Geometric Analysis of Pathological Changes in Lungs Using CT Images for COVID-19 Diagnosis*

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Abstract. The study is devoted to the analysis of dynamic changes in computer tomography (CT) images of lungs, with the presence of changes associated with COVID-19 in patients with the data confirmed by laboratory diagnostics. The assessment is carried out using the developed computational tools for visualizing pathological changes in lungs. For these purposes it is proposed to use algorithms for noise reduction, contrast enhancement, segmentation and spectral decomposition (shearlet transform). On this computational basis, we propose a methodology for geometric (texture) analysis for highlighting and contrasting local objects of interest, taking into account color coding. The results of the experimental study show that the developed computational technique is an effective tool for visualizing and analyzing the variability of the geometric (texture) features of the studied images, as well as for the dynamic analysis in time and prediction of possible outcomes.

Keywords: CT Image, Lung Pathologies from COVID-19, Follow-up Observations, Prediction of Outcomes, Geometric Image Analysis, Color-coded Contrast.

6 Introduction

Computed tomography of the chest cavity organs is widely used, being a routine research method both for detecting and confirming the pathological changes suspected on a radiograph and the primary research method with the recommendations of medical specialists [1]. Nowadays an increase in the number of studies is also stimulated by the emergence of the coronavirus-19 disease, an acute infectious disease caused by the SARS-Cov-2 coronavirus (Severe Acute Respiratory Syndrome CoronaVirus 2).

High contagiousness of the disease and its severe clinical course as well as the increased risk of complications leading to death, all this proves the study of the Covid-19 phenomenon to be the most pressing problem of the world medical community [2]. CT images visualize various typical manifestations of COVID-19 which play a key role in understanding the overall picture of the disease [3].

The idea of the study is to identify and visualize pathological changes in the early stages of the development of pneumonia from COVID-19. In particular, the study of a textural feature manifested as “ground-glass opacity”, with a possible further maximum reduction in radiation exposure without the loss of image quality for the interpretation and making an adequate conclusion. An urgent task is also to identify a number of textural indicators on the CT images for dynamic monitoring of the patient's condition and possibility of predicting outcomes in correlation with the staging of the disease and the obtained research indicators.

7 Features of CT Image Texture Analysis for COVID-19 Diagnosis

Radiological diagnostic methods are used to detect COVID-19 pneumonia, their complications, and differential diagnosis with other lung diseases as well as to determine the severity and dynamics of changes including assessing the effectiveness of therapy. Radiation methods are also required to identify and estimate the nature of pathological changes in other anatomical areas and as a means of control for invasive medical interventions [4]

CT images have the highest sensitivity in detecting changes in the lungs characteristic of COVID-19 pneumonia. The use of CT is advisable for the primary assessment of the chest cavity organs in patients with severe and progressive forms of the disease as well as for the differential diagnosis of the identified changes and evaluation of the process dynamics. According to international recommendations there are the most typical CT patterns in lungs, which allow one to talk about a high probability of COVID-19 pneumonia. The most typical feature is the presence of compaction of the lung tissue manifested as "ground-glass opacity" as described in the literature.

The term "ground-glass opacity" represents an interstitial type of infiltration of the lung tissue. On CT images it looks like a compaction of the lung tissue with preservation of visualization of the bronchial and vascular components (Fig. 1). It is caused by partial filling of air spaces, interstitial thickening (due to fluid, cells and / or fibrosis), partial collapse of alveoli, increase in capillary blood volume or their combination. The common factor is a partial displacement of air [5] (Fig. 2).

To evaluate the CT images of patients with COVID-19, it is necessary to assess the presence of typical signs, such as:

- numerous peripheral compaction of the lung tissue of the “ground glass opacity” type, mainly having a round shape, of various lengths with / without consolidation;
- thickening of the interlobar interstitium of the “cobblestone” type; a symptom of air bronchography, but also localization;
- location is predominantly bilateral, the lower lobe to the peripheral, perivascular; multilobar bilateral nature of the lesion [3].
- location is predominantly bilateral, lower lobar to peripheral, perivascular, a multilobar bilateral nature of the lesion is also possible [3].

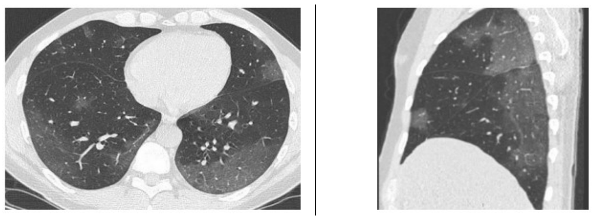

Fig. 1. A compaction of the lung tissue manifested as “ground glass opacity” with visible bronchial and vascular components.

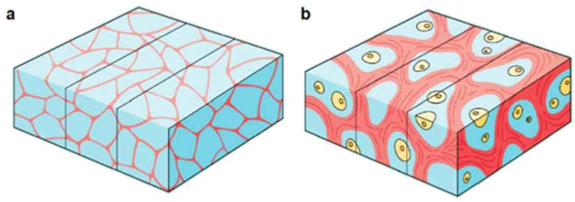

Fig. 2. Pathogenesis of the “ground glass opacity” symptom: (a) normal lung, (b) changes in the lung with “ground glass opacity”.

Another important criterion based on the nature and severity of radiological signs (according to the computed tomography) is the correlation of the percentage of lung damage which is assessed for each lung separately and the severity of the patient's general condition. Heshui Shi, Xiaoyu Han, Nanchuan Jiang et. al. (2020) studied 81 people and were able to divide all the patients into 4 groups based on the time interval between the appearance of the changes on the computed tomography [3].

At the initial examination the degree of severity and percentage of involvement in the process of the lung parenchyma are estimated. Next a dynamic study is carried out. The dynamics of the course of the identified pneumonia COVID-19 is evaluated according to clinical indications using the following imaging methods:

- Optimal – performing CT examination of the lungs according to the standard protocol without intravenous contrast enhancement;
- Possibly – RG in two projections in the X-ray room [4].

When describing the dynamics one should rely on the data of the Handbook of COVID-19 Prevention and Treatment: “Numerous ground-glass compaction areas are identified, located in the peripheral and subpleural regions of the lungs, mainly in the lower lobes. The long axis of the lesion is mostly parallel to the pleura. Patients with massive lesions of the lung tissue should be monitored by a pulmonologist because of the high risk of interstitial pulmonary “fibrosis” [6]

In this regard the most important stage in the processing of the CT images is to highlight features in the images with the most accurate assessment of the corresponding geometric indicators (markers). As a basic computational tool, it is proposed to apply the technology of image processing and analysis within the framework of the radiomics concept. In our experimental study it is proposed to use the methods of spectral decomposition of CT images for the extraction of quantitative indicators (markers) for texture and geometric analysis of the object of interest [7].

It is also proposed on this algorithmic basis to study possible options for changes in dynamics and predict outcomes in conjunction with clinical data. The study is aimed at improving the accuracy of the analysis and interpretation of the images of lung pathology with COVID-19 in order to evaluate the corresponding indicators (markers) in the format of modern radiomics technology [7], as well as to evaluate dynamic changes in the patient's lungs in order to make possible predictions of outcomes.

8 Materials and Methods

As part of the experimental study the following tasks were formulated and solved:

- Formation of elements of the database of CT images with pathological changes in the lungs, in particular, viral pneumonia caused by COVID-19. We used the data of 43 patients with different state of the lung parenchyma, which were studied in dynamic observation;
- Substantiation of the application of the method of analysis and interpretation of images based on which the algorithms of shearlet transformations with contrasting using color coding were made. These algorithms allow one to highlight complex texture (morphological) formations with the formation of quantitative features (markers);
- Performing experiments to obtain new data suitable for assessing the validity and efficiency of the applied computational technique.

Within the framework of the methodology, the main stages of processing and analysis of visual data can be highlighted [8-9]:

- Preprocessing (noise reduction, brightness and contrast correction);
- The main stage (segmentation and formation of a color-coded outline representation);
- The final stage is the extraction of features (markers) and the interpretation of the results.

We adapted a segmentation algorithm based on the principal component analysis (PCA) and discrete wavelet transform (DWT) with the use of a number of representative images of COVID-19 pneumonia. In it, according to the results of the preliminary segmentation, binarization based on the method for determining the Otsu threshold is performed. Then, the contour representation using the shearlet transform and color coding is made [10]. Finally, the characteristics of the texture of the objects of interest are calculated, which are necessary to obtain estimates of the analyzed area [11]. An example of the analysis and interpretation of an image with signs of COVID-19 based on the application of this technique is shown in Fig. 3.

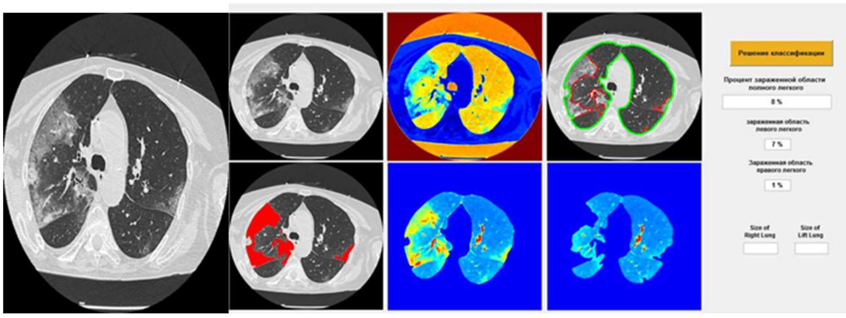

Fig. 3. Examples of calculating the lung damage.

Evaluation of “ground glass opacity” was carried out according to textural characteristics and changes in the affected area. The main point of the experimental study is the analysis of the texture (homogeneity and entropy) of the zone of pathological changes with the correction of the intensity level and its adaptation during the histogram analysis. The more uniform values of the intensity or the gamma during color coding allows us to evaluate the degree of homogeneity of the lesion without attaching additional signs (markers) with respect to the type of consolidation and reticular changes.

At less homogeneous levels, the presence of non-identical components of the studied pathological process is implied. These features are important in predicting the disease dynamics. It should be noted that if homogeneous changes persist over time with their decrease, then the likelihood of an unfavorable outcome also tends to decrease as compared to more noticeable heterogeneous changes.

9 Results of the Experimental Studies

Currently, a dataset of COVID-19 patients (43 people) with pathological changes in the lungs has been formed for which a number of visual signs was allocated (X-ray diagnostic department of the FSSCC FMBA of Russia). The main selection criteria of patients are confirmed coronavirus infection with clinical manifestations and changes in CT images of the lungs.

As part of the experimental study, the area of the involved lung parenchyma is estimated as well as the localization and description of the textural parameters (markers). The data of the dynamic observations of the CT images for each patient in the same time period are retrospectively analyzed: on the day of hospitalization, after 2-3 days, on the 5-7th (10) day and also before the discharge. The timing of the CT diagnostics is set, depending on the patient's condition.

The patients according to the severity and involvement of the lung parenchyma were divided into four categories:

- CT1 – 12 patients, the percentage of involvement of the lung parenchyma <25%;
- CT2 – 16 patients, the percentage of the lung parenchyma involvement is 25-50%;
- CT3 – 10 patients, the percentage of the lung parenchyma involvement is 50-75%;
- CT4 – 5 patients, the percentage of the lung parenchyma involvement > 75%.

An example of the analysis of the visual data of a patient with the confirmed coronavirus infection (male, 24 years old) with the severity of CT1 (<25% of the affected parenchyma) during the dynamic observation and interpretation of the image with signs of COVID-19 based on the application of the technique is shown in Fig. 4.

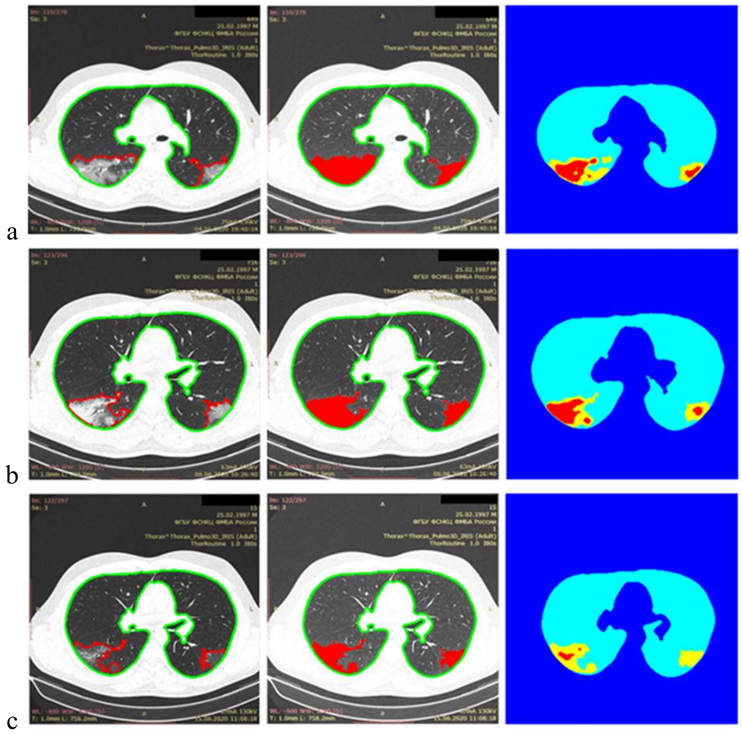

Fig. 4. Examples of the CT image processing of the lungs with COVID-19: (a) follow-up on day 3 of the disease; (b) follow-up on day 7 of the disease; (c) follow-up on day 14 of the disease.

The images presented in Fig. 4 show bilateral changes in the peripheral parts of both lungs and their dynamic changes with a different CT pattern. Based on the analysis of the images characterizing the stages of changes in the pulmonary parenchyma, the patient's condition was interpreted in dynamics.

Fig. 4 a shows the images on the 3-rd day of the disease. One can see a rather homogeneous texture of the lesion of the "ground glass opacity" type most clearly in the right lung in a percentage ratio of 9 on the right and 5 on the left with the total lesion percentage of 14 with an increase in the diameter of the vessels in the affected area, which is characteristic of this disease. The right image demonstrates the ratios of the densest part both on the right and on the left in the central regions to the less dense part along the periphery, which is 6% to 4%.

Fig. 4 b shows the images on the 7th day of the disease; a different texture of changes is noted due to the appearance of the areas of consolidation with the appearance of the symptom of "air bronchography", but with a decrease in the area of the lesion in a percentage ratio of 9 on the right and 3 on the left, with the total percentage of damage 12. The right image also shows a denser part of pathological changes by the red color in relation to yellow, which is 8% to 5% and again indicates the formation of denser areas of consolidation at the stage of the disease progression.

Fig. 4 c shows the images on the 14th day of the disease. The resolution of the previously identified area of consolidation with the formation of "ground glass" and a decrease in the zones of pathological changes is the following: the right lung – 6% the left lung – 3% and 9% – the total area of the lesion. There is also a small denser area in the structure of the right lung, which is 1% of the affected area of the right lung and 8% of the less dense area. These data indicate the resolution of the process and formation of a fairly homogeneous zone with a favorable prognosis of the outcome, without preserving gross consequences.

The assessment of the density of "ground glass" was carried out both visually with the help of a specialist and using a technique which includes the segmentation procedure. The main advantage of this technique is the ability to most reliably assess the boundaries of pathological changes with the calculation of the affected area as well as highlighting the textural features of the zone of changes. It should be noted that given the apparent homogeneity of the structure, it is important to isolate a denser component and further track its changes in order to form a more adequate prognosis for the course of the pathological process and possible outcomes even in the absence of changes in the identified zone of actions for correcting therapy.

In the dynamic assessment, at the first stage of the interpretation of the results the zones with the previously identified changes are compared with the formation of a quantitative idea of their change over time. For example, whether the consolidation has disappeared and a “ground glass opacity” zone has appeared in this place. This indicates the stage of the pathological process, being the dominant CT sign in assessing the patient's condition and predicting a possible outcome as well as prescribing correcting therapy.

At an early stage of observation (1-4 days) the main symptom is “ground glass opacity”. At the next stage of progression (5-8 days) the appearance of foci of consolidation and symptom of “cobblestone pavement” with the preservation of "ground glass opacity" is noted. The peak stage (9-13 days) is characterized by the predominance of the consolidation symptom. At the resolution stage (> 14 days), there is a regression of the identified changes.

These stages can vary (in time and texture characteristics) due to the age of the patient, severity of the course of the disease, as well as response to treatment, but in fact, the dependence remains. Further, in monitoring the patient's dynamic condition and during the corresponding assessments, a description of "fresh" changes is obtained or the disappearance of the previously identified zones of pathological changes is observed. When quantifying the area of the lesion and the ratio of the denser to the less dense part (in the dynamics of the days of the disease) one can see a correlation with the stages of the process, which is displayed on the CT images in the form of the transformation of "ground glass opacity" into consolidation and vice versa with further regression of the changes.

10 Conclusion

A brief methodological and algorithmic description of the development of the Radiomics technology for texture (geometric) analysis of the CT images with COVID-19 is presented. Adequate segmentation and visualization of pathological changes are demonstrated for further construction processing of the studied CT images in order to solve diagnostic problems.

The possibility of obtaining additional information on texture parameters (markers) is shown, expanding the X-ray diagnostic opinion of a radiologist. A quantitative percentage assessment of the degree of involvement of the lung parenchyma in the pathological process was carried out, and the possibility of dynamic observation with the formation of the prediction of the patient's condition was shown. This indicator correlated with the days of the disease and the severity of pathological changes may indicate the severity of the disease.

In the retrospective analysis, taking into account the indicators of the affected area and correlation of the ratio of the zone of denser changes (consolidation) to that of smaller changes, caused by the areas of "ground glass opacity" with the staging of the process, it is possible to reliably track the relationship:

- Day 3 of the disease (onset of the disease), the percentage of damage is 9% on the right and 5% on the left, the ratio of density characteristics is 6% / 4%;
- 7 day of the disease (onset of the disease), the percentage of damage is 9% on the right and 3% on the left, the ratio of density characteristics is 8% / 5%;
- 14th day of the disease (onset of the disease), the percentage of damage is 6% on the right and 3% on the left, the ratio of density characteristics is 1% / 8%.

As can be seen from the results of assessing "ground glass opacity" we obtained a possible gradation of this indicator into the denser and less dense parts with apparent homogeneity due to the correlation of intensity and color coded images. The use of the visualization technique for the features associated with the manifestations of COVID-19 on the CT images shows that it is possible to isolate and quantify the denser part of pathological changes for its dynamic observation and consequently, to assess the effect of therapy on this area. At the same time, the most accurate technique is to highlight the boundaries of the area of the involved parenchyma. This criterion can be a valuable indicator in predicting the outcome since with a long-existing dense zone, which during dynamic observation remains unchanged both visually and structurally in the same volume, the likelihood of fibrosis in this area increases.

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