Examination of the Behaviour of the Lungs under High-Frequency Chest Compression Airway Clearance Therapy

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Abstract—Chronic Obstructive Pulmonary Disease (COPD) is the third leading cause of death worldwide, with 3 million in 2019. Medical devices for high-frequency chest compression (HFCC) therapy are currently the most common approach to relieve COPD symptoms in the lungs. The resonance frequency of the human thorax is one of the most influential parameters for HFCC to act on the viscoelastic, shear-thinning, and thixotropic properties of bronchial mucus for airway clearance therapy (ACT). In this study, a 3D computed tomography-based finite element analysis (CT/FEA) is done by COMSOL Multiphysics® 6.1 under the frequency domain with the purpose of examining the resonance frequency and the behaviour of lungs under HFCC therapy. An excitation under 140 dB_SPL with a frequency range between 5 and 100 Hz is considered on the back-chest surface. As for comparison, the maximum kinetic energy density is 3.5 times higher than the kinetic energy density for the whole thorax because of the poroviscoelastic physical properties of the lungs. The lung kinetic energy density value reaches a peak at 56 μJ/m³ at 30 Hz, which is supported by the numerical and experimental studies in the literature.

Keywords-component; HFCC; ACT; human lungs; CT/FEA; acoustic numerical analysis

I. INTRODUCTION

Chronic obstructive pulmonary disease (COPD) affects more than 310 million people, and 3 million people died from it in 2019, according to the annual report of the World Health Organization (WHO) [1]. Airway mucus is a complex viscoelastic gel, which comes up with a defensive physical barrier and shields. In healthy individuals, mucus is generated continuously to protect the airway and humidify the air in the lungs to protect against damage from particles moving down into the lungs [2]. However, most of these respiratory diseases such as cystic fibrosis (CF), lung cancer, bronchiectasis, and asthma are related to excessive mucus accumulation in the human respiratory system's tracheobronchial region, causing breathing obstruction but mostly for [3-5]. In most cases, mucus secreted by individuals with respiratory diseases has higher viscoelasticity compared to mucus from healthy individuals, causing mucus build-up in the airways and leading to the deterioration of lung function [6,7].

Chest physiotherapy (CPT) is the standard treatment method for airway clearance therapy (ACT) in COPD with the assistance of a physiotherapist. However, airway clearance device (ACD) technologies under development are increasingly aimed at providing devices that the patients can use independently from the physiotherapist to increase the easiness and rapidity of access to treatment. With such medical devices, high-frequency chest compression (HFCC) therapy is currently the most common way to relieve COPD symptoms in the lungs by creating positive pressure air pulses to help the expectoration of the excessive mucus in the lungs [8,9]. ACT with ACD supplies an alternative or supplemental therapy, which motivates patients to apply the treatment themselves without the dependency on a physiotherapist to drain bronchial mucus and improve pulmonary function. Moreover, in addition to the accessibility of the treatment, the devices pave the way for a reduction in the cost of therapy [10]. The effect of the HFCC on the lungs with an ACD to expectorate excessive mucus is illustrated in Fig. 1.

Figure 1. HFCC effect on the lungs and bronchioles
HFCC is known for several advantages, such as providing an adequate physiotherapy method to conventional physiotherapy. It is beneficial for sputum expectoration, contributing to stability or improvement of respiratory function, and increasing airflow in the low lung volume. Furthermore, it is effective not only on Tracheal Mucus Clearance (TMC) but also on Peripheral Mucus Clearance (PMC) [11].

The popularity of HFCC with ACD has increased dramatically after the evidence by Hansen and Warwick [12] that ACD provides 1.8 times higher mucus clearance per therapy session than conventional ones. Currently, literature data on the HFCC agree on the advantages of giving adequate physiotherapy, which is helpful for sputum expectoration, stabilization and improving respiratory function. Therefore, the ACT with ACD has already begun to take the place of traditional physiotherapy.

Schieppati et al. [8] investigated the influence of the frequency range and its amplitude on mucus viscoelasticity for CF. They tested both normal and pathological synthetic mucin solutions (1 % and 4 % by weight) in vitro. The frequency range applied was from 20 Hz to 60 Hz. In the experimental study, it is found that 40 Hz coupled with a NaCl concentration of 0.5 g.L⁻¹ rehydrates the mucus and lowers its viscosity, thus possibly making it easier to expectorate. It is the only experimental study available in the low-frequency range, which has inspired the numerical research presented herein.

While HFCC therapy improves lung function and mucociliary clearance by HFCC therapy, more research is still needed to optimize the ACDs. Even though they gather around the same purpose, the operating pressure ranges vary from one device to another. For instance, to maximize mucus expectoration, one of the well-known wearable oscillating device operates at 10-15 Hz, while another at 40 Hz [8,13]. Moreover, regardless of the number of in vivo experiments, it is impossible to have a representative sample of the infinitely different features of the human subjects that need to be treated. Conversely, a numerical study could be adapted to the various parts of each human patient. Therefore, mechanical and numerical models considerably enhance our understanding of sound transmission phenomena in respiratory diseases by providing reproducibility and reliability [14,15].

To obtain accurate results from a 3D finite element model (FEM), besides the precision of the material properties of the respiratory system and the numerical model, a real Computerized Tomography (CT) geometry plays a key role [16,17]. To work with a realistic geometry, clinical image processing is crucial to take accurate results in 3D analysis. Over the past 40 years, computed tomography-based finite element analysis (CT/FEA) has provided realistic geometries for ever increasing accurate results. CT/FEA of human research is one of the promising tools, which paves the way for studies with high accuracy, reliability, ease of use, and usefulness [17].

Such model is accurate for the prediction of the behavior of internal organs when they combine with proper material properties in FEA. As for the material properties, the physical material properties of the lungs have been determined by Biot's theory [14,18,19]. Moreover, the simple viscoelastic material Voight model is used for osseous and soft tissue regions [15].

Through resonance, a comparatively weak excitation in one object can cause a strong vibration. In other words, resonance is the ability of a system to achieve maximum energy storage when absorbing energy from the external frequency's excitation. Therefore, the resonance frequency is one of the most influencing factors in HFCC therapy to supply an efficient, yet gentle therapy by providing high energy to the lungs [9,10,19].

Uzundurukan et al. [9] found the resonance frequency as 28 Hz for the whole thorax of a human torso model, and supported the numerical findings with independent experimental studies [10,19]. It is the numerical work supported experimentally, which directs this study. As for an experimental physiotherapy study, the human chest wall's resonance frequency ranges between 18.5 Hz and 35.3 Hz [10]. It varies according to weight, chest size, sex, and height of the patient, but, on average, 25 Hz and 33 Hz are the resonance frequencies of the thorax for men and women, respectively. The other study found the average chest-resonance frequencies for male and female volunteers as 26.7 Hz and 27.8 Hz, respectively [19]. However, to the best of the authors' knowledge, there is no published study that yet investigates the lungs' behaviour under HFCC therapy.

In this study, the HFCC effect on the human thorax and on the lungs has been investigated by a CT/FEA. The analysis has been done in the frequency domain using the solid mechanics toolbox available in COMSOL Multiphysics 6.1. The effect of HFCC on the kinetic energy density and strain energy density of the human thorax and the human lungs has been investigated and compared in the 5-100 Hz frequency range. Furthermore, the normal displacement and the velocity of the lungs are found numerically.

II. COMPUTED TOMOGRAPHY-BASED FINITE ELEMENT ANALYSIS

A. Geometry Modeling

The geometrical model from a CT image created in our previous study [21], which includes soft tissue, lungs, rib cage, scapula, trachea and bronchioles, is used in CT/FEA. Furthermore, numerical simulations have already been performed in the acoustic study to investigate all thorax at resonance frequency [9], which are supported by two different experimental physiotherapy studies [10,19].

To obtain accurate results for FEA, the other internal organs are considered in order to take into account their interaction with each other. The soft tissues, lungs, rib cage and scapula, trachea and bronchioles and the assembled geometry used in the 3D FEM are illustrated in Fig. 2(a) to Fig. 2(e), respectively.

B. Material Properties

The complex material properties of the human thorax are used to illustrate the key characteristics of the human internal
organisms. Thus, the behavior of such micropore structure and viscoelasticity of the different models has been represented by simplification. Further, the Voight model is used for osseous and soft tissue regions [22].

The airway material properties are directly taken from the study [18]. The lung properties are calculated by Biot’s theory to make the heterogeneous, fully saturated material features homogenized [23,24,25].

### Table I. The used physical material properties of the human organs in CT/FEA

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<tr>
<td>( \rho ) (kg/m(^3))</td>
<td>1000</td>
<td>1500</td>
<td>250.9</td>
<td>1000</td>
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<tr>
<td>( \lambda_1 ) (GPa)</td>
<td>2.6</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
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<tr>
<td>( \lambda_2 ) (GPa)</td>
<td>0</td>
<td>0</td>
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<tr>
<td>( \mu_1 ) (kPa)</td>
<td>2.5</td>
<td>( 10^7 )</td>
<td>-</td>
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<tr>
<td>( \mu_2 ) (Pa.s)</td>
<td>5</td>
<td>20</td>
<td>-</td>
<td>-</td>
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<tr>
<td>( c_{s1} ) (m/s)</td>
<td>-</td>
<td>-</td>
<td>26.87</td>
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<td>( c_{s2} ) (m/s)</td>
<td>-</td>
<td>-</td>
<td>2.42</td>
<td>-</td>
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<tr>
<td>( c_{p1} ) (m/s)</td>
<td>-</td>
<td>-</td>
<td>4.42</td>
<td>-</td>
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<tr>
<td>( c_{p2} ) (m/s)</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
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<tr>
<td>( E_1 ) (MPa)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.28</td>
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<td>( E_2 ) (MPa)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.124</td>
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<td>( \nu ) (-)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.49998</td>
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The material properties used in the study are given in Table 1, where \( \rho \) represents density, \( \lambda \) and \( \mu \) are the Lamé parameters, \( c_s \) and \( c_p \) are the shear and pressure wave speeds, \( E \) is Young’s modulus, and \( \nu \) is the Poisson ratio.

### C. Frequency Domain Analysis

In the numerical acoustic studies, the low-frequency range, applied to the human chest wall under harmonic excitation, was selected for gentle drainage of the mucus in the lungs.

![Figure 2](image.png) Representation of (a) soft tissues, (b) lungs, (c) rib cage and scapula, (d) trachea and bronchioles, and (e) assembled human thorax.

![Figure 3](image.png) Human thorax geometry: (a) the front view and (b) the back view with the shaker in orange.
ACT based on vibrations is one of the most preferred methods to promote bronchial drainage by inducing vibrations on the chest wall. 3D validated realistic CT/FEM of the human thorax is used to illustrate the HFCC effect under the frequency range of 5-100 Hz, as shown in Fig. 3.

The acoustic harmonic excitation is applied through a 0.004 m radius cylindrical shaker under 140 dB$_{spp}$ on the back-chest surface. In order to reach the objective, the effect of ACD is illustrated on the back chest surface in HFCC on the lungs for enhanced mucus expectoration. COMSOL Multiphysics 6.1 performed the mechanical analysis in the frequency domain to investigate the response of a steady-state harmonic excitation for the human thorax resonance frequency and its environment.

The kinetic energy density and elastic strain energy density data are analyzed inside the lungs in order to illustrate the HFCC effect. The frequency range has been determined according to the resonance frequency range found in former experimental and numerical HFCC studies [8,9,10,19].

### III. RESULTS AND DISCUSSION

The acceleration resonance frequency was found to be 28 Hz for the whole thorax [9] and they supported the numerical findings by independent experimental studies [10,19]. In this study, by using this generated realistic CT/FEM, the lungs’ behavior is investigated as illustrated in Fig. 4 under 160 dB$_{spp}$ to comprehend the HFCC effect on the lungs for COPD. The kinetic energy and the strain energy density for all elastic domains are integrated to give the total elastic strain energy. It contains all elastic energy stored in a specific physics interface, which allows quantifying the HFCC effect on human lungs for bronchial drainage.

The kinetic energy density and strain energy density are computed for the whole human thorax in the low-frequency range, as shown in Fig. 5a. While the strain energy density reaches the peak at 460 µJ/m$^3$ at 55 Hz, the kinetic energy density reaches the peak at 17 µJ/m$^3$ at 45 Hz.

It is evident that the human thorax consists of many internal organs, such as rib cage, scapula, soft tissue etc., which have both complex geometry and complex material features that affect the numerical results. Moreover, HFCC is applied to the human thorax to create an effect on the lungs, which exhibit poroviscoelastic properties, such that the best CPT frequency, the viscoelastic, shear-thinning, and thixotropic properties of mucus have to be also investigated in this frequency range. Although the maximum vibration occurs on the chest surface at 28 Hz [3], it can differ for airways. Therefore, the lungs are investigated by expanding the frequency interval, which includes human thorax resonance frequency, to reach the best mucus expectoration value in HFCC in the low-frequency.

The results for the kinetic energy density and the strain energy density of the lungs in the 5-100 Hz frequency range to illustrate the effect of HFCC are demonstrated in Fig. 5b. The kinetic energy density rises to a significant peak at 56 µJ/m$^3$ at 30 Hz and a small peak at 46 µJ/m$^3$ at 41 Hz.

The lungs must be investigated further around the human thorax resonance frequency to find the best mucus expectoration frequency. This is because the lungs are a complex and poroviscoelastic material, representing the most critical internal organ having a role in mucus expectoration.

As for the strain energy density, between 5 Hz and 100 Hz, it also exhibits two distinct peaks at frequencies close to that of the kinetic energy density, as shown in Fig. 5b. Therefore, the behaviour of the strain energy is in line with the kinetic energy density. Two distant peaks for the strain energy density reaching are at the same value 180 µJ/m$^3$ at 32 Hz and 42 Hz.

For comparison, the kinetic energy density in the low-frequency range is 3.4 times higher than the average value of the thorax, while the strain energy density of the average value 3.2 times higher than the average value of the lungs. The main reason for this result is the material properties of the lungs. At the same time, they are the softest material to have a minor strain energy density. Moreover, the highest strain energy density is predicted to be stored in the osseous region, such as the rib cage and scapula, which affects notably the overall average value of the human thorax in terms of having the most
complicated and the most rigid material in the human thorax. They are fully saturated poroviscoelastic materials to be affected mainly through the velocity change, affecting kinetic energy.

Further, the velocity and the total displacement of the lungs under HFCC treatment are investigated, as illustrated in Fig. 6. The velocity directly influences significantly the kinetic energy density, has the same peak as 51 µm/s at 32 Hz, and displays the same behaviour as kinetic energy density. Furthermore, it is mostly constant after 70 Hz frequency range like the kinetic energy density. However, instead of the peak at the velocity value, the displacement is 6 µm at 5 Hz and it decreases slowly with respect to increasing frequency.

The numerical findings are supported by the literature studies numerically and experimentally [2,3,8,10]. The significant peak frequency of the kinetic energy density is 30 Hz. It is close to the investigated numerical and experimental human thorax resonance frequency of approximately 28 Hz in HFCC therapy [3,8,10].

IV. Conclusion

A numerical validated whole human thorax model has been used to elucidate the internal effect of HFCC on lung behaviour in chest physiotherapy. In this paper, the kinetic energy density and strain energy density of the whole human thorax and the lungs have been investigated by using CT/FEA as a continuity of the prior study. Moreover, the velocity and displacement of the lungs under the 5-100 Hz frequency range have been studied to comprehend the lung's behaviour in detail under HFCC therapy.

For comparison, the kinetic energy density of the lungs in the low-frequency range is 3.4 times higher than the average value of the whole thorax in HFCC therapy. On the contrary, the average value of the strain energy density of the entire human thorax is 3.2 times higher than that of the lungs. In addition to the comparison, one peak is found at 30 Hz, which is consistent with reported distinct experimental and numerical data available in the literature despite the detailed complex human thorax geometry.

As a future work, considering the peak frequencies in the kinetic energy density, a set of numerical studies will be conducted to investigate further the influence of chest vibrations on bronchial mucus transport.

REFERENCES


