NEW WAY IN FRACTAL ANALYSIS OF PULMONARY MEDICAL IMAGES

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Improved fractal analysis, for the complex interpretation of standard pulmonary radiography, is intensively used. A novel approach for fractal dimension evaluation, much finer and directly applicable in pulmonary arterial network, has been considered. In this sense, the quantitative evaluation of alveolar channels is possible, and the quality of the result is associated with multiple covering possibilities of radiologic images surface, by identical two-dimensional geometric figures.

Keywords: fractal dimension, chaos, self-structuring, fractal analysis, respiratory diseases

1. Introduction

The Chaos Theory can be considered a luxuriant branch of science, physics and mathematics mainly, devoted specifically to study the chaos (as a universal category) or chaos phenomena of real world. Consequently, it can also be taken into account that it is the science of ("dealing" with) all non-linear manifestations, hard to control, but present in every phenomenon in nature, otherwise. In short, the Chaos theory makes comprehensible the intricate systems behavior or unpredictable reactions occurrence to scale change and studies extensive and complicated systems, named complex systems.

At the beginning of 20th century, the illustrious Henri Poincaré, great mathematician of French origin, initiates the study of celestial body orbits in our solar system. Following laborious and repeated systematic calculations, he noticed that if the initial conditions (starting point, for example) of some of the orbits in the solar system changed, he found very different results! In other words, Poincaré observed that a very small change to the initial conditions made it almost impossible to predict how orbits might work. This extraordinary discovery which has been

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attributed to him, makes the contemporaries consider Poincaré as the genuine parent of chaos theory.

In the mid-twentieth century, the emergence and intensive use of computers (numeric calculation machines) made it possible to re-launch the chaos theory with great success. Quite recently, at the historical scale, in the year 1960, Edward Norton Lorenz, a mathematician at the MIT (Massachusetts Institute of Technology) Private University and old meteorologist, writes and runs a computing program based on complex physical-mathematical nonlinear equations that generated an important number of variables, through which one can think that they would predict correctly the weather patterns. His success in the era and his outstanding achievements make him the second parent, the modern father of the theory of chaos. No more or less, his work titled "Deterministic Nonperiodic Flow", published in 1963, is considered today the theoretical foundation of chaos theory.

2. Chaos, Fractal Geometry and Fractal Analysis

Fractal Geometry is a new geometry [1], in fact a different non-classical geometry that exhibits some characteristics, as the self-similarity (or self-affinity) and the scale invariance. Univocally, it is characterized by the associated fractal dimension, generally denoted by D, which is a non-integer (fractional) number. Etymologically speaking, the word fractal is derived from the Latin word “fractus”. A simple fractal philosophy can be defined by a few (minimal) essentials postulates, further exemplified in a logical order.

Postulate/Lemma1. The apparent unpredictable behavior of fractal is due to its sensitivity to initial conditions.

Postulate/Lemma 2. The property of fractal self-similarity can be measured quantitatively only with fractal dimension.

Postulate/Lemma 3. The fractal dimension characterizes an object with a dimensionality greater than its topographical dimension.

Corollary. A fractal curve has a fractal dimension between a straight line and a plane ($1 < D < 2$), while a fractal surface has a dimension between a plane and three-dimensional space ($2 < D < 3$).

As a real opportunity, the fractal geometry is potentially suitable for an objective quantification of spatial or surface heterogeneity because it is believed to be effective in helping to characterize complex systems that are hard to describe using conventional Euclidean geometry. Whereas the fractal dimension, D, is a very popular and arguably important parameter in describing the fractal medical images (human organs imageries, Roentgenology, brain MR images or nuclear medicine images) some different procedures have been implemented in calculating the value and these methods are then compared reciprocally, in literature. The relationship between the fractal dimension, *D*, and the fractal scaling constant and various other parameters highlight the particularity of the studied geometrical objects.

Historically, in the last decades, the fractal dimension was reported to be susceptible in detecting mild impairments in the ventilation status in patients with suspected emphysema [2], recommending its clinical value in early diagnosis and in the monitoring of the pulmonary diseases progression in supervised patients. Further investigation of the origin of the efficacy of the fractal analysis method, considering its promising diagnostic potential and easy implementation, seems worthwhile.

At this time of exposure,a question is still legitimate. What is the Fractal Analysis? We will try to propose an intuitive definition that corresponds to its own historical calendar and explains its evolution, in the context of complex theory and other contemporary scientic challenges. Today, a collection of theoretical methods that have gradually found practical utility, methods grouped in the same topical use and same philosophy, can receive the title of Fractal Analysis. These are, without the pretense of enumerating all of them, the Haussdorf-Besicovich dimension, the fractal dimension, the large-scale correlation coefficient, the "roughness" coefficient, the "smoothing" coefficient, and the informational coefficient.

The fractal analysis and adjacent calculus programs, specifically associated with point requirements, have been developed for important topics in physics [3, 4], medicine [5, 6] and materials science [7-9], with focus on nanomaterials [10, 11]. Calculating fractal dimension and other intrinsic parameters and concepts in the theory of complexity such as Lyapunov exponents, attractors (strange attractor, the Hénon attractor), attractor reconstruction (phase space) and new predictive models are the subject of well-known articles [12] and books, in the community of specialists. The clinical part and the radiologies evaluated in the article are based on the work of one of the authors, an expert on lung disease, detection, amelioration and healing [13-16].

3. Fractal dimension evaluation in alveolar channels

As it is well known, X-rays were one of the first forms of biomedical imaging in the exploratory medicine of human body. In the pulmonary radiology, an incident radiation fascicle of X-rays has a directed trajectory, finally producing an image to be processed for diagnostic purposes. On chest radiograph, the chest, lungs, mediastinum, and heart can be seen. The lungs, due to the air contained, appear as gaseous density formations sprinkled with water opacities, representing the interstitium and the pulmonary arterial vessels. Between the two lungs is the mediastinum, which has hydrological density, radiologically. The radiological study is of great importance and can be achieved through a variety of techniques that are very useful in providing information that leads to a correct diagnosis. Also, it may be used to monitor treatment for a variety of lung conditions such as pneumonia, emphysema, and cancer without exhausting the list.

Invariably, the familiar numerical data matrices from classical geometry such as length, area, and volume depend on the scale [17] at which we decide to look at the object. Not the same thing happens in the Fractal geometry where we can write a functional relationship between the measure (M) and the scale (ε) like$M(\varepsilon) = k\varepsilon^D$, where k is a scaling constant and D is termed the fractal dimension [5]. Although the path presented above would be easier to follow, in this article we developed another method for fractal dimension evaluation, much finer and directly applicable in pulmonary arterial network. Its exposure and practical applications to some radiology will be presented below.

To properly process the pulmonary arterial network, the pixels due to media travelled by the X-rays up to the lungs, namely skin, meat-fat and ribs have been eliminated. The computer program is similar to the extraction of useful information from ambient noise, providing the image purification of parasitic pixels, to a good extent.

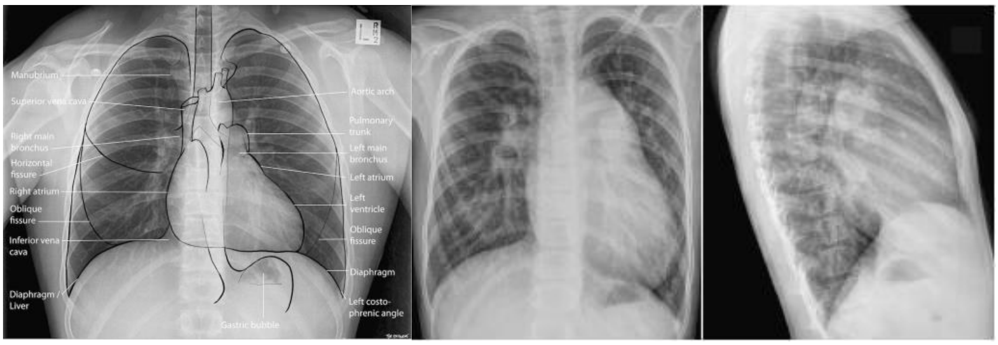

Fig. 1. The general map of a schematic lung (left-hand side), Chest box radiography in a six-year old patient (middle and right-hand side)

In the right-hand side of Figure 1 an important dimensional enlargement is observed of the torso curve AP, relative to the size of the heart, considered indicative of an increase in the blood pressure. Qualitatively, in the six-year old patient radiographed [18], we have complicated PCA with pulmonary arterial hypertension. Pulmonary arteries in the central territory are greatly expanded, and small vessels predominate at the periphery compared to the central territory.

The increase of pulmonary vascularity is characterized by the growing in the size of the vascular branches in the central and peripheral territory, with net contours to a simple observation.

Let us consider the following alveolar channels structure, using a standard pulmonary radiography in the shape of an image of (dim$x$, dim$y$) dimensions compressed in either BMP, PNG or JPG formats.

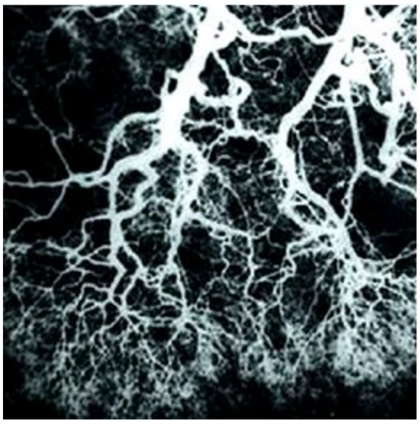

Fig. 2. First step in the preliminary process

In order to guarantee an optimal evaluation, the image must be preliminarily processed. Therefore, as in our case, the JPG compression uses 3 levels of RGB colors. Practically speaking, we are referring to a 3rd order tensor with the (3, dim*x*, dim*y*) dimensions. As the image is similar to a grey-level image, the three layers are close, as we can notice in Fig. 3.

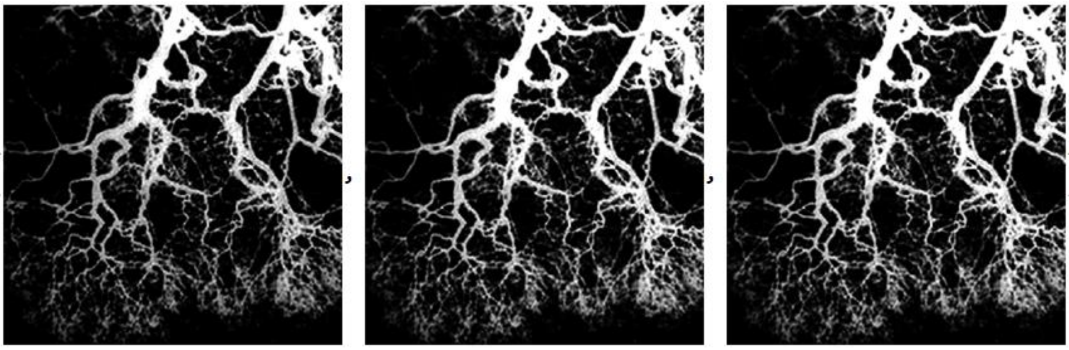

Fig. 3. One layer intermediate processing

The fractal dimension evaluation can be realized using the box-counting method. The usual method is to cover the image, in the black and white version, with square cells and then to count these cells. The fractal dimension is evaluated through the regression line slope calculation of the graphic $Log(N(r))$as function of $Log(1/r)$, where r represents the cell dimension and $N(r)$ is the minimum number of cells used to successfully cover the image. By processing one layer from Figure 3 (one can use high-pass filters, low-pass filters or band pass filters, threshold, thinning, etc.), we obtain an image similar to the one presented in Figure 4.

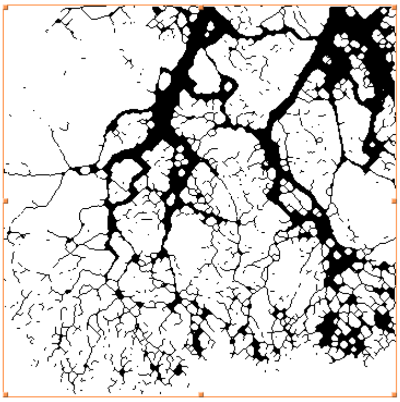

Fig. 4. Filter application for one layer processing from Figure 3

4. **Results and discussion**

The covering of the image is done using square cells of well-defined dimensions (the dimension of the cell must be a divisor of the image dimensions, in order to avoid discontinuity points of the graph in Fig. 6), as the ones represented in Fig. 5.

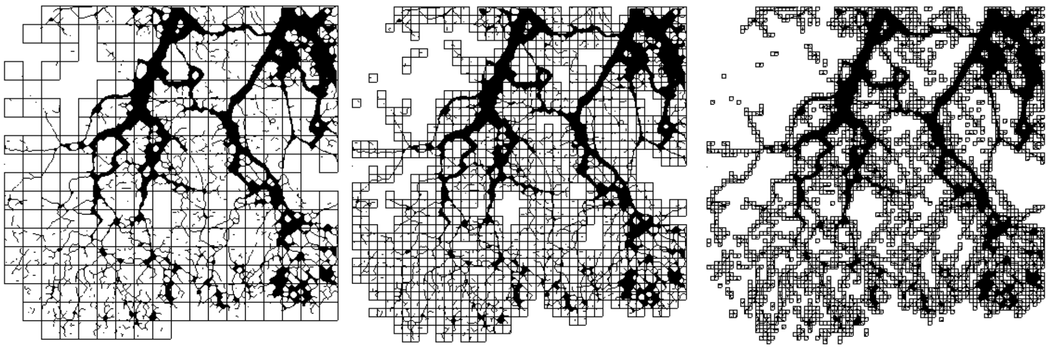

Fig 5. The covering of the image with square cells

By performing the counting, we obtain the graph in Figure 6, where the line equation leads to

$$y = 1.750x + 0.7665 \tag{1}$$

from where a fractal dimension as following results

$$D = 1.753 \pm 0.032 \tag{2}$$

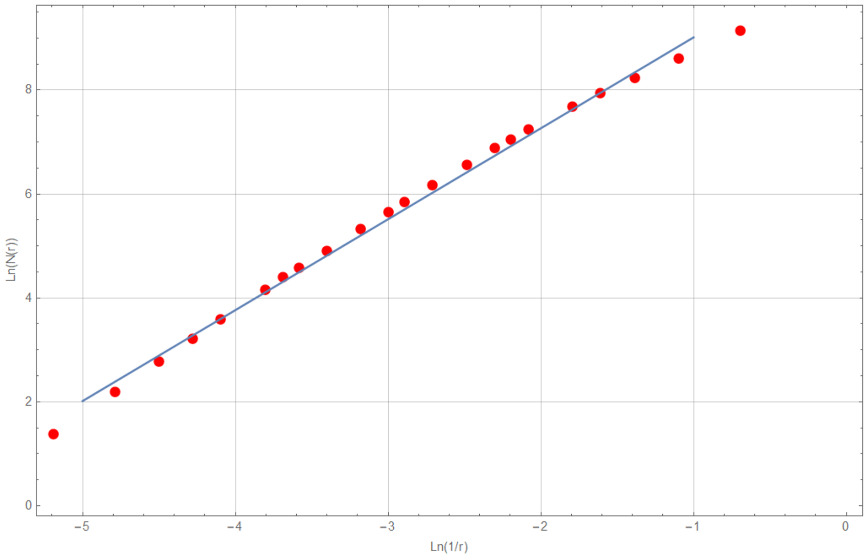

Fig. 6. Graph obtained after the box counting on the processed image

The method has been improved by not only covering the image with square cells, but also by using rectangular cells [19]. In this way, the number of points used in the fractal dimension calculation is increased and therefore allowing for error reduction (some covering examples are shown in Fig. 7).

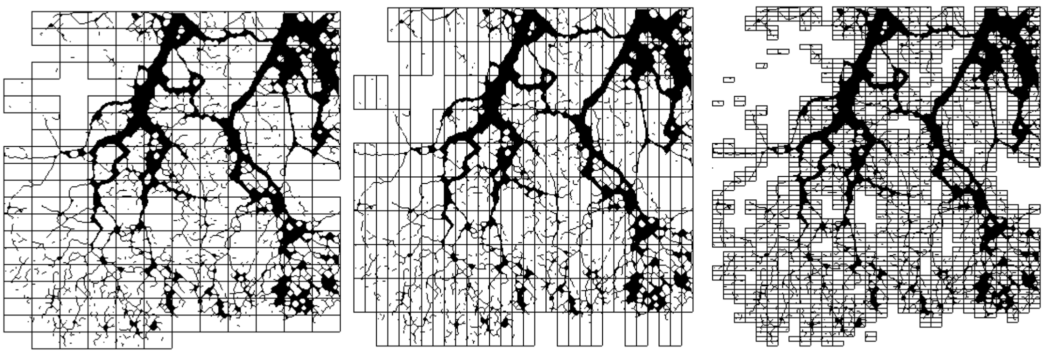
a) b) c)

Fig. 7- A few of the multiple covering possibilities are represented

Thus, to be explicit, in Fig. 7, we have **a)** cell dimensions are$\{r_x, r_y\} = \{12, 15\}$, **b)** cell dimensions are$\{r_x, r_y\} = \{16, 10\}$, **c)**cell dimensions are$\{r_x, r_y\} = \{5, 10\}$.If the covering cell dimensions are r_x and r_y, then a three-dimensional graph with the axes$Log(1/r_x)$,$Log(1/r_y)$and$Log(N(r_x, r_y))$ is obtained.

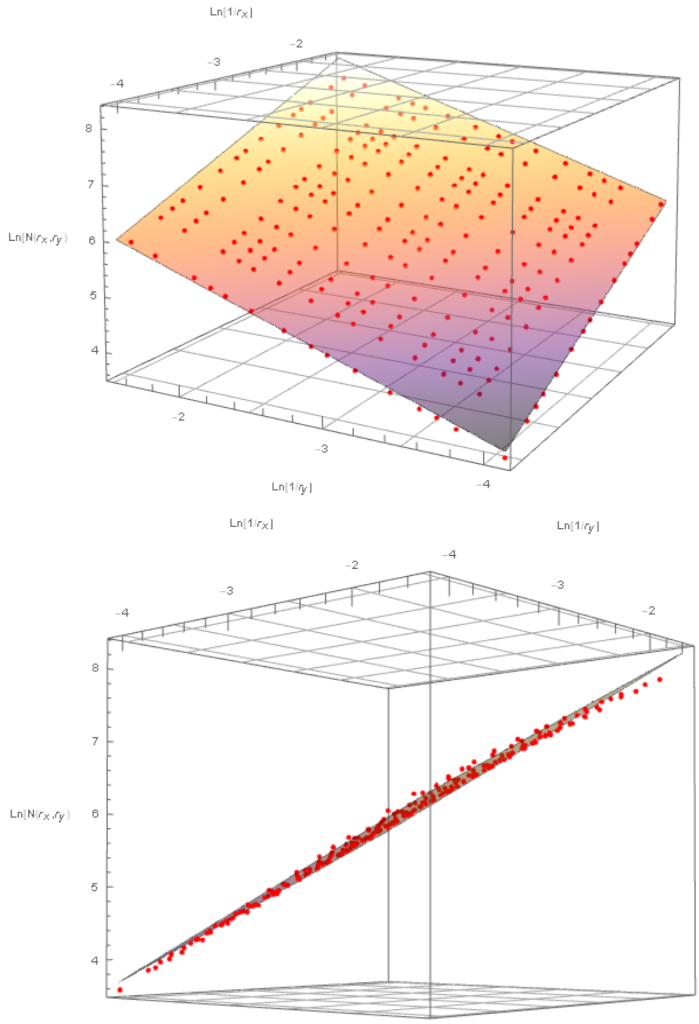

Fig. 8. Three-dimensional representation

The equation of the plane which fits the points,$z = f(x, y)$, allows us for the fractal dimension evaluation (where$x \equiv Log(1/r_x)$, $y \equiv Log(1/r_y)$,and$f \equiv Log\ (N(r_x, r_y))$).

Observation. In writing the computer programs and within the text of the presentation the notation of the logarithmic function as “log” has been used, as it is customary in informatics. However, for the realization of all the graphs, we have used the function “ln” (natural logarithm), in accordance to the program requirements of processing known data.

From the plane equation we have

$$f(x, y) = a + bx + cy \tag{3}$$

and for the case of covering the image with rectangular cells $x = y$ it results $f = a + (b + c)x$ basically $D = b + c$, but

$$b = \frac{\partial f}{\partial x} \text{and } c = \frac{\partial f}{\partial y} \tag{4}$$

Therefore, the fractal dimension *D* is the following

$$D = \frac{\partial f}{\partial x} + \frac{\partial f}{\partial y} \tag{5}$$

In our case, the numerical analysis provides

$$f = 10.988 + 0.885x + 0.895y \tag{6}$$

from where

$$D = 1.780 \pm 0.002 \tag{7}$$

4. Conclusions and future work

Medical images paradigmatically have a degree of raised organic randomness related to the natural casual consistence of the human body structure. Evidently, for this reason, both fractal analysis and the fractal mathematical modelisation have been demonstrated to be profitable in analyzing a large variety of organ radiographies in patients.

In this paper, a novel approach for fractal dimension evaluation, much finer and directly applicable in pulmonary arterial network, has been considered.

The method has been improved by covering the image with square cells, or by using rectangular cells. According to this, a few possibilities of the multiple covering are presented, each with its proven effectiveness. In this way it is possible to achieve a quantitative evaluation of alveolar channels on the X-ray radiology to the lungs.

Finally, the numerical analysis provides the explicit function f=10.988+0.885x+0.895y, and the fractal dimension is D=1.780±0.002.

The fractal dimension calculated with the algorithm developed here is recommended as a clinical indicator associated in early diagnosis and in the regular monitoring of the pulmonary diseases progression in supervised patients.

In the future, we can use the fractal analysis to confirm that the lung tumor images at exactly the same positions and dimensions at different times of investigation, in order to attest the effectiveness of the therapy. Moreover, the requirement of normal pulmonary images as references for our proposed algorithms is alleviated.

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