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Phase Congruency and Fractal Based Analysis of Coronary Angiogram along with Study Using 3D Modelling of Artery

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ABSTRACT: In this work, segmentation of blood vessels from normal and abnormal human coronary angiogram images was performed based on phase congruency. The segmented images of the detected patterns were analysed using fractal analysis. The results seem to have significant variations by differentiating normal and pathological images. Further the blood flow through the arteries is studied using 3D modelling software called COMSOL. Through this the extent of severity of coronary heart disease can be analysed.

KEYWORDS: coronary angiogram, phase congruency, fractal analysis, COMSOL

I.INTRODUCTION

Coronary Heart Disease (CHD) is the number one killer in the world according to the recent accelerating medical research and advance technology. CHD most commonly affect the older people and men on the basis of World Health Organization's survey. According to Centres for Disease Control and Prevention [CDC], 2013, the smooth and elastic arteries get cholesterol-containing deposits and inflammation on the inner walls that make the arteries more rigid and narrowed. This occurs only when the blood has high level of fat and cholesterol. The narrowed arteries (blood clot) causes blockage decrease and slowly restrict the blood flow, nutrients and oxygen to the heart. Blood clot in the artery cause stroke that is introduced by sudden loss of brain function. This decreased blood flow to heart leads to stable angina, unstable angina, myocardial infarction. When the plaque ruptures the arteries, it leads to heart attack (coronary thrombosis) or sudden cardiac death. Coronary heart disease permanently damages the heart muscle and fatal. High blood pressure is one of the major factors that lead to coronary artery disease.

The X-ray angiography is the standard technique for imaging coronary artery and effective in clinical observation as well as identification of vascular stenosis [1]. It aids in clinical diagnosis, monitoring of coronary diseases and therapeutic process [2]. The coronary arteries obtained from the X-ray angiogram are useful to provide the parameters for quantitative description of coronary geometry and motion, with which the severity of pathology evaluated and assessment and diagnosis of cardiovascular disease. The coronary arteries extracted from the successive angiographic images aids in obtaining the 3D vascular construction [3,4] as well as heart motion analysis [5,6]. However, X-ray angiogram faces a challenging task in fully automatic, robust and accurate extraction of vessels.

Among many methods of vessels extraction from angiogram, the phase congruency and fractal based analysis is performed to extract the arteries from the angiogram. Phase congruency is a dimensionless quantity that provides a absolute measure of the significance of feature points. Since, it is invariant to changes in the image brightness and contrast of the angiogram image. Fractal analysis provides quantitative measures to characterize complex shapes which possess self-similarity in an image [7]. The phase congruency and fractal based analysis are more efficient that helps in extract of tiny vessels in retina [8].

Fractal analysis is a defined as a efficient tool in automated image processing as its objective is to provide quantitative measures that help to characterize complex shapes. The fractal dimension thus obtained is the measure of the self-similarity and complexity of an image and aids in automated classification of images having branching structures [9].

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As the structures of arteries in heart are presented in 2D format, their geometric features and curvature dynamics variation of these structures are difficult to handle. Hence a 3D model is obtained through computer simulation which is gaining attention and popularity in science and engineering. Computer simulation modelling aids in designing, creating and digitally analysing the complex medical systems that cannot be directly seen. Computer simulation modelling is a discipline translates the real-world physical laws into their virtual forms. Here the computer simulation is carried out using the COMSOL Multiphysics Software which is a flexible platform that allows to add physical effects to the model and obtain the desires physical characteristic of the model.

II.METHODOLOGY

Coronary angiogram images (N=30) used for the study were obtained from OPENi website and nearby hospitals. In this paper, phase congruency is utilized for measuring symmetry and asymmetry in the Fourier domain so that the proposed method is invariant to vessel brightness and boundary sharpness variations. Phase congruency algorithm has been employed in extracting the characteristics of the blood vessels in the various images considered [8]. The input image is filtered with a bank of log Gabor filters at various orientation and frequency with each filter modelling a single channel.

To calculate 2-D phase congruency of a given image *I(x, y)*, the image is first convolved with a bank of log-Gabor filters. The image denoted by even-symmetric filter and odd-symmetric filter at scale n and orientation o denoted by M^{e}_{no} and M^{o}_{no} respectively.

The responses of each quadrature pair of filters are a vector:

$$[e_m(x,y), o_m(x,y)] - [I(x,y) * M^{e}_{no}, I(x,y) + M_{no}] \quad (1)$$

'*' is the convolution operator. From Equation, the amplitude of this response is given by

$$A_{no}(x,y) = \sqrt{e^2_{no}}(x,y) + o^2_{no}(x,) \quad (2)$$

and phase is given by

$$\phi_m = a\tan(e_{no}(x,y), o_{no}(x,y)) \quad (3)$$

The 2-D phase congruency is then calculated by

$$PC_2(x,y) = \frac{\sum_o \sum_n W_o(x,y) \lfloor A_m(x,y)\Delta\phi_m(x,y) - T_o \rfloor}{\sum_o \sum_n A_{no}(x,y) + \varepsilon} \quad (4)$$

where $\lfloor \ \rfloor$ denotes that the enclosed quantity is equal to itself if it is positive, and equal to zero otherwise; $W_o(x, y)$ is a measure of significance of frequency spread; ε is a small positive constant used to prevent division of zero; T_o is a quantity introduced to compensate image noise; and $delΦ_{no}(x,y)$ is a sensitive phase deviation function defined as

$$\Delta\phi_m(x,y) = \cos(\varphi_{no}(x,y) - \bar{\phi}_o(x,y)) - |\sin\varphi_{no}(x,y) - \bar{\varphi}_o(x,y))| \quad (5)$$

The sharp image features such as edge and line will be perceived and highlighted in the 2-D phase congruency array [6, 9]. The obtained output images are further converted into binary images for subjecting to fractal analysis and to obtain Vessel Density Index (VDI)[10]. The index represents ratio of presence and absence of vessel in a binarised phase congruency subjected retinal image.

Fractal or fractal objects are self-similar structures or scale-invariant structures [11]. It also shows self-similarity at different magnifications. The fractal dimension is a measure of the roughness of a fractal structure. The fractals that are found in nature are called random fractals, and their structure shows self-similarity only in a statistical sense. Fractal dimensions are estimated using box counting method.

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Box-counting method is used in this paper to calculate the fractal dimension of the binary vessel skeleton [11]. In box-counting algorithm, the binary image is blanketed repeatedly with square boxes of increasing side length *(L=1, 2, 4, 8,.. 128).* The number of boxes with side length *L* used (denoted by *N(L)*) are counted if and only if the box contains at least one white pixel. A linear least squares regression is applied to make a log-log plot of *N(L)* versus *L*. The negative value of line slope is used as the fractal dimension; D_f. Fractal dimension obtained for various box sizes is used for analysis with VDI.

Computer simulation is a powerful and popular interactive environment which gains attention in solving all kinds of scientific and engineering problems. Computer simulation modelling aids in designing, constructing and digitally analysing the complex system. This computer simulation modelling help in translating real-world physics law to virtual form that can be easily understood and presented. It is flexible platform that allows adding additional physical effects and analyse and evaluate the physical properties of the complex model.

With the powerful COMSOL Multiphysics model for one type of physics, it can be extended to a multiphysics model that solves coupled physics phenomena. With all inclusive modelling software, COMSOL Multiphysics software aids in obtaining a real world precision model as it mirrors what happens in the real world. The power of COMSOL Multiphysics as a standalone product is accessed through a flexible graphical user interface (GUI) or by script programming in MATLAB® language.

The model presented here represents the vasculature system specifically the upper part of the aorta. The aorta along with its blood vessels is embedded in a biological tissue namely cardiac muscle. The blood flow in the aorta exhibit a pressure on the inner wall of the artery and it branches, which results in the deformation of the tissue.

The analysis if the aorta consists of two distinct procedures: a fluid dynamic analysis (calculation of velocity and pressure distribution in the blood of the artery) and mechanical analysis of the deformation of the artery.

•Fluid dynamics analysis

Here the Navier-Stokes equations are solved in the blood domain. At each surface where the model brings a vessel to an abrupt end, it represents the load with a known pressure distribution. For a time-dependent analysis, a general trigonometric function is used for varying pressure distribution over time:

$$f(t) = (1-\alpha)\sin(\pi t) \qquad 0 \le t \le 0.5s \qquad (6)$$

$$f(t) = 1 - \alpha\cos\big(2\pi(t-0.5)\big) \qquad 0.5s \le t \le 1.5s \qquad (7)$$

•Mechanical analysis

Only the domains related to the biological tissues are active in this analysis. The model represents the load with the total stress distribution it computes during the fluid-dynamics analysis.

IV. RESULTS AND DISCUSSION

The input images of same sizes were considered for analysis. Figure 1(a) and 2(a) shows typical normal coronary angiogram and abnormal angiogram respectively. The images are subjected to phase congruency based procedure and the outputs obtained are shown in Fig 1(b) and 2(b). The visual results show that the edges of the cardiac vascular patterns were delineated well. Abnormal features such as exudates are well detected in pathological images.

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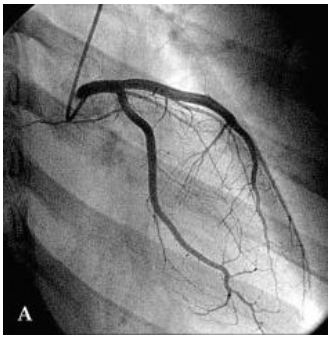

Fig 1(a) Representative normal angiogram

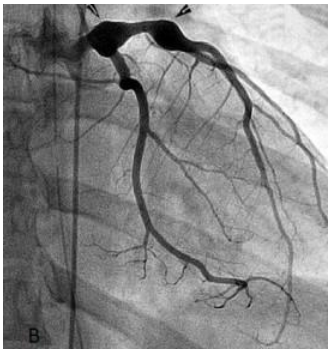

Fig 2(a) Representative abnormal angiogram

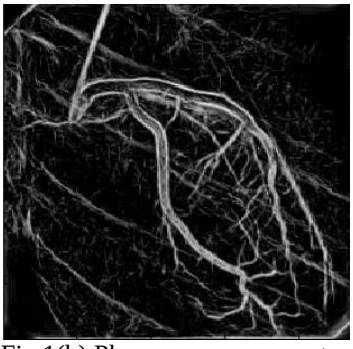

Fig 1(b) Phase congruency output

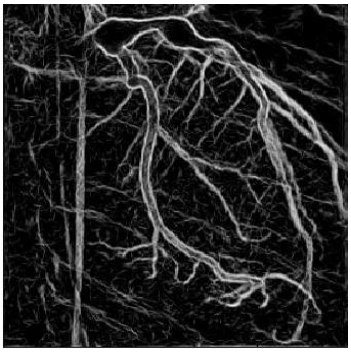

Fig 2(b) Phase congruency output

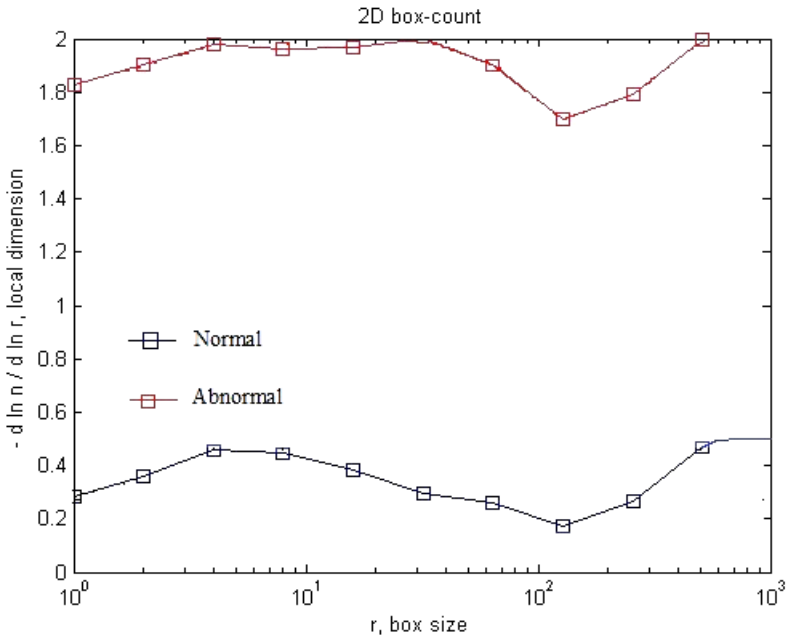

Fig 3 Variations in fractal dimension for box size 2 for coronary angiograms

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The fractal dimensions obtained for various box sizes 2, 4 and 8 show significant differences in healthy and diseased angiograms as shown in Fig 3 for box size2. The normal and diseased coronary angiogram images results in distinct values which can be interpreted with Fig 3.

Fig 4 shows the variations in blood flow in the modelled artery for a healthy person as well as a CAD affected person. It can be seen that the velocity is maximum at inlet for a healthy person, as that is the point where pressure is maximum due to systolic movement. Whereas for a CAD affected person, the velocity at inlet and outlets are irregular due to the constriction of blood flow. Table 1 shows the magnitudes of blood flow corresponding to Fig 4. Fig 5 shows the diastolic pressure distribution through the modelled artery for a healthy and CAD affected person. Table 2 shows the magnitude of pressures corresponding to Fig 5.

Healthy person (male) CAD affected person(male)

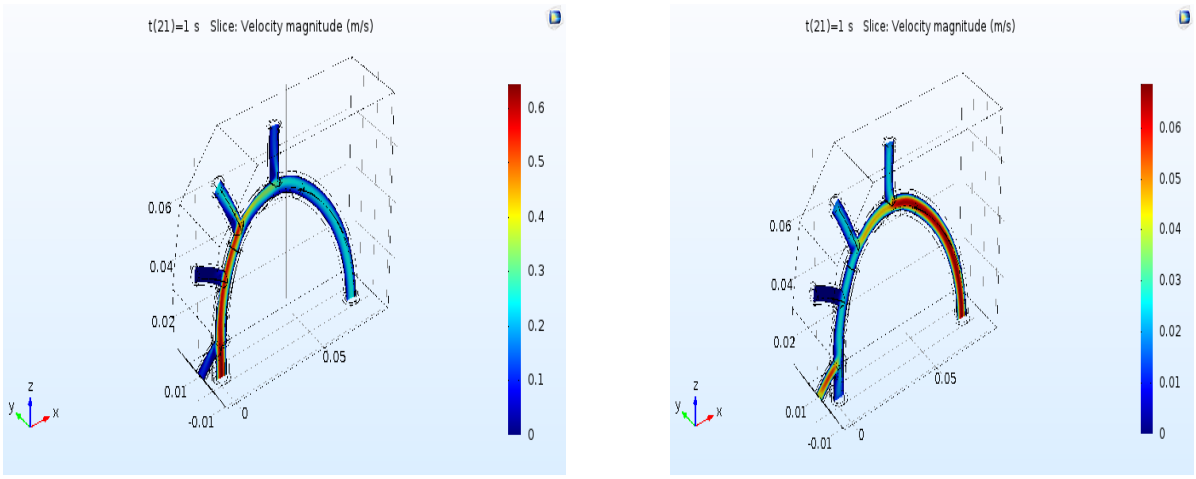

Fig 4 The velocity of blood flow in the modelled artery is found and compared for a healthy person and a coronary artery disease affected person

Table 1 Velocity magnitudes (m/s)

Healthy person (male)

Branches	Velocity (m/s)
Inlet	0.6
Outlet 1	0.15
Outlet 2	0.1
Outlet 3	0.25
Outlet 4	0.35
Outlet 5	0.25

CAD affected person (male)

Branches	Velocity(m/s)
Inlet	0.01
Outlet 1	0.05
Outlet 2	0.015
Outlet 3	0.025
Outlet 4	0.02
Outlet 5	0.06

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Healthy person (male) CAD affected person (male)

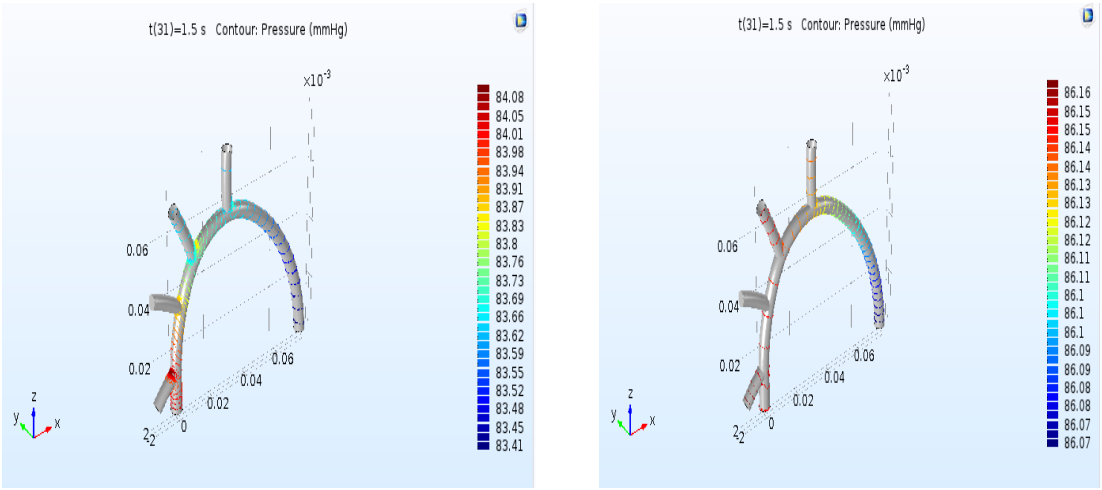

Fig 5 The pressure distribution during blood flow in the modelled artery is found and compared for a healthy person and a coronary artery disease affected person

Table 2 Diastolic pressure magnitudes (mmHg)

Healthy person (male)

Branches	Pressure (mmHg)
Inlet	84.01
Outlet 1	84.08
Outlet 2	83.91
Outlet 3	83.76
Outlet 4	83.66
Outlet 5	83.45

CAD affected person (male)

Branches	Pressure (mmHg)
Inlet	86.15
Outlet 1	86.16
Outlet 2	86.14
Outlet 3	86.14
Outlet 4	86.13
Outlet 5	86.01

V. CONCLUSION

Phase congruency based fractal analysis has been attempted in this work. The property invariant behaviour to changes in image brightness or contrast provides better detection of edges. Further, fractal based studies provides significant variations in output. Thus this study can be performed on coronary angiogram images in detecting early changes of

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pathology in vascular conditions of coronary artery disease. In addition, they can also be used to characterize the neovascularisation process in coronary artery disease since small vessels were also identified in this method and thereby the study seems to be clinically relevant.

Followed by this, the modelling of artery helps in studying the blood flow through normal and diseased arteries along with their velocity and pressure distributions. Since the study is based on fluid dynamics, better results are obtained. The analysis of blood flow developed in arteries is done based on time dependant analysis and hence there is a realistic interaction between the fluid and the structure i.e., blood and artery. Thus it helps in studying the extent of severity of coronary artery disease, due to which diagnosing the disease can be made more efficient and effective treatment can be done accordingly.

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