Fractal Characteristic Analysis of Umbilical Artery Blood Flow Using Box Dimension

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Abstract: The umbilical artery blood flow signal contains important information about the state of fetal growth and development, and reflects various problems during pregnancy, such as developmental delay, hypoxia, and maternal hypertension which can be judged by the umbilical blood flow signal. In order to reveal the complex characteristics of umbilical artery blood flow signal and realize the nonlinear analysis of umbilical artery blood flow signal, the actual signals of fetal umbilical artery blood flow were taken as the research object. By analyzing the box dimension of maternal umbilical artery blood flow spectrum, the difference between normal and sick blood flow signals is studied from a new perspective, and the distortion characteristics and pathological characteristics of sick blood flow signals are analyzed.This research shows that the health status of the fetus can be determined by the box dimension of umbilical artery blood flow signal acoustic spectrogram, and it is more convenient to use the box dimension algorithm than the traditional acoustic spectral parameter method.

Keywords: *Umbilical artery blood flow, fractal theory, Box Dimension*

1. Introduction

The umbilical artery is an important channel for the transfer of nutrients and substances from the mother to the fetus[1].The acquisition and analysis of blood flow signals from the umbilical artery of pregnant women can obtain important information about fetal growth and development[2]. At present, ultrasound Doppler technology has been widely used in clinical diagnosis of obstetrics to obtain information related to fetal development, and through the analysis and processing of such information, fetal abnormalities can be detected as early as possible for timely management and early treatment to reduce the probability of congenital diseases and improve the quality of birth.

The umbilical artery flow signal is a typical non-smooth signal with complex time-varying characteristics. The traditional method of analyzing the umbilical artery flow signal is the acoustic spectrum parameter method. The acoustic spectrum parameter method is used to determine whether the umbilical blood signal is abnormal by obtaining the magnitude of the acoustic spectrum parameter values. The common acoustic parameters include the ratio of the maximum value of systolic blood flow velocity to the value of end-diastolic blood flow velocity(*S/D*), pulsatility index (*PI*)and resistance index (*RI*)[3-5].

The envelope of the acoustic spectrogram was used to calculate the corresponding values to obtain the acoustic spectral parameters. Therefore, these parameters could not contain all information of physiological and pathological characteristics, which means that accurate diagnosis cannot be made yet by analyzing only the signal spectrum or time fluctuation pattern. For the analysis of umbilical artery blood signal and the identification of fetal health status, it may be crucial to take into account the choice of a more precise nonlinear signal processing technique.

Fractal is an important discipline for solving

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nonlinear problems, and the related research has been very active in recent years, with good results in chemical, engineering, biological, material and medical fields, especially in biomedical signal processing[6-12].

Researchers at home and abroad have applied fractal theory to deal with many types of nonlinear signals, such as biosignal detection and index extraction, image analysis and assisted functional diagnosis, heart rate variability studies and protein secondary and tertiary structure prediction, etc[13-16].For instance, fractal theory may extract the underlying information of various medical signals by examining the usual nonlinear medical characteristics of brain waves [17], ECG signals [18-19], and CT pictures [20]. Compared with the traditional acoustic spectrum parameter method, fractal theory has more powerful nonlinear information processing capability and can reflect the deep information of signals more comprehensively and thoroughly.

In our research, we introduced fractal dimension for the comparative study of nonlinear umbilical artery blood flow signals based on ultrasound Doppler signal analysis. By analyzing the box dimension of umbilical artery blood flow spectrograms in pregnant women, the differences between normal and pathological blood flow signals were studied from a new perspective, and the distortion characteristics and pathological properties of pathological blood flow signals were analyzed.

2. Fractal dimension and box dimension

2.1 Fractal dimension

Dimension is an important characteristic quantity to describe a geometric object. It is an independent coordinate number weighing quantity needed to determine the position of a point in a geometric object. In Euclidean space, dimension is a natural number[21], while fractal dimension is a fraction or decimal, which usually exceeds its topological dimension and is an invariant under scale transformation[22].

Fractal dimension describes the fractal characteristics of complex things in numerical form, which is intuitive and concise. People can not only distinguish and judge the fractal characteristics of things quantitatively through fractal dimension, but also analyze the fractal characteristics of different things [23].The definition of fractal dimension includes Hausdoeff dimension, self-similar dimension, information dimension, correlation dimension, box dimension and Lyapunov dimension[24].Box dimension is most commonly used in nonlinear analysis of image processing [25].

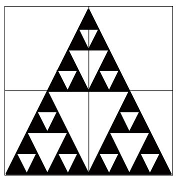
2.2 Box dimension

Box dimension is a metric parameter used to describe the irregularity of complex images. It can be applied not only to one-dimensional time series analysis, but also to two-dimensional images, which has become a widely used method to calculate fractal dimension[26]. The box counting method proposed by Chaudhuri and Sarkar expressed the fractal dimension as[27]:

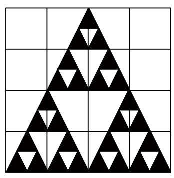
$$D = \ln(N_r) / \ln(1/r) \tag{1}$$

Where D is fractal dimension, r is grid scale; N_r is total number of boxes.

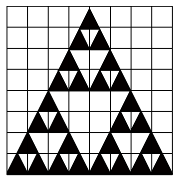
The calculation principle of box dimension is as follows: divide the image with squares of different scales to obtain the effective number of covering squares of the image, and constantly change the size of the squares to count the number of covering squares of the corresponding size to form a series of points. The fractal box dimension of the image is the slope of the line obtained by linear fitting of these points.The calculation principle is shown in Fig.1: set the side length of the square box as 1, which contains the whole Sierpinski triangle gasket. The triangle gaskets are covered by 1/2, 1/4, and 1/8... square boxes with side length respectively, and boxes with side length r_i are obtained one by one, r_i is called grid scale.



(a) Gasket covered with square using side length of 1/2



(b)Gasket covered with square using side length of 1/4



(c) Gasket covered with square using side length of 1/8

Fig.1 Sierpinski triangle gasket box counting method

The box counting algorithm is as follows: first, determine a series of side lengths and sizes as r_i and then calculate the number of boxes covering the full form with this series of boxes $N(r_i)$, and finally $\ln(1/r_i)$ and $\ln(N_{r_i})$ corresponding to different grid scales r_i are obtained, namely, the fractal dimension. The results are shown in table 1 below.

Tab.1 Calculation statistical table for Box dimension method

i	0	1	2	…	n
r_i	r_0	r_1	r_2	…	r_n
$N(r_i)$	$N(r_0)$	$N(r_1)$	$N(r_2)$	…	$N(r_n)$
$\ln(1/r_i)$	$\ln(1/r_0)$	$\ln(1/r_1)$	$\ln(1/r_2)$	…	$\ln(1/r_n)$
$\ln(N(r_i))$	$\ln(N(r_0))$	$\ln(N(r_1))$	$\ln(N(r_2))$	…	$\ln(N(r_n))$

The least square method is used to linearly fit the data set ($\ln(1/r_i)$, $\ln(N(r_i))$), and the straight line as shown in Fig.2 is drawn in the logarithmic coordinates. The slope obtained is the fractal dimension D. $\ln(1/r_i)$ $\ln(N(r_i))$, the algorithm process of calculating fractal dimension of image based on MATLAB is as follows: the image file is read for image gray processing; After edge picking and binarization, the box counting method calculates a series of "square grids with side length (r_i)" and the logarithmic data group ($\ln(1/r_i)$, $\ln(N_{r_i})$) corresponding to "number of covered grids ($N(r_i)$)". After linear fitting, its slope is the fractal dimension (D) of the image.

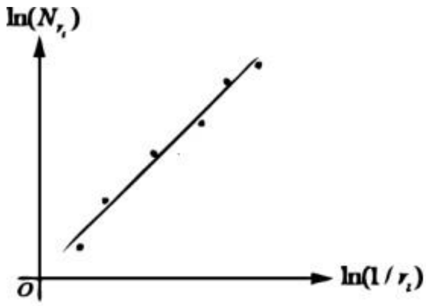


Fig.2 Diagram of box dimension calculation

3. Clinical indicators of umbilical blood flow signals

Upstream and downstream of the umbilical arteries vessels are the fetal heart and the umbilical cord lateral placental vascular bed, which travels in the amniotic fluid, respectively. Under normal conditions, the umbilical artery measures placental blood flow velocity decreases with the progression of pregnancy, whereas the uterine and umbilical arteries are more abundantly vascularized and have relatively fast blood flow velocity during contraction, which ensures normal fetal growth. When pregnancy is abnormal, the uterine and umbilical artery flow is decreased during diastole and there is also antegrade flow during diastole. Additionally, there is a substantial heavy waveform trace during systole. The umbilical artery flow velocity waveform is shown in Fig. 3.

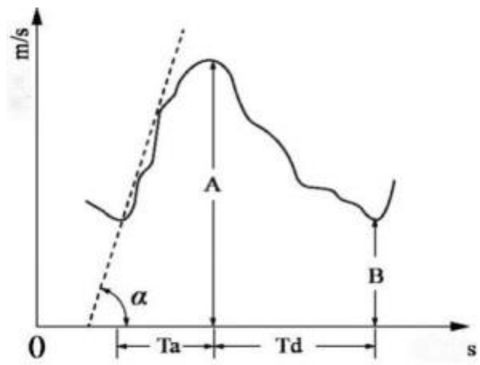


Fig.3 Schematic diagram of umbilical artery blood flow velocity waveform

In Fig.3, the highest point of systole is A and the lowest point of end-diastole is B. B greater than zero means that there is still positive blood flow at end-diastole. T_a indicates systolic acceleration time and T_d indicates diastolic time. The slope of the acceleration wave at the beginning of systole with respect to the baseline is the acceleration angle α, which is related to the intensity of myocardial contraction.

The most commonly used three indices of umbilical artery flow velocity are defined as flowering Fig.4.

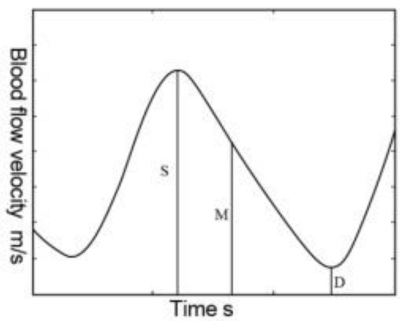


Fig.4 Schematic diagram of the definition of the umbilical artery flow velocity index

3.1 *S/D*

In the Eq.(2), S/D indicates the peak-to-valley ratio; V_p is the highest systolic peak; V_d is the end-diastolic peak; the value S/D reflects the magnitude of the change in blood flow velocity during the cardiac cycle and reflects vascular compliance.

$$S/D = V_p / V_d \qquad (2)$$

Normal values are shown in Fig.5. Clinically high *S/D* values can occur in hyperemesis, hypohydramnios, intrauterine growth retardation (IGUR) and tangled or short umbilical cords.

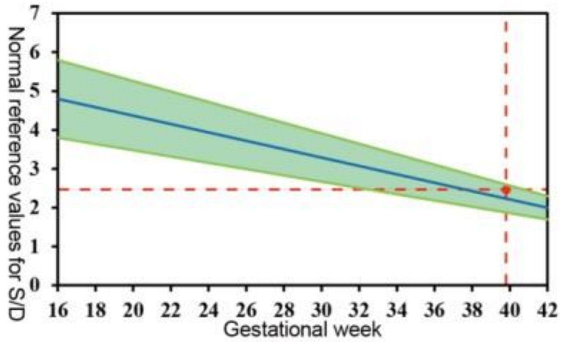


Fig.5 Normal reference values for *S/D*

In Fig.5, the horizontal coordinate is gestational week, the vertical coordinate is *S/D* value, and the green area is the normal reference value.

3.2 *PI*

$$PI = (S-D)/M = (V_p - V_d)\ /\ V_m \qquad (3)$$

Where *PI* indicates the beating index; V_m is the mean value of frequency change.*PI* reflecting vascular elasticity, the more disparate the ratio of the drop in diastolic blood flow velocity to the average velocity of the heart, the greater the *PI* value.

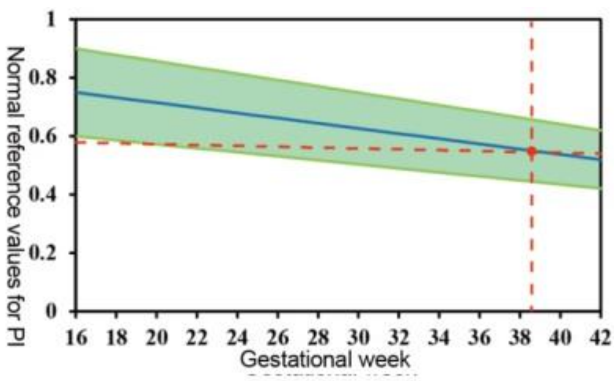


Fig.6 Normal reference values for *PI*

In Fig.6, the horizontal coordinate is gestational week the vertical coordinates is *PI* value, and the green area is the normal reference value.

3. 3 *RI*

$$RI = (S-D)/S = (V_p - V_d)\ /\ V_p \qquad (4)$$

A resistance index called *RI* denotes peripheral resistance. When there is a low impedance cycle, *RI* shows that the blood flow velocity fluctuations have an amplitude that is getting close to the maximal end-systolic blood flow velocity.

In Fig.7, the horizontal coordinate is gestational week, the vertical coordinate is *RI* value, and the green area is the normal reference value.

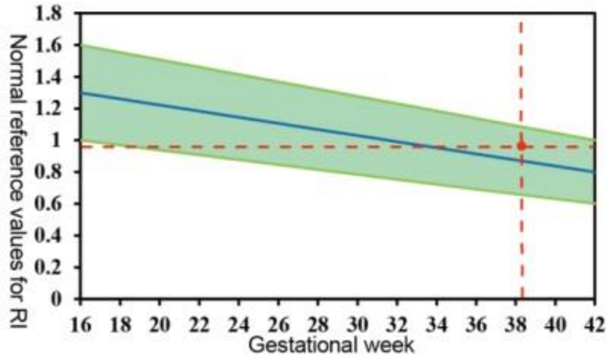


Fig.7 Normal reference values for *RI*

Clinical studies have shown that the *PI, RI* and *S/D* values of the umbilical cord blood flow signal have reasonable intervals of normality for healthy pregnant women and fetuses at different gestational weeks. In traditional clinical diagnosis, the *PI*, *RI* and *S/D* values of umbilical artery blood flow collected by Doppler flow meter are compared with the normal reference values to determine the health status of the foetus and the pregnant women.

4. Data sources and calculations

4.1 Clinical data acquisition

Clinical Data were collected in a hospital in Wuxi City, Jiangsu Province, China, using the MDF-OBM umbilical blood flow detecting device(Fig.8). According to the principle and method of umbilical artery blood flow signal acquisition, fetal umbilical artery blood flow signals of 104 pregnant women aged between 22 and 43 years old and between 26 and 40 weeks of gestation were collected from March to July 2021. Umbilical artery signal spectrogram and detection parameters were obtained. Fig.9 shows the signal spectrum of the umbilical artery flow in a normal pregnant woman at 30 weeks. Fig.10 shows the signal spectrum of the umbilical artery flow in a abnormal pregnant woman at 32 weeks.

Fig.8 MDF-OBM umbilical blood flow detecting device

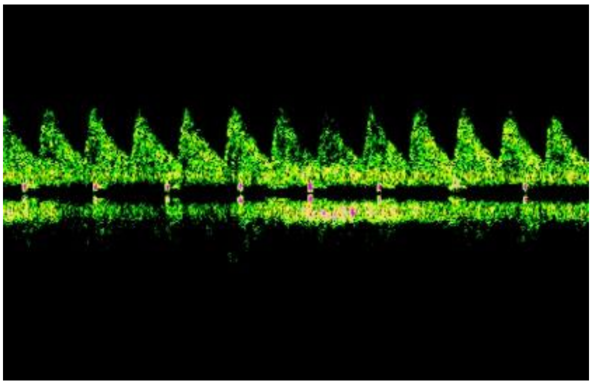


Fig.9 Acoustic spectrum of normal umbilical aretery blood flow in a pregnant woman with30 gestational weeks

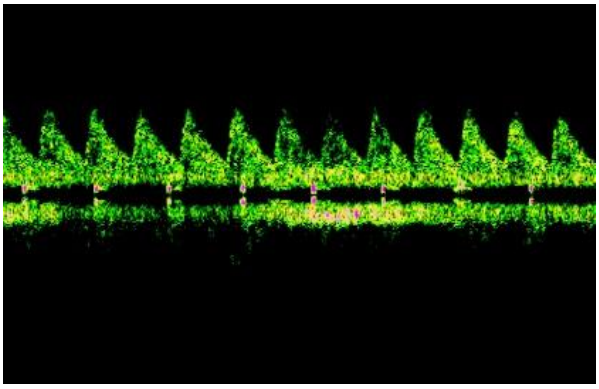
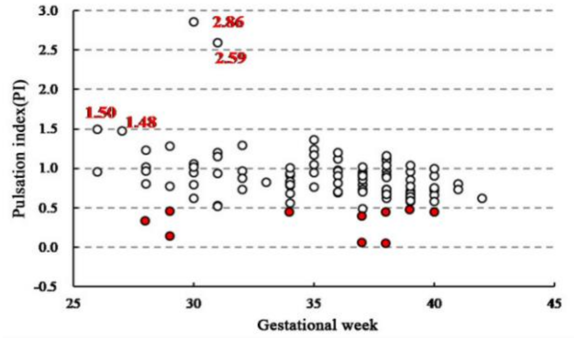
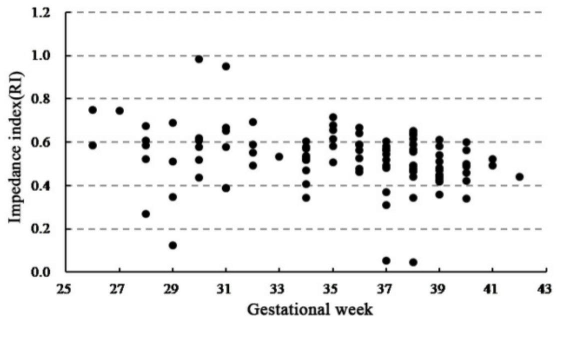


Fig.10 Acoustic spectrum of abnormal umbilical artery blood flow in a pregnant woman with 32 weeks of gestation

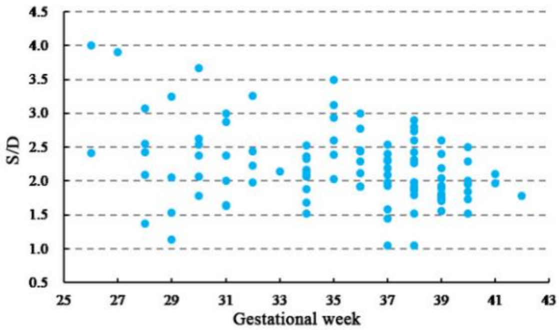
Fig.11 displays the results of the analysis and recording of 104 umbilical artery blood flow *S/D* value, pulsatile index (*PI*), and resistance index (*RI*).



（a） *PI* results



（b）*RI* results



（c） S / D results

Fig.11 Umbilical artery blood flow signal indexes of fetus at different gestational weeks

According to Fig.11, 104 fetal umbilical artery blood flow signals were clinically diagnosed and analyzed, and the results were as follows: 61 cases were normal, and 43 cases were abnormal (or questionable).According to the values, there are 28 exceptions. S / D According to the normal range of pulse index PI, 14 cases had abnormal *PI*, among which 4 cases had higher *PI*. Nine patients presented with other clinical symptoms and low *PI* index. According to the diagnosis of normal *RI* value range, there were 18 cases of abnormal umbilical artery blood flow signal, mainly manifested as low umbilical artery flow resistance.

4.2 Box dimensional analysis of umbilical artery blood flow

The fractal dimension of 104 umbilical artery flow acoustic spectrograms were calculated and analyzed using the box dimension algorithm. Fig.12 below shows the results of the box dimension calculation for the acoustic spectrogram of umbilical artery blood flow signal in 61 normal fetuses.

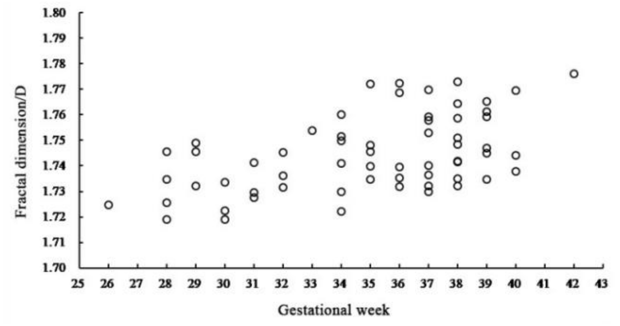


Fig.12 Fractal dimension of normal umbilical artery blood flow acoustic spectrogram

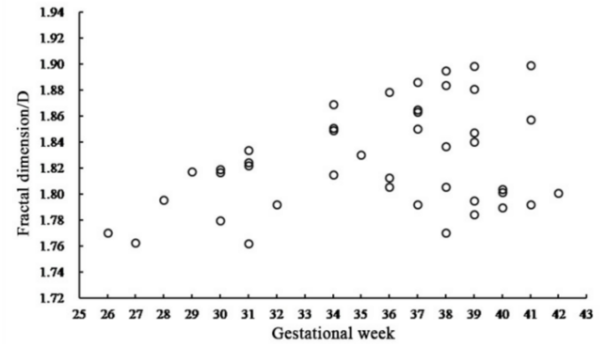


Fig. 13 Fractal dimension of abnormal or doubtful umbilical artery blood flow acoustic spectrogram

The fractal dimension of umbilical artery flow acoustic spectrograms were calculated and analyzed in 43 abnormal pregnancy group or suspected pregnancy group, and the results were shown in Fig.13 below.

According to the Fig.12 above, the fractal dimension of acoustic spectrogram of umbilical artery flow in normal pregnancy group is between 1.718 and 1.776, indicating that gestation age is correlated with fractal dimension, that is, the fractal dimension generally increases with the increase of gestation age.

As can be seen from Fig.13, the fractal dimension of acoustic spectrogram of umbilical artery flow in abnormal (or suspected) pregnancy group ranged from 1.753 to 1.901. It can be obtained that the box dimension of the abnormal umbilical artery flow sonogram is more sensitive than the traditional sonogram parameters by comparing with the clinical diagnostic results. The fractal dimension of umbilical cord blood acoustic spectrogram increased with gestational age, which was similar to that of normal gestational group.

By comparing Fig.12 with Fig.13, it can be seen that, on the whole, the fractal dimension of umbilical artery blood flow acoustic spectrogram in normal pregnancy group is smaller than that in abnormal (or doubtful) pregnancy group. The reasons are as follows: in the abnormal pregnancy group, due to pathological abnormalities, the blood supply of the fetus is not enough or stable, which causes the fluctuation of umbilical artery Doppler detection signal, so its fractal dimension is larger. In the normal pregnancy group, umbilical artery blood supply was more stable and therefore umbilical artery blood flow signal was more stable.

In conclusion, the fractal dimension of acoustic spectrogram of umbilical artery blood flow is correlated with the health of fetus and pregnant woman.There was a correlation between the fractal dimension and gestational age. The fractal dimension can be used to judge the stability of umbilical artery blood flow quantitatively.

5. Conclusion

The fractal characteristics of the umbilical blood flow acoustic spectrogram were analysed and the correlation between the fractal dimension of the umbilical artery blood flow acoustic spectrogram and the number of weeks of gestation and the fetal health status were obtained. The main conclusions are as follows:

(1) The box dimension is easier to calculate than the acoustic spectral parameter method and can reveal the complete information of the umbilical artery blood flow and the box dimension of the abnormal umbilical artery flow sonogram is more sensitive than the traditional sonogram parameters by comparing with the clinical diagnostic results.

(2) Fractal dimension can be used as an indicator for quantitative detection of fetal health status. The results show that the fractal dimension increases with the gestational week and therefore there is a correlation

between the fractal dimension and the gestational week.

(3) The fractal dimension of the umbilical artery flow acoustic spectrogram can reflect the maternal blood supply to the fetus, specifically: the fractal dimension of abnormal pregnant women is higher than that of in healthy pregnant women, so the fluctuation of the umbilical blood flow in abnormal pregnant women is more complicated and more intense.

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