
Quantification of the Respiratory Activity of the Lung using CT Images

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Abstract

We have developed a system to analyze the respiratory activity of the lung using CT images. This analysis includes functions to automatically extract the lung region from several phases of chest CT images, register the different respiratory phases, and obtain a motion vector field. This enables an overlay display of the low attenuation areas, the quantification of the expansion rate of the lung, and the measurement of local movement. With these functions, we can visualize the local respiratory activity, which was previously difficult to observe. Using this system, we hope to obtain indicators that are effective for studying the areas from which respiratory diseases originate, their severity, and their causes.

1. Introduction

In recent years, there has been a trend in the medical field for the spread of imaging systems, such as computed tomography (CT) and magnetic resonance (MR), the improvement of imaging techniques used with them and the establishment of intra-hospital infrastructure for picture archiving and communication systems. The use of 3D medical images has been increasing not only in radiology departments but also in clinical domains such as surgical departments and departments of internal medicine.

Under such circumstances, in 2008, FUJIFILM released the 3D-imaging diagnostic workstation SYNAPSE VINCENT*¹ developed based on its long-cultivated, advanced image processing technology. In addition to a variety of analytical functions to support image interpretation for radiology departments that make diagnoses via images, the product also features surgical simulation functions with 3D medical images for the surgical area where treatment is provided to patients. In particular, it is widely used at actual clinical sites in the simulation of partial liver resection. Recently, it has also provided, for the domain of respiratory organs, functions to support diagnosis of lung disease (cancer, chronic maladies, pulmonary emphysema, etc.) with CT images and surgical simulation functions using technology that allows the automatic image extraction of pulmonary arteries, pulmonary veins and bronchi from contrast-enhanced CT images of the lung.

On the other hand, for the diagnosis of the respiratory function in internal medicine, it is an important factor to identify the capacity of pulmonary ventilation associated with the respiratory activity of the lung; therefore, in addition to the identification of diseased regions inside the lung, the identification of its severity and cause has also been a subject of research in diagnostic methods.

This paper reports new technology for dynamic analysis of the lung with CT images that is expected to become a future image diagnostic method for the respiratory function.

2. Conventional methods for the diagnosis of the respiratory function

There are many diseases treated by respiratory medicine including chronic obstructive pulmonary disease (COPD),¹⁾ pulmonary embolism (PE) and interstitial pneumonia (IP) and diagnosis requires very specific and deep knowledge. In particular, COPD is one of the most fatal diseases in the world and the number of patients who suffer from that disease has been increasing.^{2), 3)} The disease is classified minutely according to the cause, such as pulmonary emphysema due to alveolar collapse and chronic bronchitis due to airway obstruction. However, the cause is often complex and correct diagnosis is not at all easy.

The following are the currently typical diagnostic methods for the respiratory function of the lung.

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2.1 Pulmonary function test (spirometry)

This method can be regarded as a de facto standard in the diagnosis of the respiratory function currently practiced, in which diagnosis is made by having patients actually take a series of breathing activities: taking a big breath and exhaling it. With this method, it is possible to make some assessment on the respiratory function of the lung as a whole but specific malfunctioning regions cannot be identified.

2.2 Diagnosis with CT images (inflated lung)

Diagnosis is made using chest CT images based on the distribution of signal values inside the lung field. Generally, regions occupied by air whose alveoli are flat have low signal values and their respiratory function is considered to have decreased. Therefore, it is possible to assess the function of the lung by identifying the distribution of those regions. However, although allowing the identification of diseased regions and sometimes their severity, this method cannot identify the cause.

2.3 Diagnosis with SPECT images

Diagnosis is made based on images that capture the state of radioisotopes (RIs), such as ^{81m}Kr and ^{133}Xe gases, staying inside the alveoli after inhalation by patients (single photon emission computed tomography, SPECT images). However, the resolution of those images is low and they can only give general information about the condition of pulmonary ventilation. Diagnosis with this method requires higher interpretation skills and longer examination time than other methods.

3. Mechanism of dynamic analysis of the lung

The new method we are now going to introduce enables more detailed, quick diagnosis than conventional methods by analyzing the movement of the lung itself with CT images captured at multiple phases of the respiratory activity.

The technique supports the diagnosis of pulmonary ventilation capacity in the respiratory activity via the high-precision registration of multi-phase CT images incorporating anatomical knowledge (e.g., the shape of the lung, positions of the bronchi) and observation of the detailed lung transformation data.

3.1 Registration technology

First, to calculate the pulmonary ventilation function of each region, it is necessary to correctly determine the movement of the detailed anatomical structures of the lung captured in CT images at its maximum inspiration and at expiration at rest. To that end, we developed a new non-rigid registration method by incorporating our long-cultivated image processing technology into conventional registration methods.^{4), 5)} The procedures are as follows: let either CT image at maxi-

imum inspiration or at expiration at rest be a fixed image; let the other image be a moving image; transform the moving image while applying non-linear transformations; calculate the metric (degree of similarity) between the fixed image and the transformed moving image; determine the transformation when the metric becomes highest by repeating the preceding two procedures; and let it be the optimal transformation between the fixed and moving images (Fig. 1). By using the determined optimal transformation, the correspondence of all the voxels between the fixed and moving images can be obtained, based on which, it is possible to calculate the movement of any region of the lung between maximum inspiration and expiration at rest.

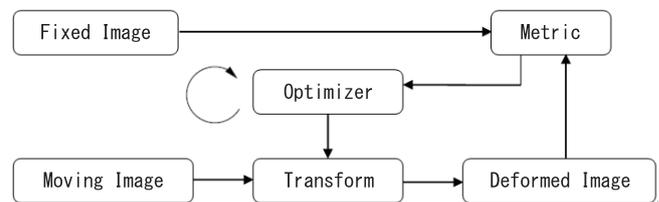


Fig. 1 Mechanism for the registration of the images

3.2 Visualization of the registration results

This system performs the mapping of voxels based on the registration results and visualizes the differences of signal values between images, thus allowing the confirmation of the precision of registration. There is a significant difference between the signal values of a blood vessel or bronchus and those of the lung field. Therefore, a deviation in registration appears as an obvious difference in color intensity in the difference image. That means, the more even the color intensity in the difference image, the more accurate and normal the registration results are.

Fig. 2 shows difference images. Fig. 2 (a) is a difference image obtained by subtracting the raw signal values of the expiration image from the inspiration image, while (b) is a

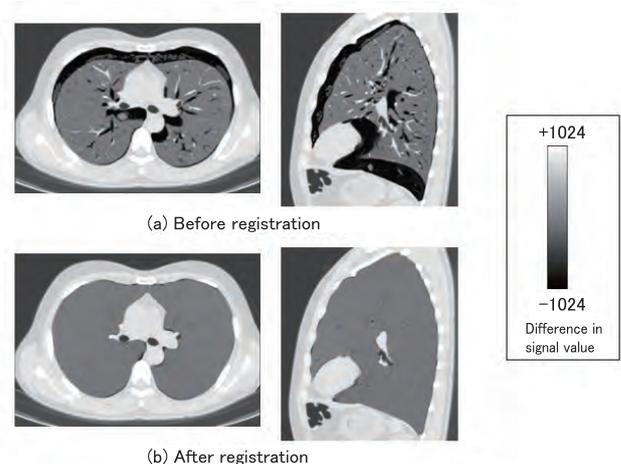


Fig. 2 Difference image



Fig. 3 Difference image

difference image obtained by subtracting the signal values of the expiration image after automatic registration from the inspiration image. In the former image, deviations of the lung field and blood vessels are represented in intense white or black. In the latter, the lung field is the same flat color and the blood vessels and bronchi are edged by the difference in color intensity around their outlines. That is because each tissue has shrunk due to the difference in pressure of the lung field during the respiratory activity. If edges are detected in the same way at both ends of each vascular channel, it means the position of the center line is correctly registered (Fig. 3).

Should there be any anatomical deviation in the results of automatic calculation for registration, higher-precision results can be obtained by manually specifying a more characteristic position with the same anatomical structure in both fixed and moving images and applying registration again.

4. Quantification of the respiratory activity of the lung

There are two criteria in the assessment of the respiratory function. One is whether the lung field and blood vessels can physiologically circulate air via the alveoli. Another is whether air itself inside the lung field is replaced with new air.

The respiratory function is quantified and visualized by calculating voxel-level changes in signal values and movement based on the correspondence between images obtained from the registration results.

4.1 Display of low attenuation areas

In the case of emphysematous lung disease, low attenuation areas (LAAs), which have low image signal values compared with those of the normal lung field, appear in the inspiration image. For the detailed quantitative diagnosis of that type of disease, such as measurement of the percentage of LAAs inside the lung field, Goddard classification to assess its severity and cluster analysis⁶⁾ to identify the extent of progress and region of the disease. On the other hand, the LAAs in the expiration image represent a phenomenon in which air inside the lung field stagnates due to the narrowed bronchiole (air trapping). The phenomenon is considered to derive from peripheral airway lesions, for which there is a technology to analyze the proportion of stenosis using the internal and external diameters of the respiratory tract.

As described, different findings can be obtained via the observation of images of different imaging phases. There is also a research paper reporting that combining the LAAs of the inspiration image with those of the expiration image is useful for the classification of COPD.⁷⁾

We therefore incorporated into this system a function utilizing the registration results that allows the observation of the regions where the LAAs of the inspiration and expiration images overlap each other as well as the individual observation of those LAAs.

Fig. 4 (a) shows the display results of the LAAs of the inspiration image, while Fig. 4 (b) shows the LAAs of the expiration image corresponding to those of the inspiration image based on the registration results. Fig. 4 (c) provides the results of overlapping images (a) and (b) and distinguishing with different colors the LAAs of the inspiration image and of the expiration image, and those common to both images.

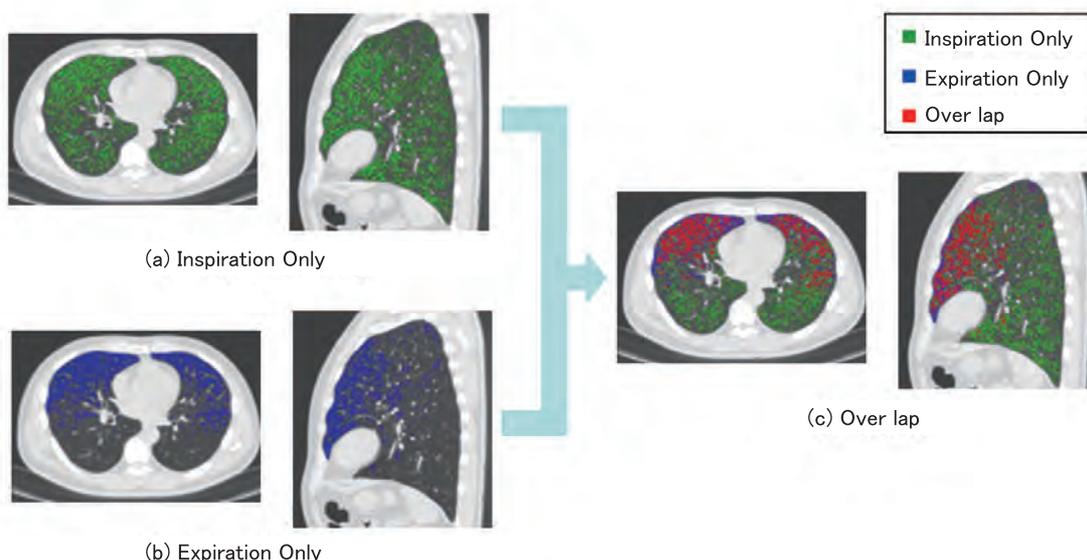
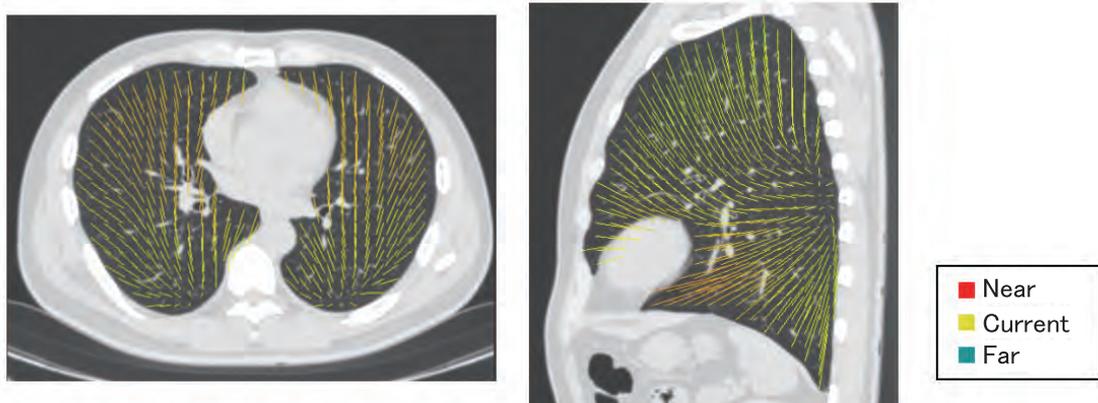


Fig. 4 LAA display



(The centers of gravity of the lungs are the corresponding position to measure the movement.)

Fig. 5 Moving line

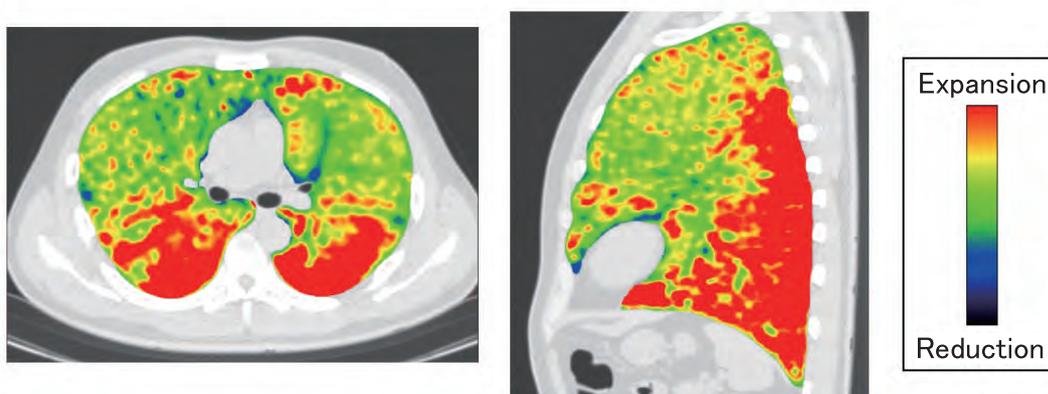


Fig. 6 Expansion rate per unit area

4.2 Visualization of movement

The constriction of the lung is not a simple radial movement from its center to the surface. The movement is characteristic. For example, near the surface, it occurs as if sliding toward the ribs and, the nearer to the diaphragm, the larger it becomes. Therefore, by visualizing the movement of the lung, it becomes possible to compare the diseased lung with the normal one as well as to identify regions that are abnormal in local movements. This system can visualize the movement of the lung that occurs between the inspiration and expiration images based on the registration results. In addition, it can measure the travel of each individually specified region.

Fig. 5 shows the results of representing the movement of the lung with lines. The direction and length of the lines indicate the horizontal movement of the lung. Vertical movement is visualized by coloring the lines according to the direction and significance of the movement. The figure was obtained via calculation with the reference position for movement measurement (point of zero of travel) set to the center of gravity of the lung field.

4.3 Visualization of the expansion rate

Air inside the lung field is exchanged mainly by the constriction of the diaphragm and intercostal muscle. Any defects in respiration weaken the constriction of the lung. There is also a possibility of the constriction being partially inhibited between the inspiration and expiration images if there is any air stagnation due to air trapping as described previously. Therefore, the observation of the expansion rate of the lung field is useful in the diagnosis of pulmonary ventilation capacity.

The left and right lungs are divided into five lobes in total. By taking into consideration those sections, it becomes possible to observe pulmonary ventilation capability section by section. This system can calculate and visualize the expansion rate for each specified region based on the registration results.

Fig. 6 is a representation of the expansion rate of the inspiration image. Because it indicates the expansion rate at inspiration relative to expiration, the blood vessels and bronchi are not expanded, while the whole lung field is. That differentiates the color of the blood vessels and bronchi from the lung field, enabling the confirmation of shape.

5. Conclusion

We developed a 3D imaging diagnostic system with a new technology for dynamic analysis of the lung. The system visualizes the movement of the lung with CT images and thereby supports the identification of diseased regions inside the lung and the diagnosis of their severity and causes. We are planning not only to add even more new lung-field analytical functions but also to improve the system so it can also perform dynamic analysis of the bronchi.

We will keep striving for the further advancement of SYNAPSE VINCENT, hoping that it will become a core system in the diagnosis and treatment of respiratory diseases, such as COPD, by being widely spread to clinical fields of respiratory medicine.

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