NUMERICAL ANALYSIS OF ENERGY DENSITY DISTRIBUTION IN THE HUMAN LUNGS UNDER LOW-FREQUENCY ACOUSTIC EXCITATION

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1 Introduction

The standard treatment for chest physiotherapy is clapping, which causes vibrations on the chest surface. It affects the viscoelastic, shear-thinning, and thixotropic properties of bronchial mucus, liquefying it to ease expectoration. Acoustic airway clearance devices (AACD) could be up to 1.8 times more effective than the standard treatment [1]. Therefore, with the help of such acoustic medical devices, high-frequency chest compression (HFCC) therapy is currently the most common way to relieve excessive mucus accumulation.

Despite the fact that HFCC therapy has been shown to improve lung function and mucociliary clearance, further research is necessary to optimize the AACD used [1,2,3]. For that reason, computed tomography-based numerical finite element analysis (CT/FEA) is necessary to obtain accurate results for the kinetic and elastic energy densities of the lungs under the frequency domain [2,4].

In a previous study, the average kinetic energy density and the strain energy density under 5-100 Hz have already been examined [2]. Nevertheless, no work has yet to be done so far to examine the influence of acoustic harmonic excitation in the low-frequency range on the interior of 3D lungs. This study aims at investigating the human lungs under AACD with a 3D-validated realistic CT/FEA of the human thorax using COMSOL 6.1 Multiphysics®.

2 Method

2.1 CT Thorax Model and Material Properties

In order to achieve accurate results from a 3D CT/FEA, image processing is deemed necessary for having realistic geometries [4]. The physical properties of the human thorax depend from one person to another in terms of weight, height, and chest size. For that reason, in this study, we use a validated CT based human thorax data [5] in order to overcome the effects of the different extreme physical features of the human and represent the average results.

Each internal organ, trachea and bronchioles, lungs, rib cage, and soft tissues are displayed in Figure 1 before assembling the thorax. They were created by using image processing of the CT data.

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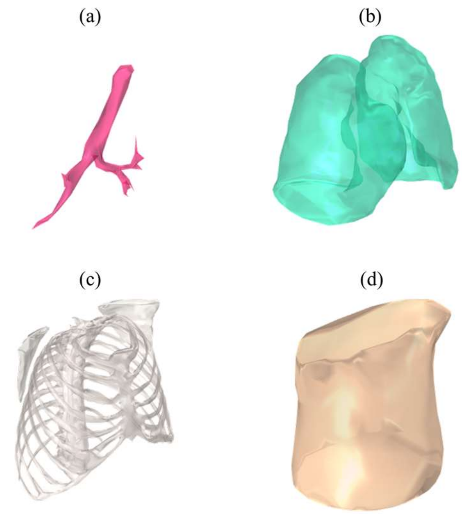

Figure 1: CT based realistic modelling of (a) trachea and bronchioles, (b) lungs, (c) rib cage, and (d) soft tissues for human thorax modelling

To represent the essential characteristics of the human internal organs, the complex material properties of the thorax are handled. Moreover, to simplify the representation of micropore structure and viscoelasticity, different models are used. For example, the Voight model is particularly useful for osseous and soft tissue regions. The material properties of the lungs have been improved by using the Biot's theory [2]. To homogenize the heterogeneous, fully saturated material features of the lungs, this theory is used to calculate the complex fast compression waves and slow compression waves as well as shear wave speeds [2].

2.2 CT-Lung Frequency Domain Analysis

The final geometry is decomposed into 14 domains, and gathers 10k boundaries, 15k edges, and 5k vertices. The complete mesh comprises 292k tetrahedra, 53k triangles, 33k edge elements and 5k vertex elements. It leads to a good mesh quality, with an average skewness quality of 0.58.

For gentle drainage of the mucus in the lungs, numerical acoustic studies selected the low-frequency range to be applied to the human chest wall under harmonic excitation. The acoustic harmonic excitation is investigated here by using a 28 mm radius cylinder as an effect of AACD with 146 dB_{SPL}. The result took about 2 h 30 min with the processor Intel(R) Core (TM) i7-9700 CPU @ 3.00 GHz with 16 GB RAM memory.

3 CT/FEA Acoustic Analysis Results

3.1 Kinetic Energy Density

The kinetic energy density distributions for the lungs under 30 Hz and 41 Hz are displayed in Figure 2. It could be deduced that the kinetic energy density of the lungs under 30 Hz excitation is accumulated mainly on the sternum and the lung part near the sternum; however, at 41 Hz, the middle region of the lungs seems to be more affected.

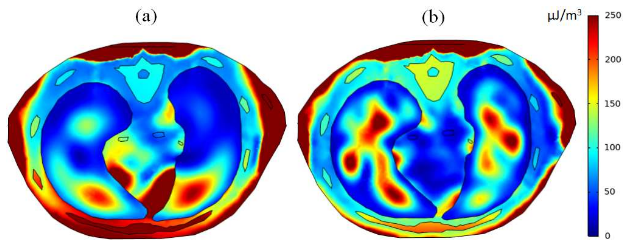

Figure 2: Kinetic energy density results of the human thorax at (a) 30 Hz and (b) 41 Hz

3.2 Elastic Strain Energy Density

The elastic energy density distribution results for the lungs under 32 Hz and 42 Hz are illustrated in Figure 3. Even though the average values are the same and match the results from the literature [2], the distributions in the lungs are different from one case to the other.

Moreover, as they are the most rigid materials in the human thorax, the highest strain energy density appears to be stored in the osseous region, such as the rib cage and scapula, as expected.

4 Discussion

The kinetic energy density in the low-frequency range appeared very sensitive to the applied frequency between 30 and 41 Hz, especially in the softer materials, like soft tissues and lungs. On the other hand, it is obvious that the strain energy density in the osseous region is higher than that of the lungs. This is mainly due to the material properties of the lungs, which are the softest material among the other biomaterials.

Despite the fact that two different frequencies have been applied to the human chest surfaces, the average values remain the same as 180 µJ/m^3 at both 32 Hz and 42 Hz, as indicated in Table 1 [2]. In this study, notwithstanding, it is revealed that their effects on the lungs differ from each other. Therefore, in order to decide the optimum frequency range in HFCC therapy, more numerical studies are needed. Owing to the fact that the characteristic size of the mucus layer is infinitely small compared to the dimensions of the human thorax, the mucus properties are not considered in this study.

5 Conclusion

In this study, the internal effects of HFCC on the lungs under an AACT device are clarified by numerical simulations. This paper revealed the kinetic and elastic strain energy density distributions on the human lungs using CT/FEA at four different peak frequencies. Though similar average values are obtained for two different frequencies, an insight into the local distributions shows that frequencies around 41 Hz lead to more homogeneous kinetic and elastic strain energy density distribution in the lungs.

As a future study, a set of new numerical simulations coupling acoustics and computational fluid dynamics are planned to imply the mucus properties. The objective will be to identify the frequency of optimizing the mucus transport in the lungs.

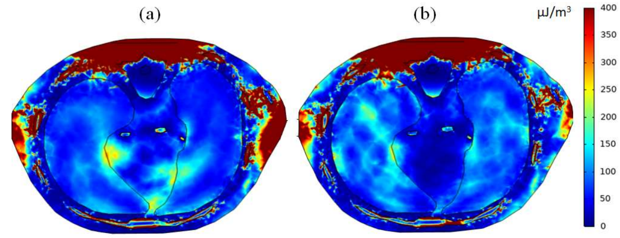

Figure 3: Elastic strain energy density results of the human thorax at (a) 32 Hz and (b) 42 Hz

Table 1: Comparison of the analysis results with respect to average peak values [2]

Average Feature	Peak Value (µJ/m^3)	Frequency (Hz)
Kinetic Energy Density	56	30
	46	41
Elastic Strain Energy Density	180	32
	180	42

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