# CHAPTER 8

# Applied chest-wall vibration therapy for patients with obstructive lung disease

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## Abstract

Patients with chronic lung disease (such as emphysema and chronic bronchitis) have ventilatory difficulties (i.e. getting adequate tidal volume), due to lung compliance and airflow resistance caused by mucus build-up in the lung airways. For these patients, high-frequency chest-compression therapy (HFCCT) is gaining acceptance (as an alternative to conventional physical chest physiotherapy). For arresting the decline in pulmonary function of patients with chronic obstructive pulmonary disease (COPD), the method involves the use of an inflatable vest system and is designed for permitting self-administration. However, the commonly used pulsating frequency range of 6–19 Hz employed in the inflatable vest system is probably not optimized for mucus drainage. This is because for maximal effectiveness, the HFCCT needs to be effected at the chest-resonance frequencies. In an effort to enhance the efficacy of the method, chest-resonance frequencies were measured on a sample of 23 volunteers. The average chest-resonance frequencies found for male and female healthy volunteers are 26.7 Hz and 27.8 Hz, respectively. The results suggest that HFCCT should be carried out at about 18–34 Hz. Ideally, however, it is necessary to first obtain the chest-resonance frequency of the patient and then administer HFCCT at that value. This is because patients suffering from COPD will have impaired respiratory muscle and will have a smaller than normal chest-wall cavity, which in-turn will affect the average chest-resonant frequency of patients suffering from COPD.

## 1 Introduction

There is often a build up of mucus within the lungs of patients caused by a variety of diseases such as cystic fibrosis, emphysema, asthma, and chronic bronchitis.

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For example, cystic fibrosis (CF) is a deadly hereditary disease that affects the mucus-secreting glands of the body so that there is an overproduction of mucus. The mucus is very thick and accumulates in the intestines and lungs, causing increased lung compliance and resistance to airflow, with impaired breathing. Hence, the excess mucus must be removed on a daily basis, so as to avoid build-up and reduce the risk of contracting infections that in turn may lead to severe impairment of lung function and ultimately to patient's demise. Traditionally, the removal of mucus from lungs is accomplished by the application of chest physiotherapy (CPT). CPT is an airway-clearance technique that combines manual percussion of the chest-wall by a respiratory therapist, strategic positioning of the patient for mucus drainage and the removal of these secretions by effective coughing and breathing techniques. Studies have shown that regular CPT is able to enhance expectoration [1–3] and slow down the deterioration of lung function [4]. The problem with conventional CPT is that it has to be administered by a trained physiotherapist. It is time consuming, and hence contributes to the low compliance rates that are reported in the range of 26 to 47% [5–8].

As an alternative to manual percussion, pneumatic chest-compression devices [9–13] have been developed to produce high-frequency chest-wall oscillation (HFCWO). Essentially, a pneumatic chest-compression device consists of a large-volume variable-frequency air-pulse delivery system and an inflatable vest worn by the patient. The technique is based on the theory that the action of the pulsating air pressure delivered to the chest-wall will transmit shock waves through the chest-wall and enhance airflow velocity through the air passages. This action produces a cough-like shear force and reduction in mucus viscosity that results in an upward motion of the mucus. Clinical trials have shown that these devices are effective in facilitating mucus clearance [14–17] and inducing HFCWO is equal to or more effective than the conventional CPT involving a respiratory therapist pounding on a patient's chest to loosen mucus for expectoration. It has also been noted that HFCWO or HFCCT is well tolerated by the majority of patients, and that there has been no adverse effects [14–17] observed in this form of chest percussion. As an example of the clinical efficacy of HFCWO, consider the case of a 48-year-old man with cystic fibrosis who had Pseudomonas aeruginosa in his sputum and had experienced a two-year worsening of pulmonary function [9]. After a year of using the HFCWO vest, his pulmonary function had improved to the level of five years earlier. Furthermore, before HFCWO therapy the technetium aerosol scan showed an absence of ventilation in the upper lobes. However, after eight months of use of the HFCWO vest, it showed restoration of ventilation in these areas. This particular HFCWO vest user did not participate in the clinical trials by Hansen and Warwick [9]. Thus, the observed improvement in his pulmonary function could be due to regular self-administered chest therapy. Hence, unlike conventional CPT, a HFCWO system can be used for self-therapy, which may promote increased patient compliance. Now, if the methodology can be further improved by determining the optimal chest-pulsating frequency (of HFCWO) to be equal to the chest-resonance frequency, the results could be even better.

The inflatable-vest system based on HFCWO works on the principle of rapid compression and relaxation of the chest-wall. The vest inflates and deflates rapidly, gently compressing and releasing the chest-wall 5–20 times per second. The oscillations can be adjusted and typically the oscillation frequency used in an inflatable vest system is set at 6 to 19 Hz. The present study is based on the premise that if the oscillation frequency of the inflatable vest is tuned to the patient's chest-dynamic characteristics, it will effectively maximize the energy transmission to the lung. This will result in optimal vibrations, which will loosen the mucus, increase the airflow velocity, and hence increase the efficiency of clearing the lungs of mucus. Hence, in the present study, experiments were conducted on 21 healthy volunteers to measure the resonance frequencies of the human chest. The volunteers were mainly in their twenties, and comprised 8 males and 13 females. The study investigated the variation of the measured resonance frequency in relation to the effects of wearing thicker clothing, breathing rate, as well as whether the test is conducted before or after a meal. The tests suggested that the results are independent of these variables. The resonance frequencies were also analyzed to test the correlation between the chest-resonant frequency in relation to the subject's mass, chest size, height and body mass index (BMI). The results indicate that since the chest-resonance frequency is highly correlated to the subject's chest size, the latter can be used to estimate their chest-resonant frequency. However, as mentioned earlier, the optimal frequency of applied HFCWO is deemed to be the patient's chest-resonance frequency (CRF). The CRF would also be affected by COPD, involving the mucus build-up, weakening of the respiratory muscle and resulting in changes to a smaller than normal chest-wall cavity. It would be interesting to determine the ranges of CRF of patients with lung diseases, and to custom-tailor the application of HFCWO (or HFCCT) to the CRF of the patient, so as to deliver maximal energy to the chest to loosen and induce drainage of the mucus.

## 2 Experimental methodology

Twenty-one healthy adults volunteered as subjects for this study. All the subjects were students, comprising 8 males and 13 females, whose age was mostly in the twenties. The subjects were measured for height, weight and chest size. Two measurements of chest size were taken for the female subjects; one is the upper chest size, (which is the circumference of the upper body around the breast) and the other is the lower chest size (which is the circumference of the upper body immediately below the breast). The same experimenter made all measurements. From the physical measurements, each volunteer's body mass index (BMI) was calculated based on the weight (kg) of the person divided by the square of the person's height (meter). The body-mass index (BMI) is one of the most accurate ways to determine whether a person is too thin, normal, overweight or obese. Alternatively, it can also be seen as a gauge of the overall mass-to-stiffness ratio of the body.

For the measurements of chest-resonance frequency, the volunteers were made to sit upright on a stool and to lean with their backs against a light stiff pad that was

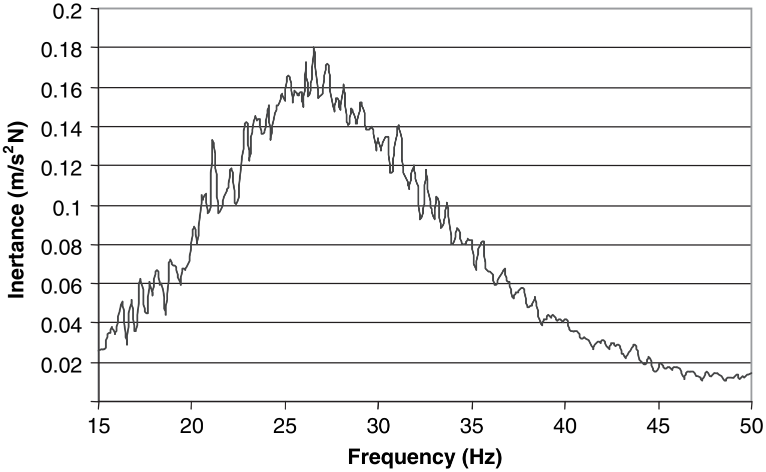

Figure 1: Typical frequency-response function.

linked by a flexible stinger to an electrodynamic shaker. A force transducer was placed between the stinger and the pad so as to record the force delivered to the subject; the output was measured using an accelerometer held firmly against the front of the chest at the sternum. The amplitude of the excitation force delivered to the subjects was adjusted manually, starting from a low level to the maximum level felt comfortable by the subjects. The level is then reduced slightly from the maximum level. White noise was used as the input signal.

The output from both the force transducer and the accelerometer was fed to a dual-channel spectrum analyzer. The setting on the spectrum analyzer was adjusted to display the frequency-response function for the acceleration response per unit input force. The coherence function [18], an indicator of how well the output of the system under test is related to the input to the system, was also displayed. A typical frequency-response function and its corresponding coherence function are shown in Figs. 1 and 2, respectively.

As with all random input signals, it is necessary to perform an averaging process so as to remove spurious random noise from the signals. The frequency-response function (FRF) and the coherence function (COH) as shown in Figs. 1 and 2, are based on 100 averages. Using 100 averages, it was found that the coherence value near the resonance frequency is always greater than 0.8 for all the tests conducted on the 21 volunteers. This implies that the results from the tests are reliable with good input signal-to-noise ratio. It can be seen from Fig. 1 that a clear maximum peak in the FRF enables the volunteer's chest-resonant frequency of 26.5 Hz to be identified. The equivalent viscous damping ratio ($\zeta$) for the chest-resonant frequency is estimated from the FRF using the half-power points; in the case of the example in Fig. 1, the damping ratio is 0.16. The vibration test was repeated for all volunteers and the chest-resonance frequencies and damping factors recorded are based on an average of two measurements.

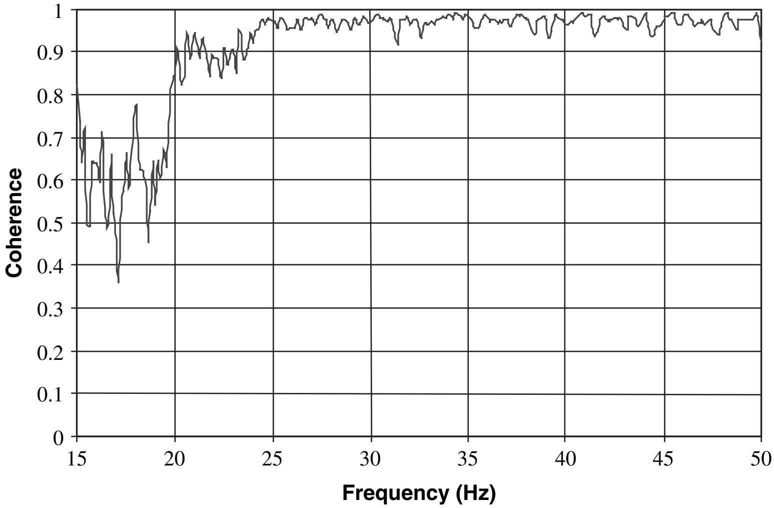

Figure 2: Corresponding coherence function.

## 3 Theoretical considerations based on guidelines for HFCCT

Let us assume that the chest vibration corresponds to the case of vibration with viscous damping, which can be represented by:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = 0,$$

wherein:

(i) The natural frequency of a person's chest vibration is $\omega_n = \sqrt{k/m}$, with $k$ representing the chest stiffness and $m$ the chest mass. The damped natural frequency of chest vibration is: $\omega_d = \omega_n\sqrt{1-\zeta^2}$

(ii) $\zeta$ is the viscous damping ratio of a person's chest vibration

When the chest is pulsed by the application of an external force (in HFCCT), we can represent the forced vibration of the chest as:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = Q\sin\omega t,$$

where $\omega$ is the applied pulsating frequency (of vest inflation and deflation) and $Q$ is the amplitude of applied force on the chest.

In response to the application of $Q\sin\omega t$, the chest-wall displacement response can be written as:

$$x = D\sin(\omega t - \theta),$$

where $D$ is the amplitude of the chest displacement and is given as:

$$D = \beta\left(\frac{Q}{\omega_n^2}\right), \quad \beta = \frac{1}{\sqrt{(1-(\omega/\omega_n)^2)^2 + (2\zeta(\omega/\omega_n))^2}},$$

and $\beta$ can be termed as the chest-vibration amplitude amplification. The implication of $\beta$ is that the amplitude of the chest displacement increases as the applied forcing frequency $\omega$ approaches the natural frequency ($\omega_n$). However, the value of $\beta$ in the neighborhood of $\omega_n$ is very much influenced by the amount of damping in the chest vibration. For varying $\zeta$, the resonance (or maximum $\beta$) occurs at the applied forcing frequency of:

$$\omega = \omega_n \sqrt{1 - 2\zeta^2},$$

and the corresponding maximum amplification is given as:

$$\beta = \frac{1}{2\zeta\sqrt{1 - \zeta^2}}.$$

## 4 Results and discussions

The experimental data for anthropometric characteristics, average chest natural frequencies and damping ratios for all the male and female subjects are presented in Tables 1 and 2, respectively. Also included in the tables are the means, standard deviations and the Pearson correlation coefficients between the resonant frequencies and the various physical attributes of the volunteers. As can be seen from the tables, the natural frequency for the human chest is specific to the individual, and varies from 24 Hz to 30 Hz. For the individuals participating in the investigation, an average natural frequency for the male participants is 26.7 Hz and for the female volunteers, the average natural frequency is 27.8 Hz.

It is important to note the significance of these varying natural frequencies. That is, when the excitation frequencies are almost equal to the human chest frequencies, large vibration amplitudes develop. At approximately 10 Hz away from the chest frequencies, the vibration amplitude drops dramatically as compared to the peak values. Therefore, the premise is that if the HFCWO vest is pulsed at the human chest frequencies, it will provide the optimal setting for the chest-wall oscillator to transport mucus in a cephalad direction. Consider the HFCWO protocol as recommended by a vest's manufacturer. Six frequencies (6, 8, 14, 18 and 19 Hz) are recommended. Except for the two highest frequencies of 18 Hz and 19 Hz, at all the other frequencies, the vibrations of the chest-wall will be low as compared to the vibrations at resonance. Even at 18 Hz and 19 Hz, the two frequencies are still far away from the average chest frequencies of the volunteers, and the difference in the vibration amplitudes will still be substantial as compared to exciting chest vibration at resonance.

Apart from the resonance frequencies, the sharpness of the peak as seen in Fig. 1 is an important factor. It is related to the damping of the chest-walls. In this exercise, we assume viscous damping and the experimental damping ratios ($\zeta$) are given in Tables 1 and 2. The average damping ratios for the male and female volunteers are 0.15 and 0.16, respectively. The sharpness of resonance ($Q$) is calculated as $Q = 1/2\zeta$. Calculated on the basis of $\zeta = 0.15$, $Q = 1/3$. Here, it is important to note that the most frequently reported complaint by patients who used the HFCWO vests was

Table 1: Measured parameters of 8 male volunteers.

| Subject | Age (Years) | Mass (kg) | Height (cm) | Chest size (cm) | Body-mass index (BMI) | Chest-resonance frequency (Hz) | Damping ratio ($\varsigma$) |
|---|---|---|---|---|---|---|---|
| M1 | 23 | 53 | 162 | 83 | 20.20 | 28.35 | 0.11 |
| M2 | 27 | 70 | 170 | 95 | 24.22 | 24.95 | 0.13 |
| M3 | 23 | 64 | 165 | 96 | 23.51 | 24.43 | 0.17 |
| M4 | 23 | 55 | 162 | 92 | 20.10 | 26.50 | 0.16 |
| M5 | 39 | 55 | 161 | 84 | 21.22 | 28.10 | 0.13 |
| M6 | 28 | 57 | 168 | 86 | 20.20 | 27.70 | 0.19 |
| M7 | 27 | 60 | 172 | 83 | 20.28 | 28.15 | 0.15 |
| M8 | 28 | 62 | 168 | 89 | 21.97 | 25.40 | 0.17 |
| Mean | 27.3 | 59.5 | 166 | 88.5 | 21.57 | 26.70 | 0.15 |
| STD | 5.3 | 5.7 | 4.1 | 5.3 | 1.55 | 1.59 | 0.03 |
| Pearson |  | –0.79 | –0.21 | –0.94 | –0.89 |  |  |

Table 2: Measured parameters of 13 female volunteers.

| Subject | Age (Years) | Mass (kg) | Height (cm) | Lower chest size (cm) | Upper chest size (cm) | Body-mass index (BMI) | Chest-resonance frequency (Hz) | Damping ratio ($\varsigma$) |
|---|---|---|---|---|---|---|---|---|
| F1 | 23 | 48 | 170 | 69 | 79 | 16.61 | 29.05 | 0.15 |
| F2 | 24 | 51 | 162 | 74 | 87 | 19.43 | 27.05 | 0.13 |
| F3 | 24 | 56 | 155 | 81 | 90 | 23.31 | 25.55 | 0.19 |
| F4 | 36 | 50 | 152 | 74 | 86 | 21.64 | 27.53 | 0.12 |
| F5 | 24 | 40 | 152 | 68 | 78 | 17.31 | 28.80 | 0.20 |
| F6 | 23 | 48 | 163 | 69 | 78 | 18.07 | 29.15 | 0.17 |
| F7 | 24 | 50 | 164 | 76 | 87 | 18.59 | 26.90 | 0.15 |
| F8 | 24 | 54 | 169 | 68 | 79 | 18.91 | 28.45 | 0.19 |
| F9 | 22 | 58 | 164 | 75 | 86 | 21.56 | 27.55 | 0.13 |
| F10 | 22 | 49 | 154 | 68 | 78 | 20.66 | 29.35 | 0.13 |
| F11 | 23 | 46 | 163 | 73 | 80 | 17.31 | 29.15 | 0.16 |
| F12 | 23 | 70 | 167 | 86 | 95 | 25.10 | 24.85 | 0.19 |
| F13 | 23 | 50 | 160 | 75 | 84 | 19.53 | 28.18 | 0.15 |
| Mean | 24.2 | 51.5 | 161.2 | 73.5 | 83.6 | 19.85 | 27.81 | 0.16 |
| STD | 3.6 | 7.1 | 6.2 | 5.4 | 5.4 | 2.51 | 1.43 | 0.03 |
| Pearson |  | –0.78 | –0.04 | –0.93 | –0.97 | –0.81 |  |  |

a sense of chest constriction while the vest was inflated. However, patients tolerated this form of chest percussion since they felt it was easier to breathe once therapy was completed [8]. It should be noted that clinical trials have shown that HFCCT devices are effective in facilitating mucus clearance [6–9], and the action of the HFCWO is at least equal to and in fact more effective than the conventional CPT involving a respiratory therapist pounding on a patient's chest to loosen mucus for expectoration. Hence, the significant of $Q = 1/3$ is that if the oscillating compressive force to the patient's chest is reduced by a third of the pressures used in the literature [6–9], and the pulsating frequencies are set at resonance, then it will probably be as effective as the original trials. Reducing the pulsating air pressure will probably help in reducing the most frequently reported complaint of chest constriction by patients.

An interesting observation from Tables 1 and 2 is that the values of the coefficient-of-correlation between the resonant frequency and chest size for male and female volunteers are –0.94 (male) and –0.93 (female lower chest size) and –0.97 (female upper chest size). Therefore, the implication is that it is possible to estimate the chest natural frequency from the chest size. Taking a linear regression analysis on all of the data for male chest sizes, the chest-resonant frequency (CRF) can be predicted according to the equation: *Male CRF = 51.549–0.281 (Chest size).* This data is plotted in Fig. 3, and can be used to estimate the male chest-resonant frequency directly from the figure. In the case of female subjects, there are two chest size values. Since, the upper chest size has a higher coefficient of correlation; a backward linear regression analysis is done on the upper chest sizes. The data is plotted in Fig. 4, and the equation for predicting the resonant frequency is: *Female CRF = 49.048–0.254 (Chest size).*

## 5 Concluding remarks

It is important to note that all the data collected from the experiment relate only to a small sample of healthy volunteers who are young adults. These chest frequencies

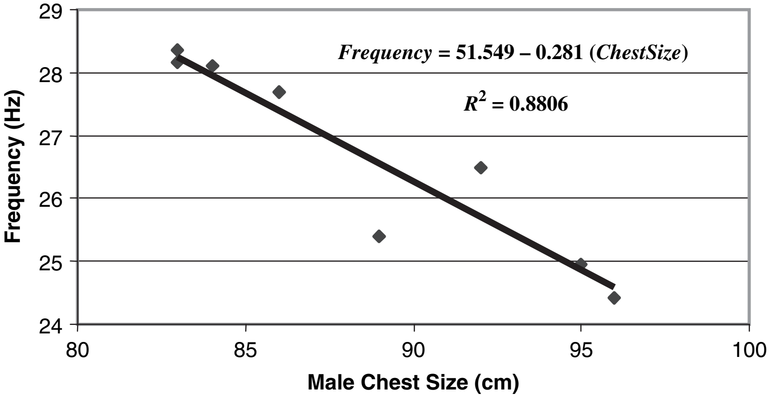

Figure 3: Graph of resonant frequency versus male chest size.

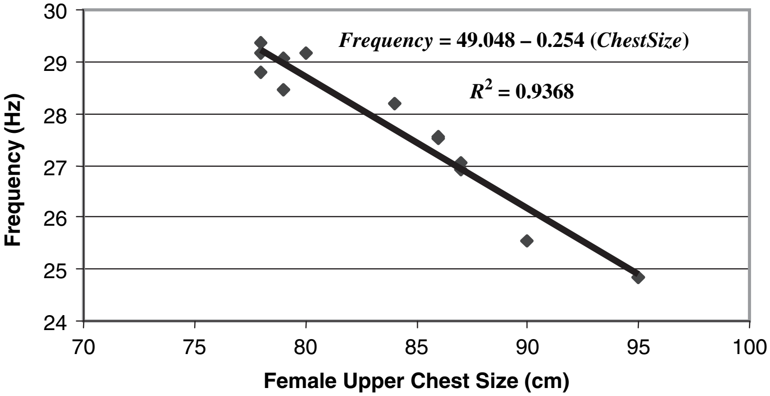

Figure 4: Graph of resonant frequency versus female upper chest size.

may inevitably be different from patients who suffer from cystic fibrosis or any form of chronic obstructive pulmonary disease (COPD). Nevertheless, Figs. 3 and 4 can be used to provide an initial estimate of the chest-resonant frequencies of patients with COPD.

To estimate the resonance frequencies of patients with COPD from their chest sizes, it will be more appropriate to obtain the data from volunteers who suffer from COPD. For these volunteers, it is not advisable to do the experiment as described in this chapter on these unhealthy subjects. For these subjects, the HFCWO vest can be used for conducting the experiments, as it has been shown to be safe and there are no detrimental effects to the users. Based on an average chest frequency of 26 Hz, the pulsating frequencies can be set between 18 Hz to 34 Hz. Alternatively, the resonant frequency of a patient with COPD can be estimated using the regression equations or directly from Figs. 3 and 4. The range for the pulsating frequency can then be set at plus or minus 8 Hz from this predicted resonance frequency. Since, at resonance, maximum vibrations occur, it can be construed that the frequency that gives the maximum airflow rate is the chest-resonant frequency.

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