ARTICLE IN PRESS
JID: JJBE [m5G;January 10, 2018;22:37]

Medical Engineering and Physics 000 (2018) 1–10

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Sin-quadratic model for chest tomosynthesis respiratory signal analysis and its application in four dimensional chest tomosynthesis reconstruction

Xi Tao[a], Hua Zhang[a,*], Genggeng Qin[b], Jianhua Ma[a], Qianjin Feng[a], Wufan Chen[a]

[a] School of Biomedical Engineering, and Guangdong Provincial Key Laboratory of Medical Image Processing, Southern Medical University, Guangzhou 510515, China
[b] Department of Radiology, Nanfang Hospital, Southern Medical University Guangzhou, 510515, China

ARTICLE INFO

Article history:
Received 19 January 2017
Revised 23 November 2017
Accepted 22 December 2017
Available online xxx

Keywords:
Chest tomosynthesis
Motion analysis
Respiratory signal
Sin-quadratic model

ABSTRACT

Chest tomosynthesis (CTS) is a newly developed imaging technique which provides pseudo-3D volume anatomical information of thorax from limited-angle projections and contains much less of superimposed anatomy than the chest X-ray radiography. One of the relatively common problems in CTS is the patient respiratory motion during image acquisition, which negatively impacts the detectability. In this work, we propose a sin-quadratic model to analyze the respiratory motion during CTS scan, which is a real time method where the respiratory signal is generated by extracting the motion of diaphragm from projection radiographs. According to the estimated respiratory signal, the CTS projections were then amplitude-based sorted into four to eight phases, and an iterative reconstruction strategy with total variation regularization was adopted to reconstruct the CTS images at each phase. Simulated digital XCAT phantom data and three sets of patient data were adopted for the experiments to validate the performance of the sin-quadratic model and its application in four dimensional (4D) CTS reconstruction. Results of the XCAT phantom simulation study show that the correlation coefficient between the extracted respiratory signal and the originally designed respiratory signal is 0.9964, which suggests that the proposed model could exactly extract the respiratory signal from CTS projections. The 4D CTS reconstructions of both the phantom data and the patient data show clear reduction of motion-induced blur.

1. Introduction

Lung cancer is one of the most common fatal cancers in both developing and developed countries [1]. Up to now, the chest X-ray radiography (CXR) remains the most commonly used imaging modality for pulmonary lesion detection with the advantages of low radiation dose, low cost and high throughput [2]. Nevertheless, CXR produces two dimensional images containing superimposed anatomic structures, which reduces its sensitivity and specificity for the detection of thoracic abnormalities [3,4].

Chest tomosynthesis (CTS) is a recently available three dimensional (3D) imaging technique and is getting an increasing concern from researchers and clinical scientists due to its ability in improving the visibility of anatomy compared with radiography by partly removing superimposed tissue. For CTS imaging, the system employs a linear movement of the X-ray tube to acquire projection radiographs in a limited angle range. Thereafter pseudo-3D images can be reconstructed using the limited-angle projections [2,5,6]. The sensitivity of CTS is at least three times higher than that of CXR for the detection of pulmonary nodules [7,8]. Furthermore, in a recent study, it was concluded that the detection rate of lung cancer with chest tomosynthesis is comparable to that of low dose CT [9]. Moreover, chest tomosynthesis provides higher resolution in the coronal plane and much lower radiation dose to patients than standard chest CT, and therefore may be considered as an imaging tool for enhancing the detection of pulmonary parenchyma and depiction of abnormalities such as pulmonary nodules in routine practice.

For CTS imaging, the projection images are acquired in a time period of several seconds, during which patients are required to be still and hold their breath. However, it is usually difficult for patients with chronic obstructive pulmonary disease to fully hold their breath during CTS scan. Respiratory motion induced artifacts therefore can be relatively common in chest tomosynthesis examinations. The respiratory motion would reduce the detectability of CTS to the level of CXR in some cases [8,10,11]. In clinical practice, a chest tomosynthesis examination is usually performed with

* Corresponding author.
E-mail address: xinsier@smu.edu.cn (H. Zhang).

https://doi.org/10.1016/j.medengphy.2017.12.003

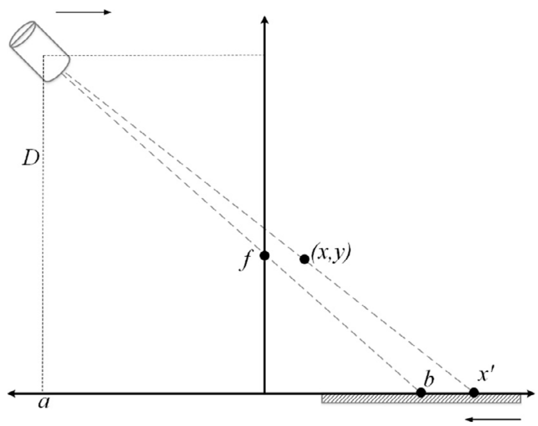

Fig. 1. Geometry of chest tomosynthesis.

patient standing in the posteroanterior (PA) or anteroposterior (AP) position without any radiopaque marker mounting on the patient chest, so it is not easy for the radiographer to judge from the projection radiographs whether the patient can hold breath or not. Therefore, it is of great clinical interest if severe motion can be automatically identified. For the CTS imaging, the X-ray tube sweeps over a prescribed linear path parallel to the detector, which causes a different motion pattern for a moving object in the projection domain compared with CT (In CT imaging, the X-ray tube rotates around the object). Thus, approaches generally used to extract respiratory signals from thoracic cone beam CT projections such like the Amsterdam Shroud (AS) method [12,13] may not be suitable for CTS.

There is no specific algorithm for extracting CTS respiratory signals at present. In CTS imaging, the tube moves linearly along the patient in the head-caudal direction and the radiographs for each view could clearly show the edge lines of the diaphragm. Based on this, we propose a sin-quadratic model that uses the physical location of the diaphragm as the surrogate signal to analyze the respiratory motion in digital chest tomosynthesis. The sin-quadratic model not only embraces the patient respiratory motion but also considers the basis motion induced by the geometry of the CTS system. The proposed method directly extracts the respiratory signal from the projections without the need of any other breath detecting device as a reference. According to the obtained respiratory signal, physicians could rescan the patient immediately or conduct motion free CTS image reconstruction. In this study, the projection radiographs were subsequently sorted into several phases using an amplitude wise method and an iterative algorithm with total variation (TV) regularization was adopted to reconstruct the CTS images at each phase 14–18. Digital phantom data and patient data were used to validate the performance of the proposed sin-quadratic model and its application in four dimensional CTS image reconstruction.

2. Methodology

2.1. Motion analysis in chest tomosynthesis imaging

2.1.1. Motion analysis of stationary object in the projection radiographs

For chest digital tomosynthesis imaging, the x-ray tube and detector are continuously moving in parallel as well as opposite directions [19–21]. The motion trajectory of a single point would be well-confined when the x-ray tube moves in an uniform manner. As illustrated in Fig. 1, the distance from source to detector is D, the fulcrum plane about which the tube and detector move in synchrony is at height f. For one projection, the X-ray tube is at location a and the detector is centered at location b, respectively. Then, for the point object located at (x, y), the relative displacement of the projected impulse in relation to the midpoint of the detector is given as:

$$m = x' - b = a\left(\frac{f}{D-f} - \frac{y}{D-y}\right) + x\frac{D}{D-y} \tag{1}$$

From the above, it can be seen m is linearly correlated to a once the CTS geometry is fixed. For systems with a stationary detector (e.g. GE Volume RAD), the linear relationship also exists. If the X-ray tube moves in an uniform manner, the moving distances of a single point in adjacent projection are nearly constant [22], which is inherent for CTS imaging mode.

The motion of the diaphragm, however, is more complicated than that of a single point. From an anatomical point of view, human diaphragm shows as a hill-like shape. Thus, even for breath-hold patient, the intersections between x-ray and diaphragm for each exposure are varied. Hence, the edge of diaphragm in the projection domain should be related to the tangential points. Visually, the movement of the diaphragm in projection domain follows a relatively smooth trajectory and the moving distances among adjacent projections are slightly varied. Therefore, the linear relationship shown in Eq. (1) is not enough to describe the moving trajectory of the diaphragm, and we use a polynomial function to fit it. Hereafter, the motion of an ideally held diaphragm in the projection domain is referred as basis motion. Fig. 2(a) illustrates the schematic of CTS scan for a diaphragm without respiratory motion.

2.1.2. Motion analysis of moving object in the projection radiographs

Rather than relying on the respiratory monitoring devices, we extract the respiratory motion information directly from the location of the diaphragm in the projection radiographs. Apart from the inherent motion induced by the imaging geometry, the projected diaphragm location of patient who could not hold his or her breath during the CTS imaging would also be affected by the respiration. As illustrated in Fig. 2(b), the motion of breathing diaphragm in the projection radiographs could be viewed as the combination of the system induced basis motion and the patient respiratory motion. Specifically, we model the motion of diaphragm as:

$$M_{diaphragm} = M_{respiration} + M_{basis} \tag{2}$$

where $M_{diaphragm}$ represents the total motion of diaphragm in the projection radiographs, $M_{respiration}$ represents the patient respiration induced motion while M_{basis} represents the basis motion. Fig. 3(a) and (b) show the diaphragm location maps of the XCAT phantom based simulated projection radiographs under the state of stationary and breathing, respectively.

2.2. Sin-quadratic model

As shown in Eq. (2), the motion of diaphragm in the projection radiographs is separated into two parts: the basis motion resulting from the imaging geometry and the respiratory motion resulting from the patient breath. Based on the analysis in Section 2.1.1, we concretely adopt the second order polynomials to fit the basis motion of the diaphragm. For the respiratory motion modeling, the patterns have been assumed to be sinusoidal in previous studies [23–28]. For instance, Vedam et al. [27] used a four-parameter sinusoidal model to predict respiratory motion for planned radiation, which showed a promising performance. Inspired by these works, we also utilize the sinusoidal model to fit the respiratory motion in CTS imaging. In addition, the scan time for CTS imaging is only about 6–12 s (12 respiratory cycles), thus the breath-to-breath fluctuations in respiratory cycle variables can be ignored.