Modeling of Estimated Respiratory Waveform

ALEKSEI E. ZHDANOV, LEONID G. DOROSINSKY
Institute of Radioelectronics and Information Technology - RTF
Ural Federal University named after the first President of Russia B. N. Yeltsin
Mira Str., 19, Yekaterinburg, Sverdlovskaya oblast', 620002
RUSSIA
jjj1994@yandex.ru l.dorosinsky@mail.ru

Abstract: In the imaging of chest or abdomen, motion artifact is a unavoidable problem. In the radiation treatment, organ movement caused by respiratory motion is a problem unavoidable also to realizing safe and effective cancer treatment preserving healthy tissue. In this article, we compare two modalities 3D CT and 4D CT and present the main difference between them, which is compensating the breathing motion. However, we record a real breathing signal using ANZAI belt, analyze the resulting signal and simulate the estimated respiratory waveform based on three different models.

Key-Words: baseline drift, Lujan model, motion artifact, fitting sine function, respiratory waveform, respiratory signal.

1 Introduction

Respiratory organ motion brings in great artifacts to lung or abdomen CT imaging. To eliminate such artifacts, special CT scan modes are developed, of which breath-hold CT scan, slow CT scan, gated CT scan and 4D CT scan have been reported, optimized and applied to clinical use. In this experiment, we introduce 4D CT modality, which overcome organ motion artifacts. 4D CT uses a new technology that captures the location and movement of a tumor and body's organs over time. This is valuable for accurately treating tumors located on or near organs that move, such as those in the chest and abdomen. This is valuable for accurately treating tumors located on or near organs that move, such as those in the chest and abdomen.

The basic idea of 4D CT is sorting the images based on the respiratory signal, which is recorded by external device (ANZAI for example). Each image is tagged and sorted according to corresponding phase, and by this way many 3D CT sets are obtained that covers the whole breathing cycle [1].

2 Method and Material

2.1 3DCT of stationary and moving phantom

We use respiratory phantom, which can incorporate stimulated motion, with low rate (10rpm) or high rate (15rpm) as we can see in Fig. 1.

Two tasks are arranged, stationary phantom and moving phantom. We use identical scan parameters for the two experiments (120 kV, 100 mAs). We use 3DCT to scan stationary phantom, low rate respiratory phantom and high rate respiratory phantom, to get a direct presentation of motion artifacts.

2.2 4DCT for compensating motion artifact

We use AZ-733V respiratory system to support the 3DCT system and this combination called 4DCT. This combination will compensate motion artifact.

We choose 0%, 15%, 50%, 85%, 100% of inhale phase and 15%, 50%, 85% of exhale phase to classify the images based on the respective phase and value.

2.3 ANZAI belt's measurement

ANZAI system is breathing monitoring systems. It is used to detect breathing signal and this signal is used as reference to compensate organ motion, and result in precise radiation treatment. The basic idea of combining respiratory signal is called respiratory gating, which is using a pressure-sensor with motion monitoring system. The goal of this signal in radiation treatment is minimizing the area of treated target tumor which moves due to patient respiration. Respiratory signal is acquired for 10 minutes from ANZAI belt around the abdomen. The recorded signal suffers from several types of artifacts such as noise, baseline-drift, saturation, etc. Fig.2 shows a respiratory signal of 7 seconds. In this figure we can notice the parameters of the signal, which they are respiratory rate, inhalation phase and exhalation phase. Fig.3 shows the signal with baseline-drift artifact. We remove it using a polynomial function that we fit to the signal to overcome this effect.

Fig. 1 Respiratory phantom used in experiment

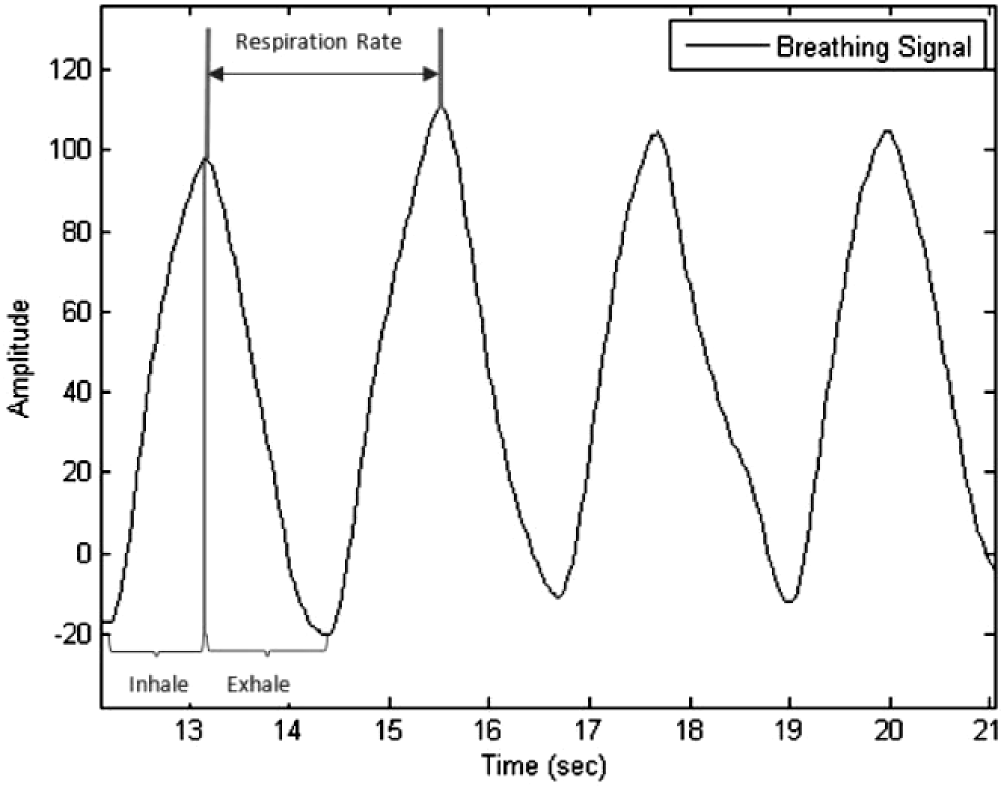

Fig. 2. Respiratory signal recorded from ANZAI belt

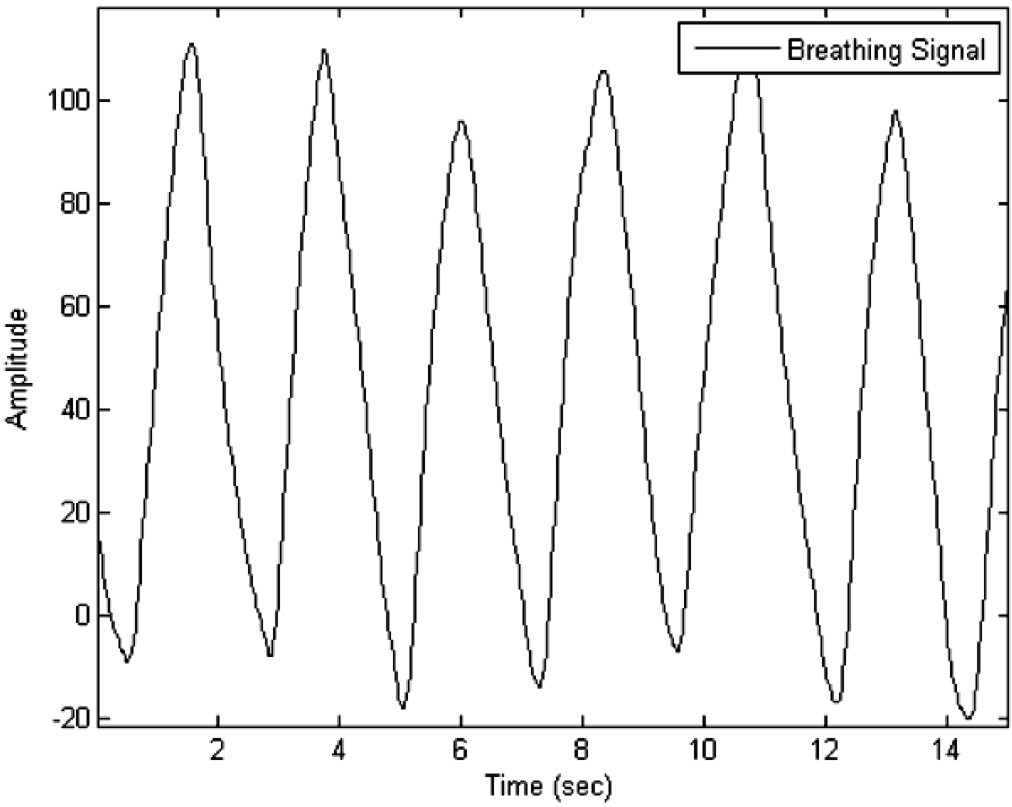

Fig. 3. Respiratory signal of 15 sec of normal breathing with baseline-drift

3 Result and Discussion

3.1 Motion artifact

In the imaging of chest or abdomen, motion artifact is a unavoidable problem. And in the radiation treatment, organ movement caused by respiratory motion is a problem unavoidable also to realizing safe and effective cancer treatment preserving healthy tissue [2, 3].

We use respiratory phantom, which can incorporate stimulated motion, with low rate (10rpm) or high rate (15rpm) as we can see in Fig. 1.

Fig. 4 and Fig. 5 show the internal structure of phantom. Inside the outer cylinder, there are 3 spheres with different material (shows different contrast), at the center of the cylinder is the support shaft. When phantom works in respiration mode, the cylinder will move in longitudinal direction, of which motion amplitude is about 3cm.

Fig. 6 shows the motion artifacts, of which the motion rate is 10rpm. From the figure we can notice that the inner sphere is seriously distorted because of respiratory motion. As is shown, upper parts of the cylinders are stretched, while the middle part of all cylinders is compressed, and the lower part of the cylinders is again stretched. During the scan, the relative velocity of cylinder to scanning plane is the sum of helical velocity and respiratory motion velocity. When helical velocity and respiratory motion velocity are the same direction, the relative velocity is greater than helical velocity, slices are missed and reconstruction area appears compressed. Relatively, when respiratory motion direction is opposite the helical velocity direction, the relative velocity is minor to helical velocity, slices are more likely to be scanned more than once, so reconstruction area appears stretched.

In clinical practice, tumors in lung or abdomen are more likely to be affected by organ motion. CT Image consequently causes inaccurate area definition and in following segmentation and irradiation as well, which affects therapeutic activities relatively.

3.2 Motion compensation

Fig. 7 shows the results after combining the motion signal during imaging (4DCT), in this figure we can see that the geometric features of inner structure of cylinder are almost restored, comparing with 3DCT with motion artifact.

Fig. 7 shows 4DCT reconstructed images using different respiration phases (0%, 15%, 50%, 85%, 100% inhale and 15%, 50%, 85% exhale), with low rate and high rate, from which we can see that the images are more accurate when the classifying area close to inhale end or exhale end and far from the start/end of inhale/exhale, the image appears slightly affected by motion because the respiration signal is not a identical, every period is slightly different from other periods, thus gating by amplitude or motion phases still cannot guarantee to scan the same motion status, but in general, the start/end of inhale/exhale period shows identical movement status, so reconstructed images from 4DCT are better than 3DCT in term of motion compensation. Comparing low motion rate with high motion rate, we found that motion with low rate brings severer artifacts. In 4DCT, a scanned object moves slowly to ensure that a scanner can collect images in all phases. But if the velocity is too slow, even close to 0, a scanner will still miss some slices, thus low motion rate tends to bring more artifacts than high rate.

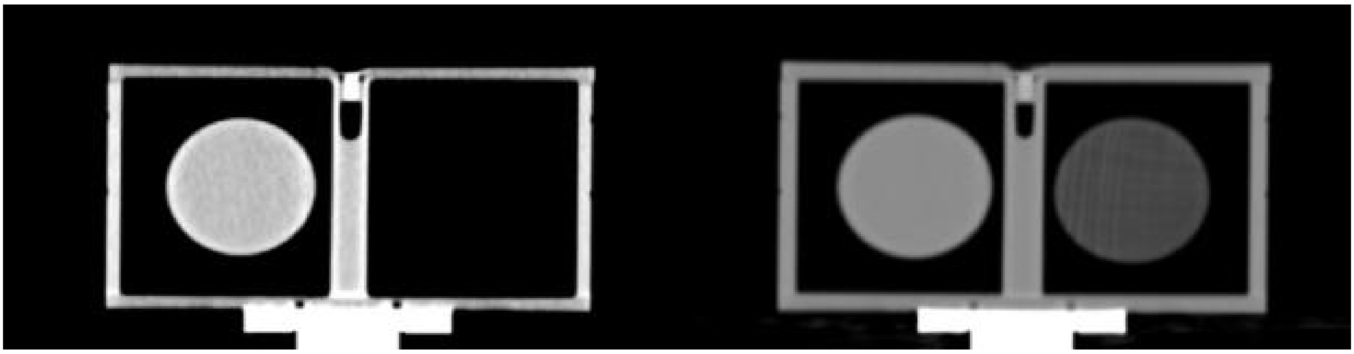

Fig. 4. Phantom structure (coronal)

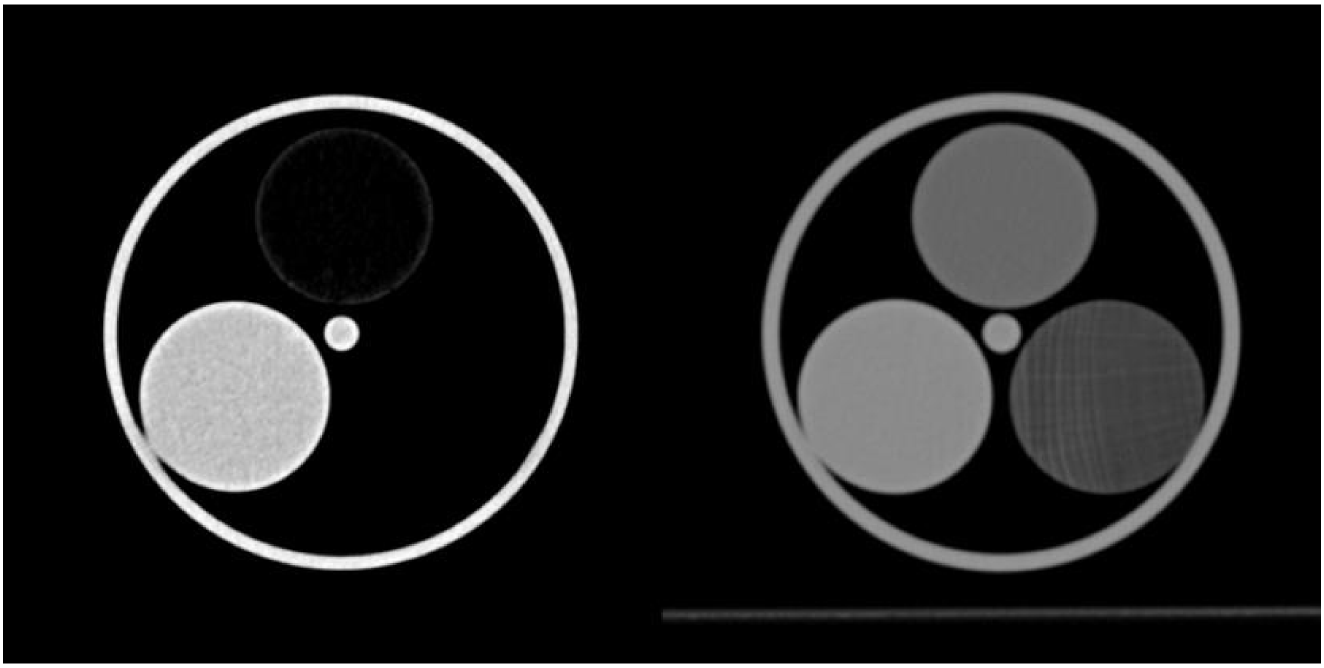

Fig. 5. Phantom structure (axial)

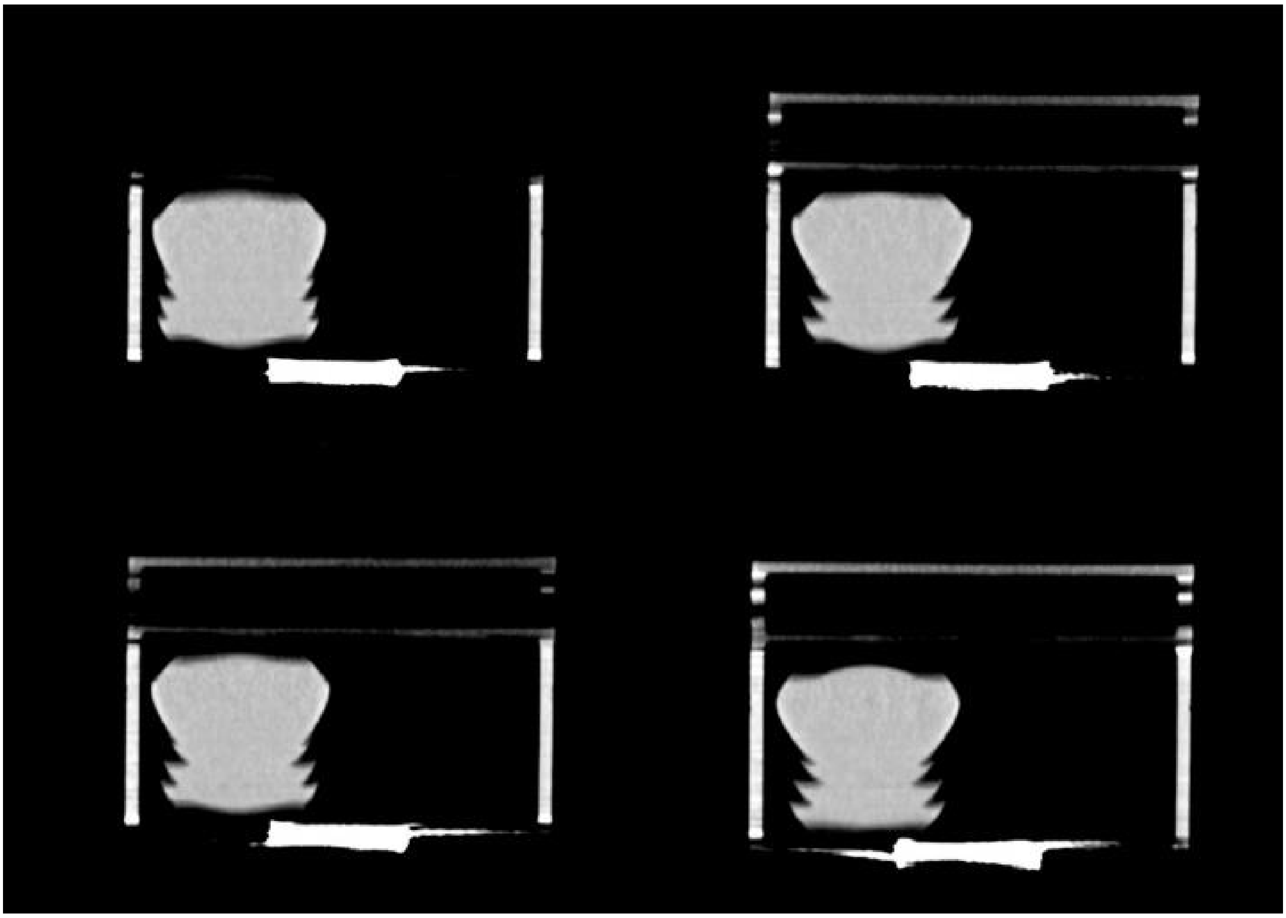

Fig. 6. 3DCT of moving phantom with motion artifacts

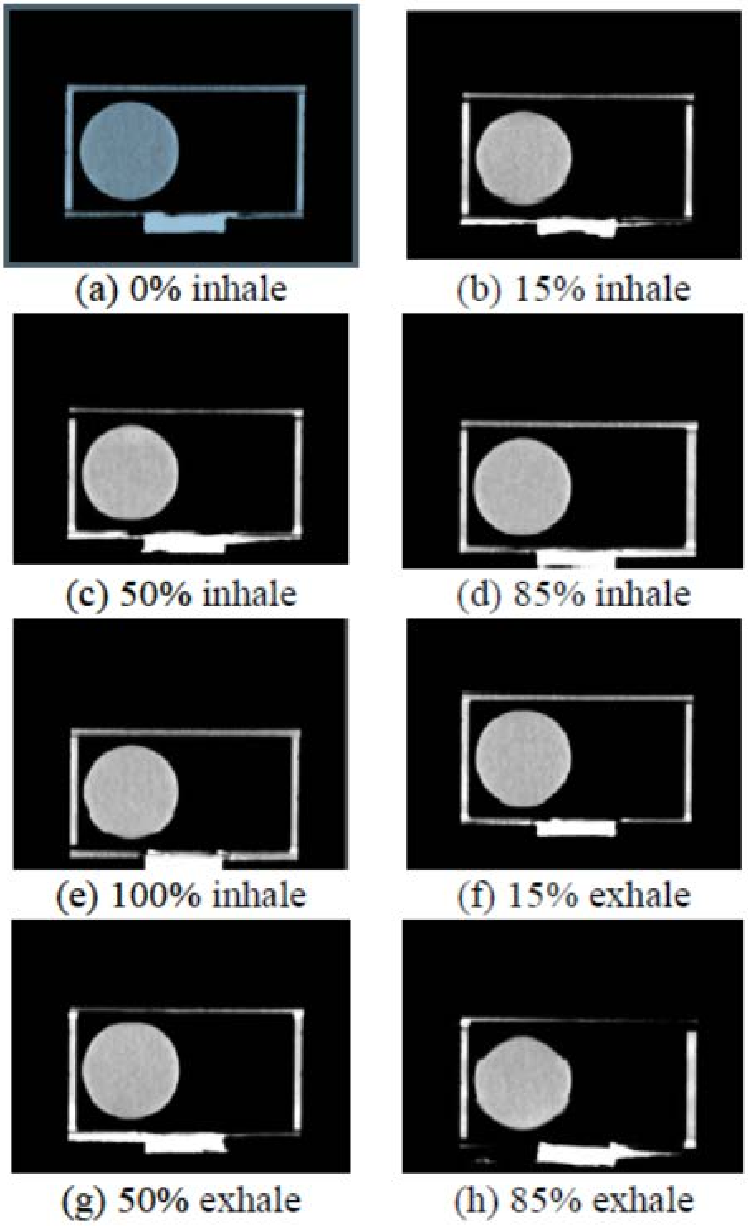

Fig. 7. 4DCT reconstructed images (coronal, motion rate = 15 rpm)

3.3 Analysis of ANZAI belt's measurements

Baseline-drift is the short time variation of the baseline from a straight line caused by electric signal fluctuations. There are several ways to remove baseline-drift such as a linear approximation, a cubic spline interpolated approximation, and a recurrent neural network approach mimicking an adaptive filter, and the final method involved calculating the first and second derivatives of the signal in order to attenuate the baseline drift.

To remove the baseline-drift, we fit a polynomial to the data. The algorithm is composed of three steps. It is calculating the coefficient for a polynomial) (x p of degree n that is a best fit (in a least-squares sense) for the data. The coefficients for a polynomial p(x) of degree 5 that is a best fit for the data. Equation (1) represent polynomial of five degree fitted to the respiratory signal to remove the baseline-drift.

$$p(x) = p_1x^5 + p_2x^4 + p_3x^3 + p_4x^2 + p_5x + p_6 \quad (1)$$

Table 1 shows the polynomial's parameters, which perform best fit to the respiratory signal. Fig. 3 shows 15 seconds of the respiratory signal, which suffers from baseline-drift. The signal after removing baseline-drift using polynomial fitting to the data. Baseline-drift is common effect for all biological recorded signals. Fig. 8 shows the difference between the respiratory signal with baseline-drift and without it.

Table 1. Parameters of the polynomial function

p_1	p_2	p_3	p_4	p_5	p_6
10.23	-9.38	-37.87	15.81	23.12	44.59

Fitting sine function to the respiratory signal. The fitting algorithm is working based on fitting sine wave to the breathing signal by taking the maximum amplitude value and the minimum value of the signal. The difference between the min and max values will be used as peak to peak amplitude [4].

Next step is computing zero-crossing and estimating the period and the offset. The fitting function is calculated from sine function as we can see in equation (2). The last step is to fit the sine signal to the respiratory signal by calculating the least-square cost function and minimizing it as in Fig. 9. The parameters of the fitted function are listed in Table 2. We apply the fitting function after removing the baseline-drift artifact.

$$b(1)sin\left(\frac{2\pi x}{b(2)}+\frac{2\pi}{b(3)}\right)+b(4) \quad (2)$$

Table 2. Parameters of the fitting function

$b(1)$	$b(2)$	$b(3)$	$b(4)$
50.876	2.327	-0.734	0.000

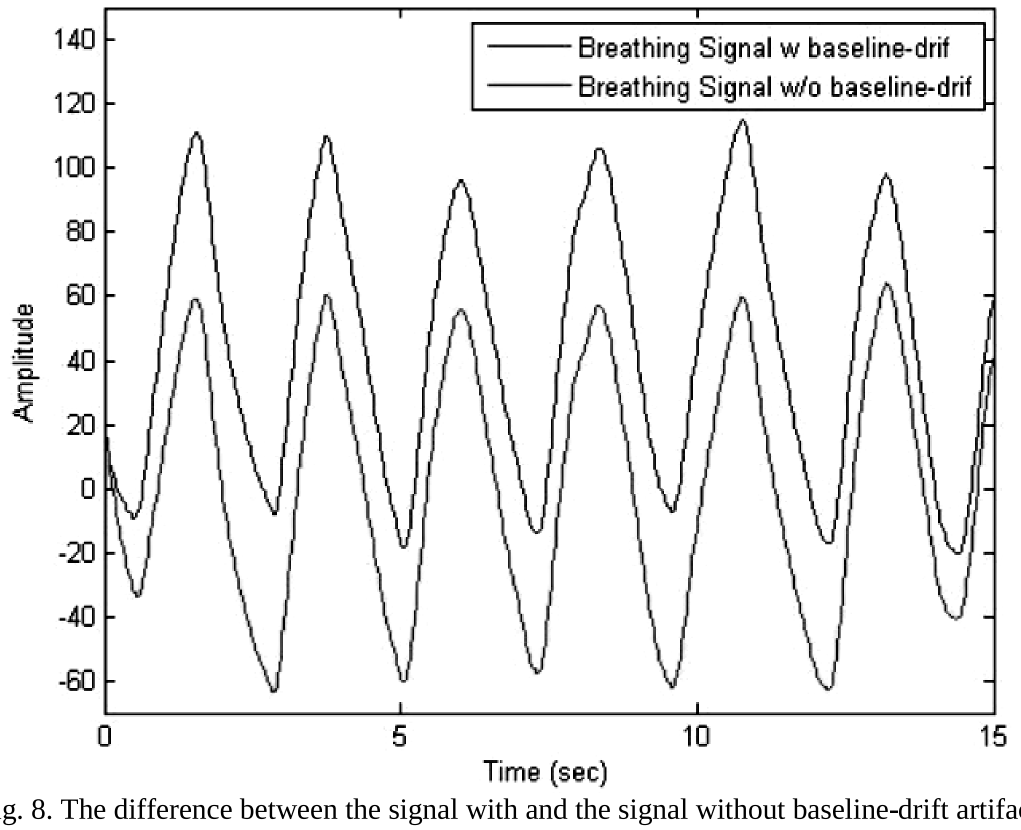

Fig. 8. The difference between the signal with and the signal without baseline-drift artifact

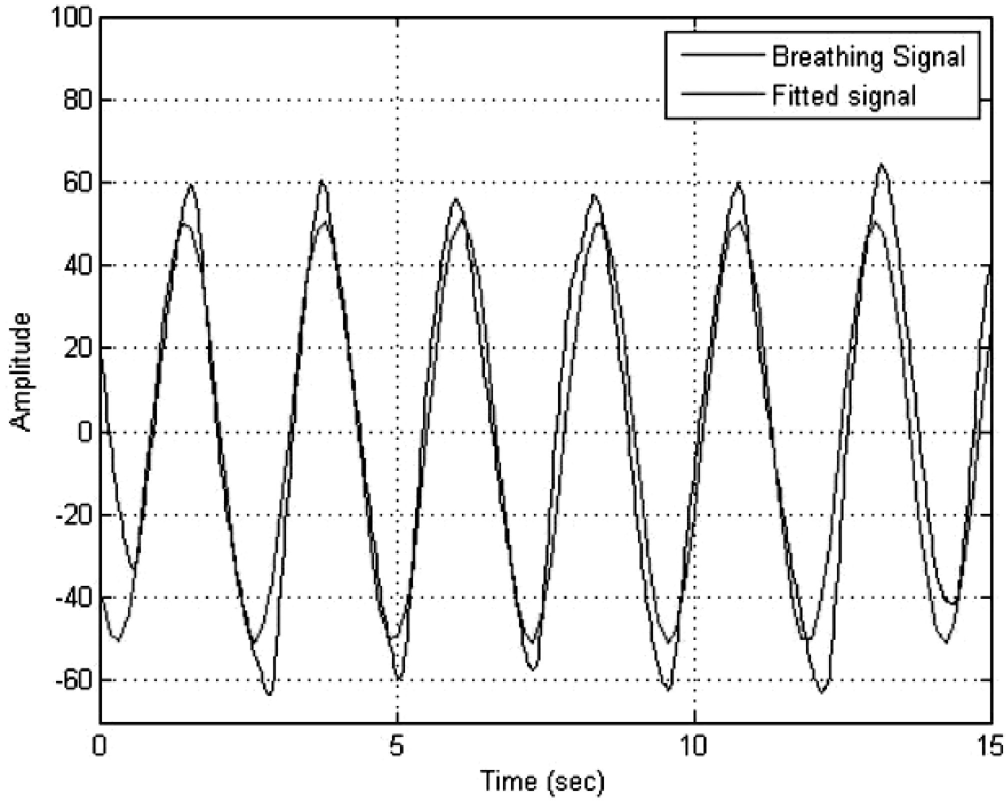

Fig. 9. Respiratory signal (black) and sine wave fitted to the respiratory signal (grey)

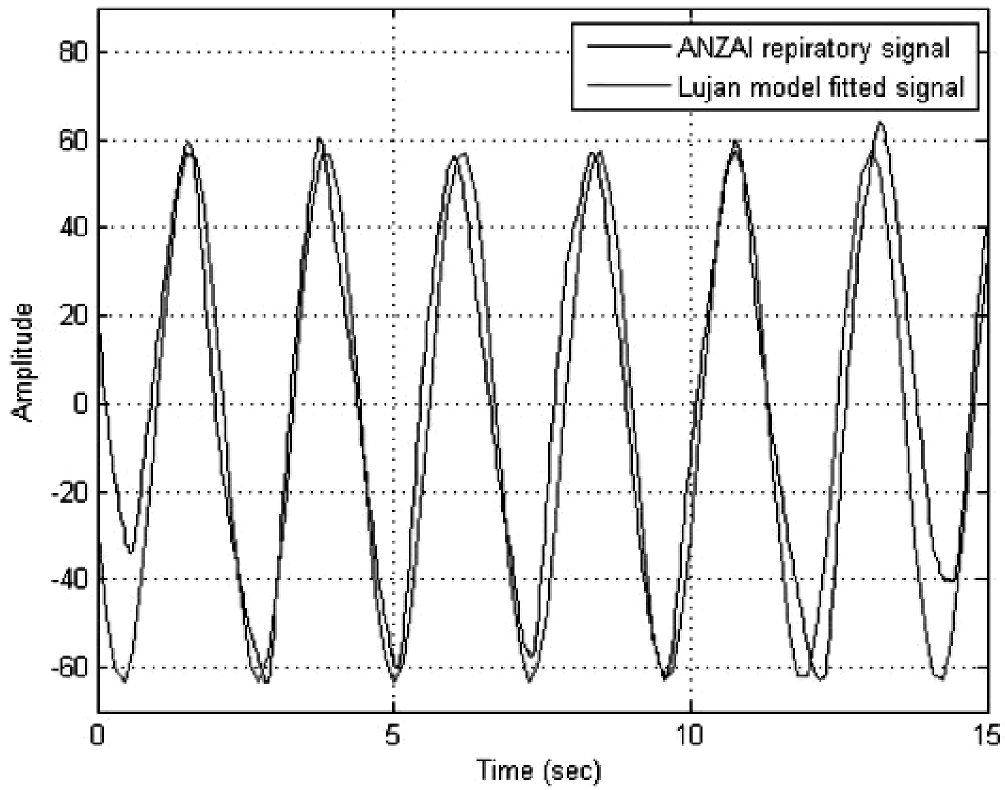

Fig. 10. ANZAI respiratory signal (black), Lujan et. al. model (fitted function to the respiratory signal) (grey) (n = 0.7215)

Table 3. Lujan model parameters

b	τ	φ	n	V_0
49.556	2.327	-1.207	0.721	0.000

Respiratory Cycle Modeling (Lujan model). It is generally assumed that all the points in the volume reach their final position at the same time and that the temporal behavior along the trajectory is determined by a 1-D breathing signal. Several models of breathing cycles have been proposed in the literature. Lujan et al. model models the dynamic breathing volume curve. It is based on a periodic but asymmetric function (more time spent at exhalation versus inhalation) [5, 6, 7].

In (3), V_0 is the volume at exhalation, corresponds to the tidal volume (TV) which is the amount of air breathed in or out during normal respiration, $V_0 + b$ is the volume at inhalation, τ is the period of the breathing cycle, n is a parameter that determines the general shape (steepness or flatness) of the model, and φ is the starting phase of the breathing cycle in Fig. 10. This model represents a priori knowledge of a conventional breathing cycle.

$$V(t) = V_0 + b\, cos^{2n}\left(\frac{\pi}{\tau}t + \varphi\right) \quad (3)$$

In Table III the result after fitting Lujan model to our respiratory signal. After fitting the signals to two different functions, sine function and Lujan model, we find that both signals are suitable to represent the respiratory signal. As we can notice from Table 2 and Table 3 that the results of the both fitting function are almost the same. The most important step for the both fitting function is setting the start point, which plays a big role of initialization the fitting function.

Respiratory rate. Breaths per minute is called the ventilation rate. It is 25 breathing cycle in one minute in our experiment. The normal value is based on the normal range and it is for adult 30-60 Breaths per minute.

4 Conclusion

4D CT provides solution for breathing motion effect by combining the breathing signal of a sensor to 3D CT to compensate the motion effect. In this article, we performed the software for analyzing a respiratory signal and calculation the estimated respiratory waveform by mathematical methods which was shown before. All the methods describe respiratory signal with relatively same accuracy. To acquiring a respiratory signal our program use ANZAI belt, respiratory signal data upload to program in txt format. The program output display as estimated respiratory signal in txt file and plots calculated by three methods. Thus, performed program is the first step to developing device which consists software and hardware.

References:

[1] E. Lujan, E. W. Larsen, J. M. Balter, R. K. Ten, *The International Jornal of Medical Physics Research and Practice*, Vol. 26, No.5, 1999, pp. 715-716.

[2] Y. Nagata, Stereotactic Body Radiation Therapy: Principles and Practices, Springer, 2015.

[3] K. G. A. Gilhuijs, K. Drukker, A. Touw, P. J. Van de Ven, M. van Herk, *Medical Physics*, Vol. 15, No.5, 1998, pp. 703–708.

[4] R. Iyer, A. Jhingran, Radiation injury: imaging findings in the chest, abdomen and pelvis after therapeutic radiation, US National Library of Medicine, 2006.

[5] R. Zeng, Estimating Respiratory Motion from CT Images via Deformable Models and Priors, University of Michigan, 2007.

[6] A. Amini, A. Manduca, X. Hu, Medical Imaging: Physiology, function, and structure from medical images, Parts 1-2, SPIE, 2005.

[7] J. Van Dyk, The Modern Technology of Radiation Oncology: A Compendium for Medical Physicists and Radiation Oncologists, Volume 2, Medical Physics Pub., 2005.