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Biophysics of Chest Vibrations

Alexander I. Dyachenko[1,2,3,4]

[1] Prokhorov General Physics Institute of RAS, Moscow, Russia

[2] Institute of Biomedical Problems of RAS, Moscow, Russia

[3] Bauman Moscow State Technical University, Moscow, Russia

[4] Moscow Institute of Physics and Technology (University), Dolgoprudny, Russia

***Corresponding author:** Alexander I. Dyachenko, Prokhorov General Physics Institute of RAS, Moscow, Russia; Tel: +7-903-675-17-00; Fax: +7-499-135-01-58; E mail: alexander-dyachenko@yandex.ru

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Abstract

The purpose of this mini-review is to outline diversity of chest wall vibrations, specify biomechanical peculiarities and point out a few problems crucial for development of diagnostic and therapeutic applications of chest wall vibrations. The review considers two types of chest wall vibrations: spontaneous, induced by breathing, and forced (or artificial), induced by external vibration forces. Spontaneous vibrations emerge in airways and lung tissues due to vortexes, flatter and stress relaxation in pulmonary parenchyma. The vibrations propagate in lung to the chest wall and could be registered by a stethoscope at the chest wall surface as respiratory sounds. Another type of vibrations emerges due to heart contraction and become apparent at the chest wall surface as heart sounds. Respiratory and heart sounds are used for diagnostics of respiratory and heart diseases. Computerized respiratory sounds analysis (CRSA) is a new technique emerged last years and based on respiratory acoustics and biomedical engineering. Forced vibrations are the lung and chest wall vibrations induced by external vibrations effecting airways orifice and/or chest wall. Diagnostic and therapeutic forced vibrations differ in both frequency and amplitude. Diagnostic vibrations imposed at the airway orifice include forced oscillatory technique, estimation of airway cross-section by analysis of acoustic pulse response measurements. Stress and deformation oscillations used for diagnostic techniques usually are small to avoid any mechanical nonlinearity. Diagnostic vibrations imposed at the chest surface include a special kind of forced oscillatory technique with pressure oscillation around the entire chest and a technique of percussions imposed locally to the areas of interest on the chest wall. Elastic waves propagate in airways, pulmonary parenchyma and chest wall during vibrations. Peculiarities of elastic waves propagation in these structures are discussed. A high sound or low ultrasound window presents new emerging perspective area for biomedical engineering aimed to develop a technique for lung sound/ultrasound imaging. There are a few kinds of therapeutic forced vibrations aimed to enhance airway sputum removal if the production of sputum is too large due to decease.

Keywords: Chest vibrations, Diagnostic vibrations, Therapeutic vibrations, Respiratory acoustics, Oscillation mechanics of the lung, Computer simulation, Chest therapy, Computer-assisted methods, Lung, Physiology, Models, Anatomic, Sputum.

Introduction

Vibrations of a mammalian chest is a unique biomechanical process involving stresses and strains in a unique biphasic medium of lung with two media: low density compressible gas and high density incompressible soft tissues. This peculiarity of media cause specific acoustical and other physical phenomena in lung and chest.

The purpose of this mini-review is to outline diversity of chest wall vibrations, specify biomechanical peculiarities and point out a few problems crucial for development of diagnostic and therapeutic applications of chest vibrations.

In this review, we consider two types of chest wall vibrations: spontaneous, induced by breathing, and artificial, induced by external vibration forces.

Different types of chest wall vibrations could be observed in the human chest wall and lungs. Spontaneous vibrations are induced by subject's breathing. Forced vibrations are induced by external vibrations.

All the mechanical oscillations in the respiratory system could be considered as vibrations, including breathing itself and all emerging deformations and stresses in respiratory tissues with a breathing frequency. These "trivial" spontaneous vibrations will not be considered in this review.

Very large traumatic vibrations resulting from blast wave exposure or another external powerful force are out of our scope as well. So in this brief review our attention is limited to spontaneous or forced vibrations with diagnostic or therapeutic value. Chest vibrations under consideration include a wide range of frequencies and estimated amplitudes of alveolar pressure oscillations presented in Figure 1. To better present spontaneous and forced chest vibrations, the later with breathing frequency are included as zone 1 in Figure 1, but large traumatic vibrations are excluded from Figure 1.

Spontaneous vibrations

Spontaneous vibrations in the lungs and chest wall at frequencies other than breathing frequency occur as results of breathing in the form of respiratory sounds or as a result of non-breathing mechanical activity in the chest (i.e. heart beat).

Respiratory sounds are the most well-known spontaneous vibrations in the chest. Many clinical, experimental and theoretical researches and technical developments devoted to respiratory sounds are presented in the site of the International Lung Sounds Association- ILSA [1] and scholar journals. Computerized lung sound analysis changed all the area from observational to more data-based stage [2,3]

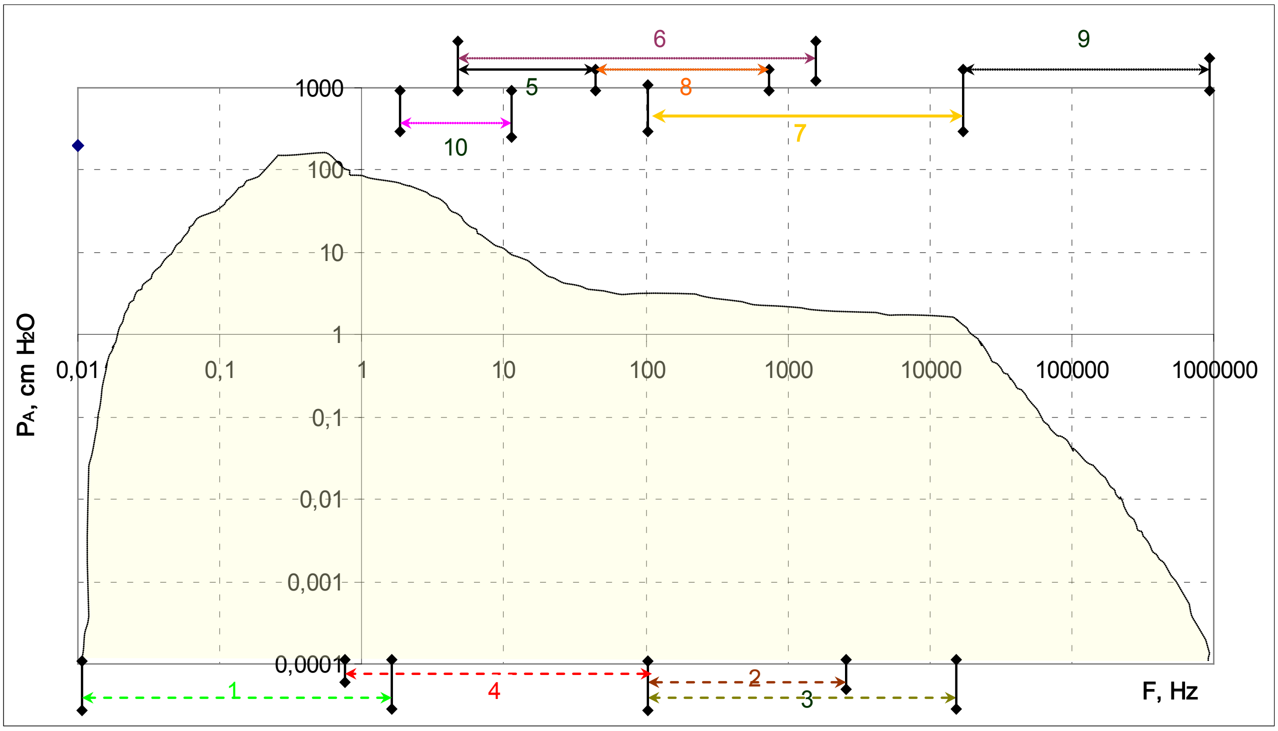

Figure 1: Frequency bands and estimated amplitudes of alveolar pressure oscillations in spontaneous and forced chest vibrations.

Double arrows indicate frequency ranges of zones of spontaneous or forced vibrations of definite kinds. Numbers of zones and double arrows have the same color.

1 – Spontaneous breathing and respiratory maneuvers;

2 – Respiratory sounds;

3 – Expanded range of respiratory sounds near the mouth orifice;

4 – Heart sounds;

5 – Forced oscillation technique;

6 – Expanded lung impedance measurements;

7 – Estimation of airway cross-section by analysis of acoustic pulse response measurements;

8 – Percussion sounds;

9 – Low frequency ultrasound;

10 – Therapeutic vibrations.

Solid line presents maximal amplitudes of spontaneous or forced alveolar pressure oscillations. Colored area presents a range of amplitudes. In zone 9 amplitudes are tentative.

Breathing generates respiratory sounds due to a few mechanisms. The mechanisms include generation of sound by vortexes, by flatter and by stress relaxation in pulmonary parenchyma [4]. Vortexes appear in transitional and turbulent flows in the airways. Large flow in a channel with abrupt change in a channel profile can induce a flow separation, i.e. divergence of adjacent streamlines. Flow separation in a 3-dimensional structure such as airways produces vortexes. Vortexes can arise in airways bifurcations during both expirations and inspirations [5,6]. Computational fluid dynamics boosted study of flows in airways and revealed many peculiarities of vortexes [6]. Oscillations of pressure in vortexes induce vibrations in airways, lung tissues and chest wall, i.e. respiratory sounds. Vortexes are the main source of normal lung sound and some other respiratory sounds [4,7]. Duration of forced expiratory tracheal noises increases with gas density, which is an additional proof that vortexes are the main reason of the noises [8]. Exact place of the "sounding" vortexes in the airways is still controversial and additional studies to locate vortexes are still needed.

Flatter is a vibration generated by the loss of stability of a soft structure due to its contact with a flow of a fluid. Flatter probably is the main mechanism of wheezes [9-11].

Formation of liquid bridges during expiration and rapture of the bridges during inspiration [12,13] with subsequent stress relaxation in pulmonary parenchyma [14] are the main mechanisms of crackles. Distraction of liquid bridges and removal of sputum from airways is one of the purposes of physical therapy (see further). So understanding dynamics of liquid bridges in airways is important for both diagnostics and therapy of lung deceases.

The frequency band of respiratory sounds spans from less than 100 Hz to over 12600 Hz.

Usually respiratory sounds are recorded on the surface of chest wall or the neck. Over chest wall, the most traditional site of respiratory sound recording, respiratory sounds spans from less than 100 Hz to more than 1000 Hz [4]. Lower than 100 Hz there are respiratory sounds but they are mixed with heart sounds. For this reason heart sound filtering from lung sounds is an important task [15,16]. Heart sounds are presented in Figure 1 as zone 4. Over trachea, in sounds called tracheal sounds, the lower spectral limit is considered to be 100 Hz [4], although many consider frequencies just above 200 Hz [17]. Upper frequency in tracheal sound expands over 1500 Hz with traceable sounds up to 4000 Hz[4]. The most researchers consider tracheal sounds to be from less than 100 Hz to 3000 Hz [4], and this range cover all the respiratory sounds band (zone 2 in Figure 1). Attenuation of lung sounds in soft tissues of lungs, chest wall and neck seems to be the main cause of absence of recordable respiratory sounds at higher frequencies.

Respiratory sounds in the frequency band from 100 Hz up to 12600 Hz could be registered with a microphone located near mouth of patients with cystic fibrosis by a technique of computer bronchophonography [18]. This phenomenon of expanded band of respiratory sounds is presented as zone 3 in Figure 1. There are very scanty studies of respiratory sounds in this frequency band. One may suppose that these high-pitched sounds are just artifacts or sounds generated in the pipelines between a mouth and a microphone. But in Geppe N. et al. [18] and other studies of the same group they demonstrated that in the frequency band over 5000 Hz there is no sound energy in normal subjects breathing and there is significant sound energy in breathing of patients with cystic fibrosis. Sites of the high-pitched sounds generation should still be specified.

Forced vibrations

Forced vibrations are the lung and chest wall tissues vibrations induced by external vibrations effecting lung tissues. External vibrations are imposed to the respiratory system with diagnostic and therapeutic purposes.

Diagnostic forced vibrations include a few techniques with forced perturbations exerted at the airways orifice – mouth. The most widespread technique is impulse oscillometry and other variants of forced oscillatory technique [19], with measurement of mechanical impedance of the respiratory system in a frequency band from about 5 Hz to about 70 Hz. In this frequency band wavelength is much more then lung dimensions permitting to use lumped-parameter models of the respiratory system for analysis of oscillations (zone 5 in Figure 1). Measurement of respiratory impedance in a higher frequencies range provides more insight into lung mechanics but should be considered on the bases of lung models with distributed parameters (zone 6 in Figure 1). Another technique is an estimation of airway cross-section by analysis of acoustic pulse response measurements [20,21] with an acoustic pulse delivered into the mouth in the frequency ban from 100 Hz to above 10000 Hz (zone 7 in Figure 1). Oscillatory mouth pressure amplitude is usually about 1 cm H_2O to grant mechanical linearity of the respiratory system.

Another kind of diagnostic forced vibrations is clinical chest percussion: light tapping of the chest and listening or registration of percussion sounds [22]. Percussion sounds band is depicted as zone 8 in Figure 1. Since first computer-aided studies of percussion sounds [23] new approaches to computerized analysis biophysical processes involved in percussion chest vibrations [24] as well as detection of lesions in the lung [25] and pleura [26] came into study. A physical approach to chest percussion demonstrated a clinical value [27,28].

Hereinbefore cited studies described results of automated analysis of percussion sounds generated by manual chest wall tapping. Further step in automation of chest percussion was a development of automated tapping of chest wall by a plunger driven by a computer [29]. Chest wall tapping generates low-frequency elastic waves on the chest wall [30,31]. Speed and attenuation of the waves determine the size and frequencies of oscillating part of chest wall and hence the percussion sounds used by a physician for diagnostics. Character of vibrations of pulmonary parenchyma underlayer, its depth under chest wall, its influence on the audible percussion sounds are very sparsely known and are challenges for future experimental and theoretical studies.

A new area of respiratory acoustics emerged last years due to obtained permeation of low frequency ultrasound in frequency band 5-40 kHz and a few higher frequencies up to 750 kHz through human thorax [32], zone 9 in Figure 1. They estimated sound speed about 1500 m/s in frequency band from 10 to 20 kHz. Another group have registered slower waves in 10-19 kHz band with speeds from 50 m/s to 300 m/s [33]. An earlier study of sound transmission between trachea and back in the frequency band 1-20 kHz revealed no transmission between 5 and 12 kHz, but some transmission at 12 kHz [34]. Low frequency ultrasound is suitable for detecting air trapping [35]. Physical bases for permeation of low frequency ultrasound through lung remain vague. D. Reuter et al. [32] suggested that blood containing in the lungs could be the carrier of low frequency ultrasound. It does not explain well relatively low sound attenuation. Let's consider mechanisms of sound propagation and attenuation in the lung. At low frequencies 100-1000 Hz a low speed of sound in the lung about 20-60 m/s depending on lung density is well described by a notion of biphasic medium where soft tissues phase determines medium density and gas phase determines medium compressibility [36]. Multiphase continuum mechanics analysis was a basis of the 4-phases model of pulmonary parenchyma [37], in which parenchyma was considered as a continuum with two bulk phases – gas and soft tissues, and two surface phases – entrances to airways and blood vessels. Continuum approach suggested averaging of equations over characteristic size of about 1 cm and is correct if sound wavelength is at least a few cm. With these suggestions from 4-phases model of pulmonary parenchyma another model of sound propagation in the pulmonary parenchyma was produced [38]. It described effect of lung volume on sound speed and other effects, but not strong attenuation at frequencies up to 10 kHz and permeation at 10-20 kHz.

Attenuation of sound in the pulmonary parenchyma from 100 to 600 Hz is primarily because of thermal losses due to heat transfer during compression and expansion of gas in alveoli and other airways [36]. An estimation of thermal sound attenuation in pulmonary parenchyma suggested thermal independence of gas bubbles which is true if a distance between bubbles is more than 0.1 of a bubble radius [36]. This is not quite true for bubbles – alveoli, so a more complete model of sound attenuation is needed even for frequencies of a few hundreds Hz. Nevertheless the model [36] predicted significant increase of attenuation with frequency increase from 100 to 600 Hz. One may suggest that this could be true with further increase of frequency up to 10 kHz. If sound speed does not increase much with frequency then at frequencies about 10 kHz a traditional continuum approach to pulmonary parenchyma would fail. A new model is crucial for research of propagation of sound and low ultrasound in the lung and development of a new technique of ultrasound lung imaging.

Therapeutic forced vibrations

To increase the mucus removal therapists apply vibrations to the airways and/or chest wall service. The therapeutic vibrations are usually more powerful than diagnostic vibrations.

The respiratory system remained a linear one despite rather big vibration changes in intrapleural pressure up to 10 cm H_2O [39]. The therapeutic vibrations could be applied orally or to the chest wall. In all the ways the vibrations penetrate all the chest causing alveolar and pleural pressure oscillations [40]. A sputum in the airways is a viscoplastic medium. To be removed from the airways it should undergo rather high shear stresses exceeding a threshold of fluidity. Does oscillating shear stress in viscoplastic sputum exceed a threshold of fluidity and how it affects the net outflow of sputum should still be a matter of research. Clinical studies deliver contradictory results. This could be a result of very high differences in amplitude and frequencies of therapeutic vibrations delivered by physiotherapists manually. In a study [41] a repeatability of amplitude and frequency of vibrations exerted by each of 8 physiotherapists was good during the same therapeutic session. But vibrations differed much in 24 hours and 6 months. Moreover vibrations differed between physiotherapists: amplitude from 2 to 66 N and frequency from 3 to 11 Hz (zone 10 in Figure 1). These differences in delivered vibrations could be a reason for contradictory results pointed out by a few systematic reviews of physical therapy and therapeutic vibrations in particular [42,43].

In Bradley JM et al. [44] there is a meta-analysis of five reviews devoted to application of 12 techniques of physical therapy to cystic fibrosis patients. They noted that there are positive effects of chest conventional physiotherapy and less proofed positive effects of other vibration and oscillatory techniques. Other systematic reviews support conclusion that there are no strong proofs on therapeutic effects of oscillating devices for airway clearance [45]. Though clinicians and researchers do not put much attention to details of applied vibrations and biophysics of sputum, they could be crucial for clinical effectiveness of therapeutic oscillation and vibration techniques. Therapeutic forced vibrations remain an empirical therapy. Theoretical and experimental studies with consideration of effects of chest vibrations on distraction of liquid bridges and removal of sputum from airways are a new challenging area in biophysics of chest vibrations.

Summary

In this mini-review a diversity of chest vibrations is presented with emphasis of diagnostic and therapeutic applications. Spontaneous vibrations include respiratory sounds and heart sounds. Forced vibrations include a variety of diagnostic forced vibrations techniques: forced oscillatory technique, estimation of airway cross-section by analysis of acoustic pulse response measurements, chest wall percussion and low frequency ultrasound. Therapeutic forced vibrations present an area of great clinical importance but scanty notice of chest vibrations biophysics. This and other emerging problems for chest vibrations biophysics are depicted.

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