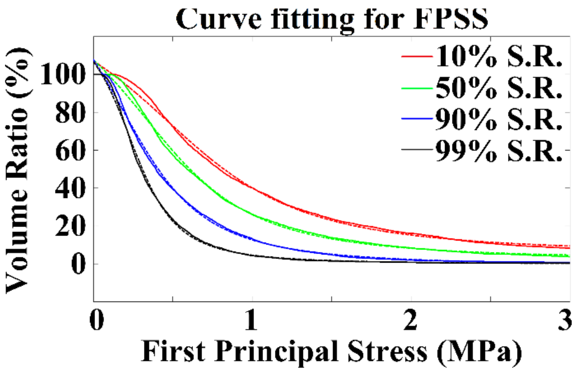

Figure 3. Results of the sigmoidal curve fitting for FPSS at survival rates of 10 (red), 50 (green), 90 (blue), and 99% (black) when the value of the PPD was 2 ms. Solid lines: original $V_{ACC} - V_{LUNG}$ ratio graphs; dashed lines: curve-fitted $V_{ACC} - V_{LUNG}$ ratio graphs. S.R.: survival rate

After the simulation, the maximal values of FPSS were determined at each mesh. And some graphs that demonstrate the volume ratios between the meshes whose representative index values were above a specific index value and the overall meshes constituting the thorax model ($V_{ACC} - V_{LUNG}$ ratio graphs) were drawn. Then, sigmoidal curve fitting $\left(y = C\frac{-(x+B)}{\sqrt{A+(x+B)^2}} + D\right)$ was applied to each of the $V_{ACC} - V_{LUNG}$ ratio graphs (Figure 3), the values of the decay parameters for each fitted curve (A for sigmoidal curve fitting) were calculated, and finally, the distributions of the decay parameters at each of the four survival rates were investigated to determine the effectiveness of the FPSS for the accurate estimation of the survival rate.

III. RESULTS

Figure 4 represents the $V_{ACC} - V_{LUNG}$ ratio graphs for each of the simulated blast conditions (Figure 1). The $V_{ACC} - V_{LUNG}$ ratio graphs for each of the survival rates of 10, 50, 90, and 99% were separately distributed for FPSS. The decay of the $V_{ACC} - V_{LUNG}$ ratio graphs of FPSS became steeper as the survival rate increased.

Table Ⅱ demonstrates the calculated values of constants A, B, C, and D in the fitting equation and the values of the root-mean-square error (RMSE) between the original $V_{ACC} - V_{LUNG}$ ratio graphs and the curve-fitted $V_{ACC} - V_{LUNG}$ ratio graphs. As shown in the table, there is no overlap of the decay parameter A for FPSS, which implies that, the survival rate can be estimated accurately by the decay constant A for FPSS.

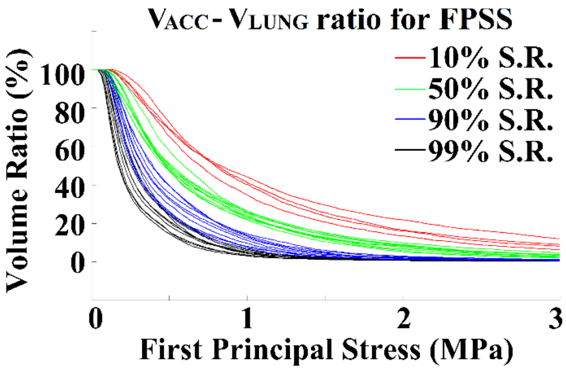

Figure 4. $V_{ACC} - V_{LUNG}$ ratio graphs for FPSS at survival rates of 10 (red), 50 (green), 90 (blue), and 99% (black). S.R.: survival rate

Table Ⅲ demonstrates the results of non-parametric Mann-Whitney U tests for the decay parameter A between various pairs of survival rates. The overall pairs of survival rates showed statistically significant (p-value < 0.05) differences.

IV. DISCUSSION

A. $V_{ACC} - V_{LUNG}$ Ratio Graphs

MacFadden *et al.* [14] demonstrated that the degree of pulmonary contusion becomes more severe as the values of those mechanical parameters (normalized work) become higher; Champion *et al.* [15] divided the severity of the contusion based on the area of the injury (i.e., the larger the contusion area, the more severe the damage is). Considering these previous studies, it can be concluded that the severity of the PBLI is highly correlated with the magnitude of the blast-induced mechanical parameters and the extent of the damaged area; i.e., the BOP-induced lung damage is severe when the damaged area which is represented by seriously high values of mechanical parameters is large. Therefore, in order to include both of those factors to estimate the degree of BPLI, the $V_{ACC} - V_{LUNG}$ ratio graphs were utilized.

B. Clinical Application

If the blast conditions that cause the injury of a PBLI patient (such as W and R) are gathered, the value of the decay parameter of the sigmoidal curve-fitted $V_{ACC} - V_{LUNG}$ ratio graph for FPSS can be calculated by the BOP simulation with the real blast conditions. Then, the estimated survival rate (an indication of the severity of the injury) of the patient is calculated, and finally, appropriate medical treatments based on the estimated severity of the injury are administered to the patient, which may result in improved treatment efficiency and reduced mortality.

TABLE II. THE CALCULATED VALUES OF CONSTANTS A, B, C, AND D IN THE SIGMOIDAL CURVE FITTING EQUATION, AND THE VALUES OF ROOT-MEAN-SQUARE ERROR BETWEEN THE ORIGINAL $V_{ACC} - V_{LUNG}$ RATIO GRAPHS AND THE CURVE-FITTED $V_{ACC} - V_{LUNG}$ RATIO GRAPHS. S.R.: SURVIVAL RATE

	Survival Rate	**A**	**B**	**C**	**D**	**RMSE**
FPSS	10%	$(11.04 \pm 3.51) \times 10^{11}$	$(-2.72 \pm 1.97) \times 10^{5}$	82.84±13.40	87.19±13.91	1.38±0.23
	50%	$(5.80 \pm 0.87) \times 10^{11}$	$(-0.94 \pm 1.17) \times 10^{5}$	97.35±12.00	97.92±11.75	1.41±0.28
	90%	$(2.18 \pm 0.68) \times 10^{11}$	$(-1.34 \pm 0.28) \times 10^{5}$	86.26±3.97	85.84±4.05	1.64±0.22
	99%	$(0.93 \pm 0.19) \times 10^{11}$	$(-1.15 \pm 0.55) \times 10^{5}$	82.94±7.64	83.03±7.82	1.58±0.24

TABLE III. THE CALCULATED P-VALUES OF THE NON-PARAMETRIC MANN-WHITNEY U TESTS

S.R.	10-50%	10-90%	10-99%	50-90%	50-99%	90-99%
p-value	0.003	0.003	0.003	<0.001	<0.001	<0.001

C. Limitations

This study has some limitations. First, the CAD model used in this study is not the same as the actual shape of the human chest and therefore, for more reliable simulation, in future studies, a more realistic model of the human body should be used and perform the same investigation. Second, the current BOP model can calculate only the simple and free-air blast that has one explosion source of BOP and no reflected pressure. Therefore, to calculate the BOP of multi-explosion or to implement the reflected pressure, several new equations for complex BOP calculation are needed.

V. CONCLUSION

In this study, we proposed an objective index which was helpful in the estimation of the severity of the lung damage. Our experimental results demonstrated that the decay parameter of the sigmoidal curve-fitted $V_{ACC} - V_{LUNG}$ ratio graphs for FPSS can play a key role. Although the current study has several limitations, we expect that the results of this study have potential to be applied to the clinical field to improve the efficacy of medical treatment for blast injury patients.

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