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HALLMARKS OF FRACTALITY IN BLOOD DYNAMICS

BY

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Abstract. By understanding blood as a fluid tissue moving along a cylindrical structure with a mucous wall (Taylorian movement of a fluid inside another) we can explain with a deterministic mathematical model the physiopathological changes and the diversity of effects they have on the cardiovascular system. Moreover, by reducing the hologram paradigm from an universal scale to a microscopical and molecular scale, we can understand, speculatively at this moment, the healing processes as a holographic result, the healthy cells from the periphery of the affected area containing all the information which is necessary for the reproduction through self-similarity of the destroyed cells.

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1. Introduction

In the following we want to present the implications of fractality in the circulatory system (Tesloianu, 2014):

– non-linear dynamics and chaos theory can be employed to approach phenomena that cannot be explained through classical mechanics, real world needing, for a description based on mathematical modelling, formulas that are adapted to the continuous changes that occurs as result of complex biological phenomena; we will accept and define a real component and a “virtual” one (that can be activated depending on the conditions at a certain moment), the best example in these case being the development of collateral circulation in the presence of a hemodynamically significant and long-lasting vascular stenosis, a type of circulation developed in existing but unused vessels – “virtual” - which are activated when needed.

– a non-linear object looks different depending on the resolution scale at which it is observed; thus, the complexity profile is imposed in correlation with the resolution scale at which observation is made.

– sensibility to initial conditions (Tesloianu *et al*., 2015): if, for predictable systems, a small perturbation of the initial state of the system generates a small change of its final state, in the case of chaotic systems, particularly biological ones, small perturbations can lead to divergent and unpredictable states, the “butterfly effect” being a well-known example in this sense. In 1963 Edward Lorentz was the first meteorologist who gave a logical explanation to the fact that meteorological predictions are only probable and never certain: according to him, the concept being developed and confirmed by other researchers too, the wing-beating of a butterfly in Europe can cause a tornado in America in certain given circumstances, that are basically impossible to predict accurately, respecting meteorological models;

– differences in the applicability of the superposition principle (Tesloianu *et al*., 2015): in a linear system the resulting effect of two different causes represents the superposition of the effects of the two causes taken individually; in a non-linear system the summation of two elementary action can lead to new effects, due to interactions between constituent elements, with the apparition of structures and events that are unpredictable in space and time – determinist chaos.

According to Mandelbrot (Mandelbrot, 1983), the fractal, as a geometric object, has the following characteristics:

– is autosimilar: through observing a portion of the fractal there will be the same information as in the entire fractal;

– has a simple and recursive definition as a function $f(x)$;

– has an infinite detaliation and complexity;

– has a fractal dimension (D) or the Hausdorff dimension; this dimension measures the number of smaller diameter sets which are needed to cover a figure - if this number is an integer, then the dimension is topological, otherwise it is fractal.

The key terms of fractal geometry are:

– initiator: the geometrical figure from which the fractal is generated, usually a simple geometrical figure: line, square, circle, rombus;

– the construction law: the method through which the fractal is generated;

– the generating process: effectively constructs the iterations of the fractal object, starting from the current iteration and applying the construction law on it; the process of repeating the same step generates new generation of fractal sets.

2. Methods

With the help of fractals, we can find fractal curves that approximate a set of data from the human body (registered temperatures in a certain period of time, arterial pressure fluctuation). Fractals can be used to build models of unpredictable and chaotic systems like those found in cardiology; below we will define the possibilities of integrating and logically proving these systems.

In the following we assume that the motions of a complex fluid's entities occur on fractal curves. Therefore, a fractal space-time manifold, compatible with such movements, can be defined. Then, through non-differentiability, the breaking of differential time reflection invariance is implied. In this framework, the common definitions of the derivative of any given function with respect to time (Nottale, 1989; Nottale, 2011):

$$\frac{df}{dt} = \lim_{\Delta t \to 0} \frac{f(t+\Delta t) - f(t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{f(t) - f(t-\Delta t)}{\Delta t} \tag{1}$$

are equivalent in the differentiable case. One passes from one to the other by the transformation $\Delta t \to -\Delta t$ (time reflection invariance at the infinitesimal level). Two functions (df_+ / dt) and (df_- / dt) are defined as explicit functions of t and dt in the non-differentiable case:

$$\begin{aligned} \frac{df_+}{dt} &= \lim_{\Delta t \to 0} \frac{f(t+\Delta t, \Delta t) - f(t, \Delta t)}{\Delta t} \\ \frac{df_-}{dt} &= \lim_{\Delta t \to 0} \frac{f(t, \Delta t) - f(t-\Delta t, \Delta t)}{\Delta t} \end{aligned} \tag{2}$$

The sign (+) corresponds to the forward process and (–) to the backward one.

It follows that, in the space coordinates $d\boldsymbol{X}$, we can write (Nottale, 1989; Nottale, 2011):

$$d\boldsymbol{X}_{\pm} = d\boldsymbol{x}_{\pm} + d\boldsymbol{\zeta}_{\pm} = \boldsymbol{v}_{\pm} dt + d\boldsymbol{\zeta}_{\pm} \tag{3}$$

with $\boldsymbol{v}_{\pm}$ the forward and backward average velocities

$$\begin{aligned} \mathrm{v}_{+} &= \frac{d\mathrm{x}_{+}}{dt} = \lim_{\Delta t \to 0_{+}} \left\langle \frac{\mathrm{X}(t+\Delta t) - \mathrm{X}(t)}{\Delta t} \right\rangle \\ \mathrm{v}_{-} &= \frac{d\mathrm{x}_{-}}{dt} = \lim_{\Delta t \to 0_{-}} \left\langle \frac{\mathrm{X}(t) - \mathrm{X}(t-\Delta t)}{\Delta t} \right\rangle \end{aligned} \tag{4}$$

and $d\xi_{\pm}$ a measure of non-differentiability (a fluctuation which is induced by the trajectory's fractal properties) with the mean

$$\langle d\xi_{\pm} \rangle = 0 \tag{5}$$

While the velocity-concept is classically regarded as a single concept, if space-time, in our case, is a fractal, we must introduce two velocities (v_{+} and v_{-}) instead of just one. This "two-values" of the velocity vector is a new, specific consequence of non-differentiability that has no standard counterpart (in the differential physics sense).

We must note that, we cannot, however, favor v_{+} rather than v_{-}. Therefore, a solution arises: to take into consideration both the forward ($dt > 0$) and backward ($dt < 0$) processes together. It is thus necessary to introduce the complex velocity (Nottale, 1989; Nottale, 2011):

$$\mathrm{V} = \frac{\mathrm{v}_{+} + \mathrm{v}_{-}}{2} - i\frac{\mathrm{v}_{+} - \mathrm{v}_{-}}{2} = \frac{d\mathrm{x}_{+} + d\mathrm{x}_{-}}{2dt} - i\frac{d\mathrm{x}_{+} - d\mathrm{x}_{-}}{2dt} \tag{6}$$

If $(\mathrm{v}_{+} + \mathrm{v}_{-})/2$ may be considered as a differentiable (classical) velocity, then the difference $(\mathrm{v}_{+} - \mathrm{v}_{-})/2$ is the non-differentiable (fractal) velocity.

By using notations $d\mathrm{x}_{\pm} = d_{\pm}\mathrm{x}$, Eq. (6) becomes:

$$\mathrm{V} = \left(\frac{d_{+} + d_{-}}{2dt} - i\frac{d_{+} - d_{-}}{2dt} \right)\mathrm{x} \tag{7}$$

This allows us to write a definition for the operator

$$\frac{\hat{d}}{dt} = \frac{d_{+} + d_{-}}{2dt} - i\frac{d_{+} - d_{-}}{2dt} \tag{8}$$

Now, we assume that the fractal curve is immersed in a 3-dimensional space, and that *X*, having the components X^{i} ($i = \overline{1,3}$) is the position vector of a point on the curve. We also consider a function $f(\mathrm{X},t)$ and the following Taylor series expansion up to the second order:

$$\begin{gathered} df = f(X^i + dX^i, t+dt) - f(X^i, dt) = \\ = \left(\frac{\partial}{\partial X^i} dX^i + \frac{\partial}{\partial t} dt\right) f(X^i, t) + \frac{1}{2}\left(\frac{\partial}{\partial X^i} dX^i + \frac{\partial}{\partial t} dt\right)^2 f(X^i, t) \end{gathered} \tag{9}$$

From here, using the notations, $dX_{\pm}{}^i = d_{\pm}X^i$, the forward and backward mean values for this relation become:

$$\begin{gathered} \langle d_{\pm} f\rangle = \left\langle \frac{\partial f}{\partial t} dt \right\rangle + \langle \nabla f \cdot d_{\pm}\mathrm{X}\rangle + \frac{1}{2}\left\langle \frac{\partial^2 f}{\partial t^2}(dt)^2 \right\rangle + \\ + \left\langle \frac{\partial^2 f}{\partial X^i \partial t} d_{\pm}X^i dt \right\rangle + \frac{1}{2}\left\langle \frac{\partial^2 f}{\partial X^i \partial X^l} d_{\pm}X^i d_{\pm}X^l \right\rangle \end{gathered} \tag{10}$$

Moving forward, let us stipulate that: the mean values of the function *f* and its derivates coincide with themselves, and the differentials $d_{\pm}X^i$ and *dt* are independent, and as a result the averages of their products coincide with the product of average. Then Eq. (10) becomes

$$\begin{gathered} d_{\pm} f = \frac{\partial f}{\partial t} dt + \nabla f \langle d_{\pm}\mathrm{X}\rangle + \frac{1}{2}\frac{\partial^2 f}{\partial t^2}\langle (dt)^2\rangle + \\ + \frac{\partial^2 f}{\partial X^i \partial t}\langle d_{\pm}X^i dt\rangle + \frac{1}{2}\frac{\partial^2 f}{\partial X^i \partial X^l}\langle d_{\pm}X^i d_{\pm}X^l\rangle \end{gathered} \tag{11}$$

and more, by using (3):

$$\begin{gathered} d_{\pm} f = \frac{\partial f}{\partial t} dt + \nabla f d_{\pm}\mathrm{x} + \frac{1}{2}\frac{\partial^2 f}{\partial t^2}(dt)^2 + \\ + \frac{\partial^2 f}{\partial X^i \partial t} d_{\pm}x^i dt + \frac{1}{2}\frac{\partial^2 f}{\partial X^i \partial X^l}\left(d_{\pm}x^i d_{\pm}x^l + \langle d\xi_{\pm}^i d\xi_{\pm}^l\rangle\right) \end{gathered} \tag{12}$$

Since the fractal properties of the trajectory, having the fractal dimension D_F (Mandelbrot, 1983), are described by $d\xi_{\pm}^i$, it is only natural to impose that $\left(d\xi_{\pm}^i\right)^{D_F}$ be proportional with dt, *i.e.* (Nottale, 1989; Nottale, 2011):

$$(d\xi_{\pm}^i)^{D_F} = \sqrt{2D}dt \tag{13}$$

where D is a proportionality coefficient (the fractal non-fractal transition coefficient).

We shall focus now on the mean $\left\langle d\xi_{\pm}^{i} d\xi_{\pm}^{l} \right\rangle$. If $i \neq l$, this average is zero because of the independence of $d\xi^{i}$ and $d\xi^{l}$. Therefore, by using (13) we obtain:

$$\left\langle d\xi_{\pm}^{i} d\xi_{\pm}^{l} \right\rangle = \pm\delta^{il} 2D(dt)^{\left(2/D_F\right)-1} \tag{14}$$

with

$$\delta^{il} = \begin{cases} 1, & if \quad i = l \\ 0, & if \quad i \neq l \end{cases}$$

having considered that

$$\begin{cases} \left\langle d\xi_{+}^{i} d\xi_{+}^{l} \right\rangle > 0 \text{ and } dt > 0 \\ \left\langle d\xi_{-}^{i} d\xi_{-}^{l} \right\rangle > 0 \text{ and } dt < 0 \end{cases}$$

Now we can write Eq. (12) as:

$$\begin{aligned} d_{\pm} f = {} & \frac{\partial f}{\partial t} dt + \nabla f d_{\pm}\mathrm{x} + \frac{1}{2}\frac{\partial^2 f}{\partial t^2}(dt)^2 + \frac{\partial^2 f}{\partial X^i \partial t} d_{\pm}x^i dt + \\ & + \frac{1}{2}\frac{\partial^2 f}{\partial X^i \partial X^l} d_{\pm}x^i d_{\pm}x^l \pm \frac{\partial^2 f}{\partial X^i \partial X^l}\delta^{il} D(dt)^{\left(2/D_F\right)-1} \end{aligned} \tag{15}$$

If we divide by dt and we do not take into consideration the terms containing differential factors, (15) can be reduced to

$$\frac{d_{\pm} f}{dt} = \frac{\partial f}{\partial t} + \mathrm{v}_{\pm}\nabla f_{\pm} \pm D(dt)^{(2/D_F)-1}\Delta f \tag{16}$$

In this context, we will calculate $\hat{d}f / dt$. According with (8) and considering (16 a, b), we will have:

$$\begin{aligned} \frac{\hat{d}f}{dt} = {} & \frac{1}{2}\left[\frac{d_{+} f}{dt} + \frac{d_{-} f}{dt} - i\left(\frac{d_{+} f}{dt} - \frac{d_{-} f}{dt}\right)\right] = \\ = {} & \frac{1}{2}\left[\left(\frac{\partial f}{\partial t} + \boldsymbol{v}_{+}\nabla f + D(dt)^{(2/D_F)-1}\Delta f\right) + \left(\frac{\partial f}{\partial t} + \boldsymbol{v}_{-}\nabla f - D(dt)^{(2/D_F)-1}\Delta f\right)\right] - \\ & - \frac{i}{2}\left[\left(\frac{\partial f}{\partial t} + \boldsymbol{v}_{+}\nabla f + D(dt)^{(2/D_F)-1}\Delta f\right) - \left(\frac{\partial f}{\partial t} + \boldsymbol{v}_{-}\nabla f - D(dt)^{(2/D_F)-1}\Delta f\right)\right] = \\ = {} & \frac{\partial f}{\partial t} + \left(\frac{\boldsymbol{v}_{+} + \boldsymbol{v}_{-}}{2} - i\frac{\boldsymbol{v}_{+} - \boldsymbol{v}_{-}}{2}\right)\nabla f - iD(dt)^{(2/D_F)-1}\Delta f \end{aligned} \tag{17}$$

or using Eq. (6):

$$\frac{\hat{d}f}{dt}=\frac{\partial f}{\partial t}+\boldsymbol{V}\cdot\nabla f-iD(dt)^{(2/D_F)-1}\Delta f \tag{18}$$

This relation allows us to define the fractal operator (Agop *et al*., 2008):

$$\frac{\hat{d}}{dt}=\frac{\partial}{\partial t}+\boldsymbol{V}\cdot\nabla-iD(dt)^{(2/D_F)-1}\Delta \tag{19}$$

By applying the fractal operator (19) to the complex velocity (6) and also by accepting the scale covariance principle (Nottale, 1989; Nottale, 2011) in the form:

$$\frac{\hat{d}\boldsymbol{V}}{dt}=-\nabla U \tag{20}$$

the following motion equation results:

$$\frac{\hat{d}\boldsymbol{V}}{dt}=\frac{\partial \boldsymbol{V}}{\partial t}+\left(\boldsymbol{V}\cdot\nabla\right)\boldsymbol{V}-iDdt^{\left(\frac{2}{D_F}\right)-1}\Delta\boldsymbol{V}=-\nabla U \tag{21}$$

where U is an external scalar potential. Eq. (21) is a Navier – Stokes type equation. It can be interpreted that at any point of a fractal path, the local acceleration, $\partial_t\boldsymbol{V}$, the non-linear (convective) term, $\left(\boldsymbol{V}\cdot\nabla\right)\boldsymbol{V}$, the dissipative term, $Ddt^{(2/D_F)-1}\Delta\boldsymbol{V}$, and the external free term ∇U make their balance. It follows that the complex fluid can be assimilated to a "rheological" fluid, its dynamics being described by the complex velocities field, $\boldsymbol{V}$, and by the imaginary viscosity type coefficient, $iDdt^{(2/D_F)-1}$. The "rheology" of the fluid imparts hysteretic properties to the complex fluid (the complex fluid has a hysteresis cycle, memory (Agop *et al*., 2008).

3. Results and Discussions

Neglecting the convection $\boldsymbol{V}\cdot\nabla\boldsymbol{V}$, Eq. (21) with $U=\text{const.}$ can be written as

$$\frac{\partial \boldsymbol{V}}{\partial t}-iD(dt)^{(2/D_F)-1}\Delta\boldsymbol{V}=0 \tag{22}$$

or, by separating the resolution scales

$$\frac{\partial \boldsymbol{V}_D}{\partial t}-D(dt)^{(2/D_F)-1}\Delta\boldsymbol{V}_F=0 \tag{23}$$

for the differentiable scale, and

$$\frac{\partial \boldsymbol{V}_F}{\partial t} - D(dt)^{(2/D_F)-1}\Delta \boldsymbol{V}_D = 0 \tag{24}$$

for the fractal scale. The velocity fields can be totally separated, first by applying Eqs. (23) and (24) to the Δ operator, *i.e*.

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\Delta \boldsymbol{V}_D\right) - D(dt)^{(2/D_F)-1}\Delta^2 \boldsymbol{V}_F = 0 \\ &\frac{\partial}{\partial t}\left(\Delta \boldsymbol{V}_F\right) + D(dt)^{(2/D_F)-1}\Delta^2 \boldsymbol{V}_D = 0 \end{aligned} \tag{25}$$

then, by substituting the dissipative terms taking into account Eqs. (23) and (24). Therefore the Kirchhoff-type equations (Audoly and Neukirch, 2005) result:

$$\left(\frac{\partial^2}{\partial t^2} + D(dt)^{(4/D_F)-2}\Delta^2\right)\begin{pmatrix}\boldsymbol{V}_D\\ \boldsymbol{V}_F\end{pmatrix} = \begin{pmatrix}0\\0\end{pmatrix} \tag{26}$$

For the one-dimensional case, the previous equations with the substitutions

$$\begin{aligned} &\frac{x}{L} = \bar{\xi},\ \frac{t}{T} = \bar{\tau},\ \frac{L^4}{T^2} = D^2(dt)^{(4/D_F)-2}, \\ &(V,U) \equiv \bar{\mathrm{K}}_i\left(\bar{\xi},\bar{\tau}\right),\ i = 1,2 \end{aligned} \tag{27}$$

take the unitary form (Audoly and Neukirch, 2005):

$$L^4\frac{\partial^4 \bar{\mathrm{K}}_{\mathrm{i}}}{\partial \bar{\xi}^4} + T^2\frac{\partial^2 \bar{\mathrm{K}}_{\mathrm{i}}}{\partial \bar{\tau}^2} = 0 \tag{28}$$

We can impose „clamping” conditions at $\bar{\xi} = 1$ for Eq. (28):

$$\frac{\partial^2 \bar{\mathrm{K}}_{\mathrm{i}}(1,\bar{\tau})}{\partial \bar{\xi}^2} = 0,\ \frac{\partial^3 \bar{\mathrm{K}}_{\mathrm{i}}(1,\bar{\tau})}{\partial \bar{\xi}^3} = 0 \tag{29}$$

and for boundary conditions at $\bar{\xi} = 0$:

$$\bar{\mathrm{K}}_{\mathrm{i}}(0,\bar{\tau}) = 0,\ \frac{\partial \bar{\mathrm{K}}_{\mathrm{i}}(0,\bar{\tau})}{\partial \bar{\xi}} = 0 \tag{30}$$

These four boundary conditions in $\bar{\xi}$ associated with the two initial ones

$$\bar{\mathrm{K}}_{\mathrm{i}}(\bar{\xi},0)=\bar{\mathrm{K}}_{i0},\ \frac{\partial\bar{\mathrm{K}}_{\mathrm{i}}(\bar{\xi},0)}{\partial\bar{\tau}}=0 \tag{31}$$

imply a unique solution $\bar{\mathrm{K}}_{\mathrm{i}}(\bar{\xi},\bar{\tau})$ to Eq. (23) – see Fig. 1.

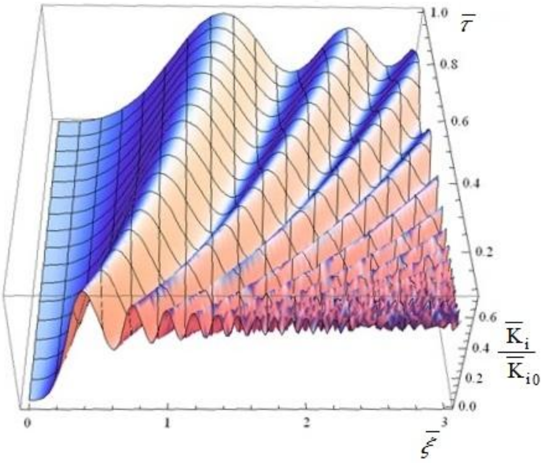

Fig. 1 – Numerical solution of the Kirchhoff Eq. (52) with "clamped-free" unitary conditions, for a uniform initial $\bar{\mathrm{K}}_{\mathrm{i0}}$. $\bar{\mathrm{K}}_{\mathrm{i}}(0,\tau)$ relaxes to zero within the first few time-steps

Both the velocity field "self-similarity" through the field equation scale resolution independence (either the differential, or the fractal one), and its "interferentiality" through Kirchhoff type solutions determines the holographic property of the fractal medium.

By corroborating the above stated facts, it can be affirmed that the autosimilarity of the transfer processes of biological compounds can be assimilated to that of a hologram, in the sense that in any finite volume of a biological liquid we will find its entire "image" (at any scale, beginning with the cellular one and finishing with the organ - organism one (Aronstein and Strout, 1997)); as a consequence, we can understand the tissues and organs as repetitive and reproductible matrices of a basis structure, a structure that is replicative and regenerative depending on conditions, influenced by both the internal and external environments and temporo-spatially dependent on this conditions in a measure that is permanently variable on a time-velocity integral. Thus, by understanding blood as a fluid tissue moving along a cylindrical structure with a mucous wall (Taylorian movement of a fluid inside another) we can explain with a deterministic mathematical model the physiopathological changes and the diversity of effects they have on the cardiovascular system; moreover, by reducing the hologram paradigm from an universal scale to a microscopical and molecular scale, we can understand, speculatively at this moment, the healing processes as a holographic result, the healthy cells from the periphery of the affected area containing all the information which is necessary for the reproduction through autosimilarity of the destroyed cells. All the information held by the whole unit is contained in each part of a hologram contains; recent discoveries made in two different fields by the cuantic physics expert David Bohm (London University) and the neurophysiologist Karl Pribarm (Stanford University) determined the emergence of the idea that the universe is a gigantic hologram created by the human mind, in conformity with mathematical models. Pribarm believes that the brain itself is a hologram (Pricop *et al*., 2013), considering that information is not codified in neurons, but in nervous impulse configurations which intersect at this level. Basically, the de Broglie hypothesis about the wave-corpuscle duality is reconfirmed (de Broglie, 1964).

4. Conclusions

Each of the information units mentioned above seem to be interconnected with all the others, this coresponding to the intrinsic characteristic of the hologram. As reality is only a holographic illusion, Pribram affirms that the old paradigm according to which the brain produces conscience and conscious thoughts can no longer be true. Moreover, the researcher affirms the reverse (Luis, 1993): conscience and conscious thoughts create the physical appearance of the brain, of the human body and of everything that surround us and are perceived as being real. In such a context, information seems to play an essential role (Onicescu, 1966). Thus, at this moment it has been proved and has been accepted that every fluid carrying information (such as blood) can play the role of a laser ray. Unlike photography, holograms contain information that is not strictly located in certain points, but can be considered ”global’, distributed along the entire surface of the hologram.

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CARACTERISTICI ALE FRACTALITĂȚII ÎN DINAMICILE SÂNGELUI

(Rezumat)

Prin asimilarea sângelui cu un țesut fluid ce se deplasează printr-o structură cilindrică cu pereți din mucus (mișcare de tip Taylor a unui fluid în interiorul altul fluid) putem explica, utilizând un model matematic determinist, modificările fiziopatologice și efectelor lor diverse asupra sistemului cardiovascular. Mai mult, prin reducerea paradigmei holografice de la o scară universală la scară microscopică/moleculară, putem analiza, cel puțin speculativ, procesele de vindecare ca un rezultat al holografiei, celulele sănătoase de la periferia zonei afectate conținând toate informațiile necesare reproducerii prin autosimilaritate a celulelor afectate.