Celal Bayar University Journal of Science

Obtaining the Heart Rate Information from the Speckle Images by Fractal Analysis Method

Ayla Burçin Şişli[1], Arman Jalali Pahnvar[2], Mehmet Engin[3], Erkan Zeki Engin[3*]

[1]Ege University, Graduate School of Natural and Applied Science, Department of Biomedical Technologies,
[2]Ege University, Graduate School of Natural and Applied Science, Department of Nuclear Sciences,
[3]Ege University, Faculty of Engineering, Department of Electrical and Electronics Engineering,

*erkan.zeki.engin@ege.edu.tr

Received: 16 January 2019
Accepted: 17 March 2020
DOI: 10.18466/cbayarfbe.513732

Abstract

Heart rate is the main data that shows if the heart is working properly. Therefore, obtaining the heart rate information has a vital importance. There are some methods to measure the heart rate, but the most commonly used one is the Electrocardiography (ECG). However, this method is expensive and non-portable. Therewithal, optical studies have recently been conducted to measure heart rate. Being non-invasive, inexpensive, and safe are the advantages of optical measurements. Laser speckle contrast imaging is an effective and simple technique for imaging heterogeneous environments such as human and animal tissues. By laser speckle contrast analysis, heart rate can be obtained easily. It is the standard technique, but fractal analysis method is also very convenient way to study speckle images because speckle pattern is quite appropriate for studying fractality due to its granular structure. In this paper, we present fractal analysis method for obtaining heart rate information from speckle images. The results of this method for the various in-vivo and in-vitro data were compared with the reference model results of speckle contrast analysis method and it is observed that the proposed analysis method has provided sufficient results.

Keywords: Fractal analysis, box-counting, speckle, heart rate

1. Introduction

The heart circulates oxygen and nutrient-rich blood throughout the body. When it is working improperly, just about everything is affected. Heart rate is central to this process because the function of the heart is directly related to it. A normal heart rate for adults is between 60 to 100 bpm. This parameter gives us vital physiological information. It can help monitor health situation and spot developing health problems. Heart rate is an important point of view in terms of metabolism and development of blood circulation of an organism [1, 2].

To measure the heart rate, Electrocardiography (ECG) is widely used method. In this method, electrical activity of heart is recorded by the probes placed to the body. However, being expensive and non-portable are disadvantages of this method [3, 4]. When normal ECG technique is insufficient, Holter ECG is a great option to monitor the activity of heart. In this method, the cardiac rhythm is monitored and recorded 24 hours by a portable device called 'holter' [5]. In addition, ultrasound based alternative method can be used to measure heart rate via ECG signal [6]. Lastly, laser speckle contrast analysis is another method to measure the heart rate. In this method, contrast analysis is applied to the speckle patterns obtained by the speckle method [4]. In our study, it is aimed to measure heart rate by applying fractal analysis method to speckle patterns.

Speckle pattern is quite appropriate for studying fractality due to its granular structure (speckle). These speckles generally show statistical behavior. The well-known analysis method of active series of speckles is relied on laser speckle contrast. However, fractal statistics is also very convenient way to study speckle images. The behavior of the process at different times can be measured by calculating the fractal statistics of the speckle signal. Evaluation of the fractal dimension of speckle images gives very important information coming from flow process. The fluid is always pulsed at almost the same frequencies with the human heart [7-9].

In this paper, the heart rates that were measured by fractal analysis method from in-vitro and in-vivo speckle images (frames) will be shown. Three different sets of in-vivo and three different sets of in-vitro images were used for this study. Differential box-counting method was performed to measure the change of fractal dimension according to time for speckle images. At the end, all the results were compared with the model results obtained by laser speckle contrast analysis method which we got from another study [4].

2. Materials and Methods

2.1 What is Speckle?

The term speckle refers to a random granular pattern. This pattern is a random intensity distribution produced by the scattered light that is formed when coherent light scatters from a random medium (Figure 1). Because of its randomness, it can only be described statistically. This random interference pattern in the image plane changes because of the phase shifts in the scattered light produced by the motion of scattering particles inside of the medium. The speckle image contains spots of different sizes and intensities. In speckle based techniques, the sample is mostly enlightened by a laser and the scattered light is gathered by a sensor. The collected light gives us significant information about the living medium. By laser speckle contrast imaging method, it is possible to ensure exhaustive information about system dynamics [7-10]. The speckles could be divided in two groups according to their formation geometry. When the laser illuminates a sample and the speckles resulting from the back-scattered radiation is directly collected using a screen or a sensor array in the absence of lens system are known as objective speckles. In contrast, when the speckles are obtained through a lens system, the resulting speckles are known as subjective speckles [11].

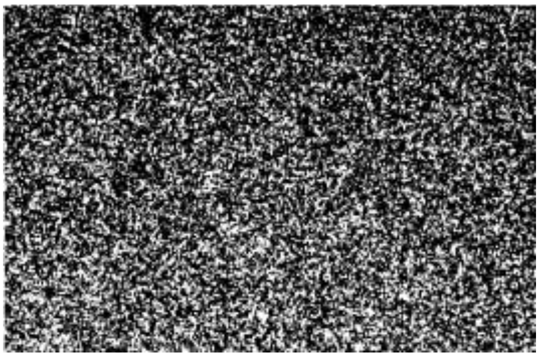

Figure 1. A typical laser speckle contrast pattern [12].

2.2 Fractal Analysis of Speckle Images

A fractal is a geometrical figure used to define and imitate inherently occurring items. Artificially created fractals generally show almost identical patterns at increasingly small scales [13]. A fractal dimension is a ratio that ensures a statistical index of complexity collating how particular in a fractal pattern varies with the scale [14, 15]. Fractal analysis identifies fractal properties of input. It is possible to get lots of information such as heart rate by this method [16]. Fractal analysis is now widely used in all areas of science [17, 18].

Breaking the image into small structures shows the measure of fractality. In scaling law, an image is a combination of 'N', which is the distinct, non-overlapping replicas of itself. The replicas can be reduced by a ratio 'r = M/s'. Here, 'M' is size of the image and 's' is the size of the length scale of the created replicas. N is connected to these parameters by the equation of ‘ $N_s \cong r^{-D}$ ’. Here, 'D' is the fractal dimension (FD) [9]. In order to perform fractal domain analysis of image, there are number of techniques such as variance methods, box-counting methods [19]. It is a great way to measure the distribution of a structure in a surface and could be distinctly connected to the measurement of a spatial distribution in a speckle image. The time advancement of this within the area beneath investigation is exceptionally valuable in the consideration of dynamical systems. In the box-counting method, the speckle image, in which the main features of fractals can be observed, is divided into boxes on a certain scale and the fractal dimension is calculated by using the important boxes, which are determined through this method. When the amount of boxes (N_s) is predicted between the range of s, then the connection between $\log(N_s)$ and $\log(1/s)$ can be seen. The resultant slope shows the fractal dimension. The relation is shown as:

$$FD = \lim_{s\to 0} \frac{\log(N(s))}{\log\left(\frac{1}{s}\right)} \quad \textbf{(2.1)}$$

The differential box-counting can be applied instead of traditional box-counting when an image is considered as a surface where its height is relative to its intensity or its gray value.

In this study, differential box-counting has been applied by considering the image as a 3D surface. Hereby, the speckle images were replaced with the fractal images. The FD of each image was computed and then the time series of it were used to define the matching frequency spectrum for analyzing dynamics [9].

2.2.1 Box-Counting Method

Box-counting method is used to collect data for analyzing complex patterns. This method is performed by splitting the image, object, etc. into smaller box-shaped pieces [20, 21]. This is one of the most often used methods for computing FD of an image [22].

Generally, box-counting technique uses the geometric-step (GS) method. In GS method, the step size is limited to a power of two, hence the potential wasted pixels of the image are prevented [23].

The box-counting method consists of three main steps; generation of a set of box sizes 's' for placing grids on the image, calculation of the number of boxes, N_s , required for complete coverage of the object for each s, and determination of FD by using the slope of points (log(1/s), log(N_s)). In the differential box-counting method, how to calculate N_s is explained below [23].

On each block, (s x s x s') size boxes form a column, where s' refers to the height of any boxes, and G/s'=M/s, where G refers to the amount of gray level. k^{th} and l^{th} boxes represent minimum and maximum gray level in the $(i, j)^{th}$ block, respectively. The boxes covering this block are calculated as:

$$n_s(i,j) = l - k + 1 \qquad \textbf{(2.2)}$$

For the case of all blocks, N_s is calculated as:

$$N_s = \sum_{i,j} n_s(i,j) \qquad \textbf{(2.3)}$$

Then, from the least squares linear fit of log(N_s) versus log (1/s), the FD can be evaluated for each image.

2.3 Algorithm

In this study, the algorithm seen in Figure 2 was used to obtain the heart rates from the speckle videos. After calculating the heart rates, they were compared with the model results that obtained by laser speckle contrast analysis method [4] and then the errors were computed.

2.4 Setups of the Reference Model Results

The model results were obtained by laser speckle contrast method. The speckle images used in the study were obtained by different setups and conditions. At the end of the processes, three different in-vitro and three different in-vivo speckle videos were observed. After recording the videos, they were divided into 220 frames (Figure 3) and analyzed [4].

2.4.1 In-vitro Setup

In addition to the equipment in the in-vivo system, there is also a speaker in this system (Figure 4). The required system was set up and video recordings were taken at different times from the egg shell. In order to simulate the in-vivo environment, egg shell in different color and roughness was glued to the membrane of the speaker. Artificial heart beats (or the vibrations) were obtained by adjustable voltage amplitude and frequency regulated signal generator. Under this periodic excitation, speckle videos were recorded in order to calculate fundamental vibration frequency corresponding to the actual heart rate in in-vivo conditions. These 10-second speckle videos were then divided into 220 frames. Then, the speckle contrast values were calculated from these frames using the speckle contrast analysis method [4].

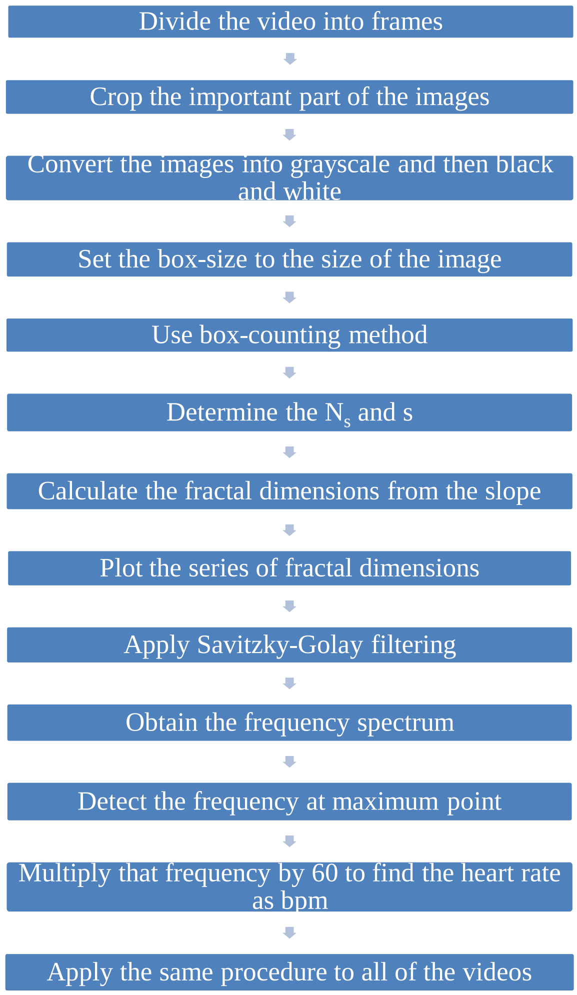

Figure 2. The flowchart of the proposed method

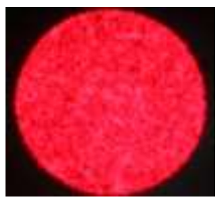

Figure 3. The speckle image obtained from a frame [4].

Two different excitation function types, sinusoidal and ramp were used in this system [4]. In this study, the speckle contrast values calculated from the measurements observed under 1 V – 1 Hz, 1 V – 2 Hz, and 1 V – 3 Hz excitation were used. As an excitation function type, sinusoidal was used in this study.

Celal Bayar University Journal of Science
Volume 16, Issue 1, 2020, p 47-53
Doi: 10.18466/cbayarfbe.513732

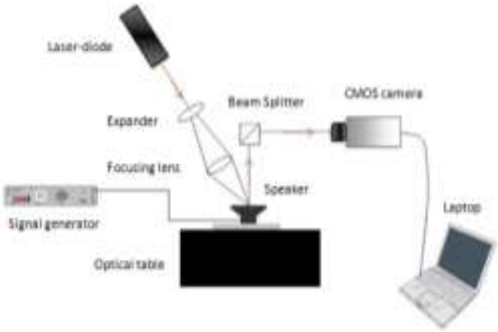

Figure 4. The in-vitro setup [4].

2.4.2 In-vivo Setup

The chicken egg was held in artificial incubator at 37.8±1°C temperature and 50-60% relative humidity for the in-vivo measurements. All procedures were performed in accordance with regulation (2014) of Turkish Ministry of Forest and Water Affairs for experimental animals' ethic board for measuring process. The required system was set up and video recordings were taken at different times from the egg. There were laser-diode source, lens and CMOS camera in this system. These 10-second speckle videos were then divided into 220 frames. Then, the speckle contrast values were calculated from these frames using the speckle contrast method [4].

For the measurement, the egg was taken from the incubator and placed in the measuring hole of the optical setup (Figure 5). To obtain a speckle image, three points on the most pointed part of the egg shell were marked as a triangle, and then a point at the center of the triangle was marked. These marked points were used as targets for each laser light focus. After the speckle contrast analysis, a contrast value was calculated for each image. Finally, at the end of the algorithm, a single heart rate was obtained by taking the average of the heart rates corresponding to the four marked laser targets [4].

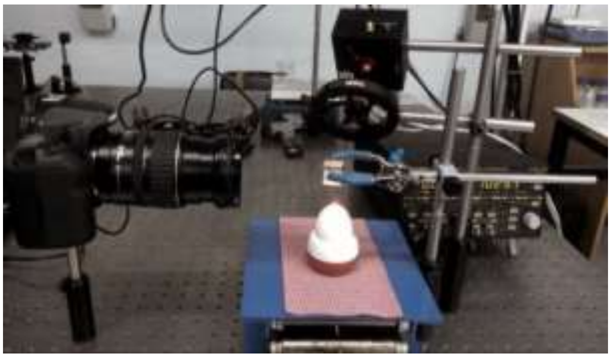

Figure 5. The in-vivo setup [4].

In this study, the speckle contrast values calculated from the measurements observed on 8, 10, and 18 day chicken embryos were used.

3. Results and Discussion

At the end of the process, fractal dimensions and heart rate (in Hz) graphs of chicken embryos were plotted. The heart rates (in Hz) were obtained by applying FFT on the fractal dimensions. After multiplying the X values (Figure 6) in the Heart Rate Graphs by 60, the heart rates were obtained as bpm.

The errors of in-vivo results are less than the errors of in-vitro results. However, according to the all results, the errors are smaller than 10%. Based on this ratio, it can be said that fractal analysis method gives a valid results. So, this method can be used to obtain the heart rate.

3.1 In-vitro Results

Values of the fractal dimensions and the heart rate (in Hz) of 1 Hz data can be seen in Figure 6. By multiplying the X value in Heart Rate Graph by 60, it can be said that the heart rate of 1 Hz data is '54 bpm'. However, according to the contrast analysis method, the heart rate of 1 Hz data is '60 bpm'. As we can see in the Table 1, the error is 10%, here.

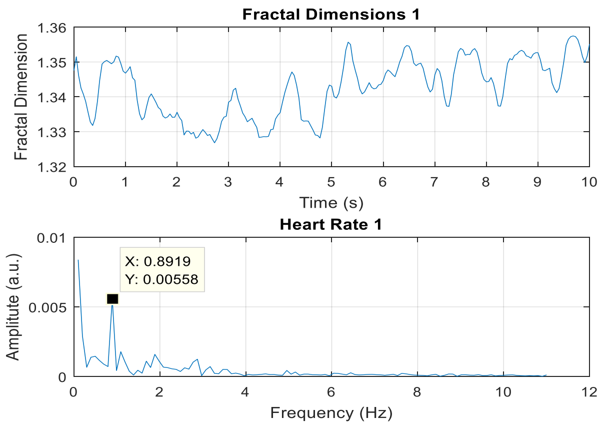

Figure 6. Fractal dimensions and the heart rate for the 1 V – 1 Hz sinusoidal signal.

Values of the fractal dimensions and the heart rate (in Hz) of 2 Hz data can be seen in Figure 7. It can be said that the heart rate of 2 Hz data is '108 bpm'. However, according to the contrast analysis method, the heart rate of 2 Hz data is '120 bpm'. As we can see in the Table 1, the error is 10%, here.

Values of the fractal dimensions and the heart rate (in Hz) of 3 Hz data can be seen in Figure 8. It can be said that the heart rate of 3 Hz data is '162 bpm'. However, according to the contrast analysis method, the heart rate of 3 Hz data is '180 bpm'. As we can see in the Table 1, the error is 10%, here.

Table 1. The comparison of spectral contrast and fractal analysis in-vitro results.

Excitation	Results from speckle contrast analysis		Results from fractal analysis		Error(%)
	Frequency (Hz)	Heart Rate (bpm)	Frequency (Hz)	Heart Rate (bpm)	
1 V – 1 Hz	1	60	0.9	54	10%
1 V – 2 Hz	2	120	1.8	108	10%
1 V – 3 Hz	3	180	2.7	162	10%

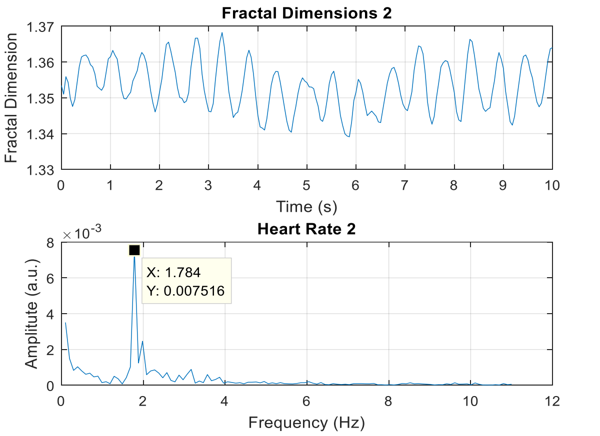

Figure 7. Fractal dimensions and the heart rate for the 1 V – 2 Hz sinusoidal signal.

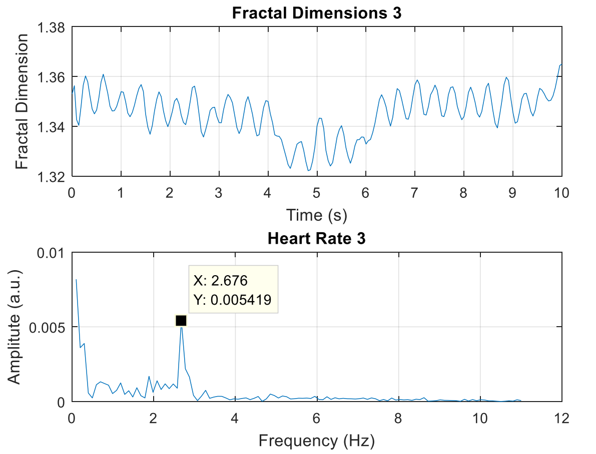

Figure 8. Fractal dimensions and the heart rate for the 1 V – 3 Hz sinusoidal signal.

All the results, comparisons and the errors for the in-vitro study can be seen in Table 1. As seen in Table 1, the speckle contrast method can be used as a reference method, because excitation frequencies can be detected with this method without error. It is thought that the reason of the fixed error (10%) between the two methods is that the excitation wave shape (sinusoidal) and amplitude do not change.

3.2 In-vivo Results

Values of the fractal dimensions and the heart rate (in Hz) of 8 day chicken embryo can be seen in Figure 9. It can be said that the heart rate of 8 day chicken embryo is '143.34 bpm'. However, according to the contrast analysis method, the heart rate of 8 day chicken embryo is '151.86 bpm'. As we can see in the Table 2, the error is 5.6%, here.

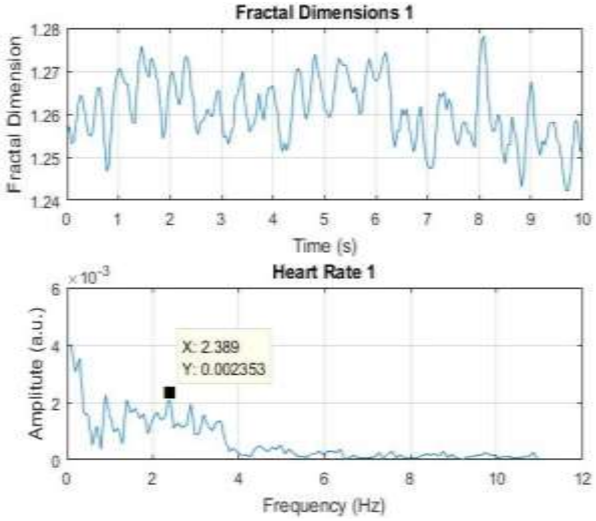

Figure 9. Fractal dimensions and the heart rate of the 8 day chicken embryo.

Values of the fractal dimensions and the heart rate (in Hz) of 10 day chicken embryo can be seen in Figure 10. It can be said that the heart rate of 10 day chicken embryo is '237.84 bpm'. However, according to the contrast analysis method, the heart rate of 10 day chicken embryo is '241.86 bpm'. As we can see in the Table 2, the error is 1.7%, here.

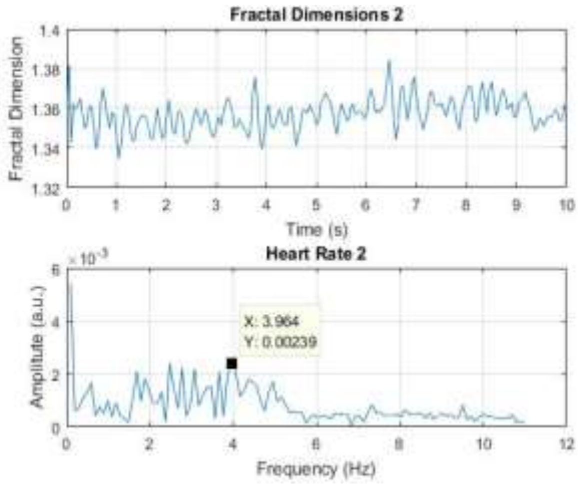

Figure 10. Fractal dimensions and the heart rate of the 10 day chicken embryo.

Celal Bayar University Journal of Science
Volume 16, Issue 1, 2020, p 47-53
Doi: 10.18466/cbayarfbe.513732

Table 2. The comparison of spectral contrast and fractal analysis in-vivo results.

Day of embryo	Results from speckle contrast analysis		Results from fractal analysis		Error(%)
	Frequency (Hz)	Heart Rate (bpm)	Frequency (Hz)	Heart Rate (bpm)	
8	2.531	151.86	2.389	143.34	5.6 %
10	4.031	241.86	3.964	237.84	1.7 %
18	3.656	219.36	3.584	215.04	2 %

Values of the fractal dimensions and the heart rate (in Hz) of 18 day chicken embryo can be seen in Figure 11. It can be said that the heart rate of 18 day chicken embryo is '215.04 bpm'. However, according to the contrast analysis method, the heart rate of 18 day chicken embryo is '219.36 bpm' and the error is 2%.

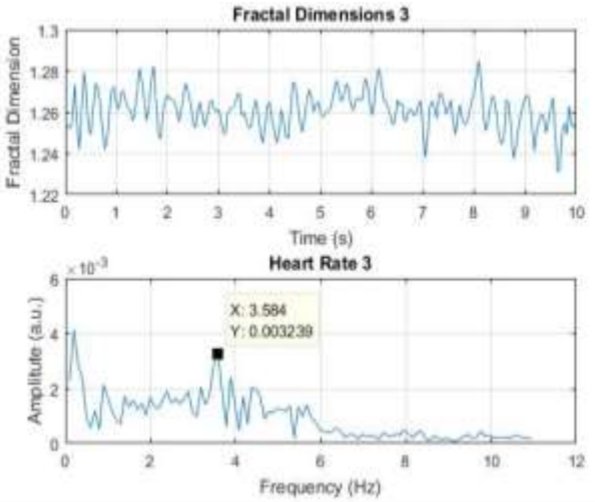

Figure 11. Fractal dimensions and the heart rate of the 18 day chicken embryo.

All the results, comparisons and the errors for the in-vivo study can be seen in Table 2. When the table values are examined, it is observed that daily age of embryos affect error rates. Heart rate in the early period (8 days and before) embryos is not rhythmic because heart rate is not completed yet.

4. Conclusion

In this study, it was investigated the fractal dimension change of in-vitro and in-vivo speckle images to obtain the heart rates and compared it to the model results, which were measured by laser speckle contrast analysis method. At the end, the errors between the results were calculated.

When in-vitro results are examined, it is seen that the results are sufficiently accurate. Therefore, it can be said that if the proposed system is made industrial prototype (like reference system), it can be used in the monitoring of embryo viability in poultry sector.

Author’s Contributions

Ayla Burçin Şişli: Drafted and wrote the manuscript, performed the result analysis.

Arman Jalali Pahnvar: Performed the experiment.

Mehmet Engin: Supervised the experiment’s progress and edited the manuscript.

Erkan Zeki Engin: Supervised the result analysis.and helped in manuscript preparation.

Ethics

There are no ethical issues after the publication of this manuscript.

References

1. Cohn A.E. 1925. Physiological Ontogeny: A chicken embryos. V. on the rate of the heart beat during the development of chicken embryos, *J. Exp. Med.*, 42(3): 291–297.

2. Writing Group Members, et al. 2006. Heart disease and stroke statistics—2006 update: a report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee, *Circulation*, 113.6, e85-e151.

3. Malik, Marek, et al. 1996. Heart rate variability: Standards of measurement, physiological interpretation, and clinical use, *European Heart Journal*, 17(3): 354-381.

4. Pahnvar, A.J. 2016. Estimation of near subcutaneous blood microcirculation related blood flow using laser speckle contrast imaging, Ege University Graduate School of Natural and Applied Sciences Department of Electrical and Electronics Engineering.

5. Laguna, P., et al. 1990. New algorithm for QT interval analysis in 24-hour Holter ECG: performance and applications, *Medical and Biological Engineering and Computing*, 28(1): 67-73.

6. Gottdiener, John S., et al. 2004. American Society of Echocardiography recommendations for use of echocardiography in clinical trials: A report from the American society of echocardiography's guidelines and standards committee and the task force on echocardiography in clinical trials, *Journal of the American Society of Echocardiography*, 17(10): 1086-1119.

7. Boas, David A., and Dunn, A.K. 2010. Laser speckle contrast imaging in biomedical optics, *Journal of Biomedical Optics*, 15(1): 011109.

8. Dainty, J. Christopher, ed. 2013. Laser speckle and related phenomena, *Springer Science & Business Media*, 9.

9. Nemati, M., et al. 2016. Fractality of pulsatile flow in speckle images, *Journal of Applied Physics*, 119(17): 174902.

10. Zhang, X., et. al., A low-cost and smartphone-based laser speckle contrast imager for blood flow, *BIBE 2018; International Conference on Biological Information and Biomedical Engineering*, Shanghai, China, 2018.

11. Escobar, C.P.V., New laser speckle methods for in vivo blood flow imaging and monitoring, Universitat Politecnica de Catalunya ICFO, 2014.

12. Briers, J. D. 2001. Laser Doppler, speckle and related techniques for blood perfusion mapping and imaging, *Physiological Measurement*, 22(4): 35-66.

13. Boeing, G. 2016. Visual analysis of nonlinear dynamical systems: Chaos, fractals, self-similarity and the limits of prediction, Systems, 4(4), 37.

14. Falconer, K., Fractal geometry: mathematical foundations and applications, Wiley, 2013.

15. Tamas, V., Fractal growth phenomena, World Scientific, 1992.

16. Tan, C.O., et al. 2009. Fractal properties of human heart period variability: physiological and methodological implications, *The Journal of Physiology*, 2009, 587.15, 3929-3941.

17. AC03515164, A., ed., Fractals: complex geometry, patterns, and scaling in nature and society, World Scientific, 1997.

18. Gültepe, M.D., and Tek, Z. 2018. Investigation of phase transitions in nematic liquid crystals by fractional calculation, *Celal Bayar University Journal of Science*, 14(4): 373-377.

19. Lopes, R., and Nacim B. 2009. Fractal and multifractal analysis: a review, *Medical Image Analysis*, 13(4): 634-649.

20. Mandelbrot, B.B., The fractal geometry of nature, New York: WH Freeman, 1983, Vol. 173.

21. Iannaccone, P. M., and Khokha, M., Fractal geometry in biological systems: an analytical approach, CRC Press, 1996.

22. Li, J., Qian, D., and Caixin, S. 2009. An improved box-counting method for image fractal dimension estimation, *Pattern Recognition*, 42(11): 2460-2469.

23. So, G.K., Hye-Rim, S., and Gang-Gyoo, J. 2017. Enhancement of the box-counting algorithm for fractal dimension estimation, *Pattern Recognition Letters*, 98: 53-58.