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IMAGE & SIGNAL PROCESSING

The Correlation between Osteoporosis and Blood Circulation Function Based on Magnetic Resonance Imaging

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Abstract
In order to investigate the relationship between changes in blood circulation and bone mineral density (BMD) loss, the characteristic parameters reflecting the function of tissue oxygen metabolism are obtained by means of blood oxygen level-dependent magnetic resonance imaging (BOLD-MRI), image processing and semi-quantitative analysis. The correlation and variance analysis of the characteristic parameters of different BMD groups are carried out, and the physiological parameters of bone marrow blood perfusion are obtained by dynamic enhanced MRI (DCE-MRI). Multivariate logistic regression analysis is carried out with the physiological parameters of blood oxygen metabolism function and bone marrow blood perfusion as independent variables and BMD as dependent variables. It is found that there are significant differences in oxygen metabolism between individual muscles in different BMD groups and between skeletal muscles of different types of muscle fibers. Age, total volume of bone marrow and oxygen metabolism ability of tibial anterior muscle have significant independent effects on osteoporosis. It shows that the changes of blood circulation in bone marrow and surrounding muscle tissue are indeed one of the causes of osteoporosis.

Keywords Osteoporosis · MRI · Blood circulation function

Introduction

Osteoporosis is a systemic osteopathy characterized by reduced bone mass, reduced bone strength and reduced bone mineral density (BMD), resulting in increased bone fragility and prone to fracture [1, 2]. With the increasing trend of social aging, the elderly population in China will gradually increase, and the number of people suffering from osteoporosis will also increase [3]. Osteoporosis will become a more and more serious social problem. It not only threatens the health and quality of life of the elderly, but also brings huge social burden.

Magnetic resonance imaging (MRI) can diagnose osteoporosis and other diseases by detecting BMD, and has sufficient spatial resolution and contrast resolution [4–6]. Blood oxygen level-dependent magnetic resonance imaging (BOLD-MRI) and dynamic enhanced MRI (DCE-MRI) are two commonly used imaging techniques to study tissue blood perfusion and oxygen metabolism [7–9]. BOLD-MRI is a kind of MRI technology, which uses the change of the ratio of oxyhemoglobin concentration to deoxyhemoglobin concentration as a contrast agent. BOLD-MRI can well reflect the function of oxygen metabolism in tissues, while DCE-MRI can reflect the function of tissue blood perfusion.

Two imaging methods are used to explore the relationship between the changes of blood perfusion in bone marrow and surrounding tissues and osteoporosis, so as to reveal the etiological mechanism of osteoporosis in a deeper level and provide scientific basis for the diagnosis and treatment of osteoporosis. Multivariate logistic regression analysis is carried out with the physiological parameters of blood oxygen metabolism function and bone marrow blood perfusion as independent variables and BMD as dependent variables.

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Analytical methods and materials

Research object

The experimental data were provided by by Huangshi Central Hospital, Affiliated Hospital of Hubei Polytechnic University

(Edong Healthcare Group, Huangshi City, China). All the experimental data are authorized by the subjects for medical research. All subjects have no bone metabolic disorders except osteoporosis. A total of 118 samples (mean age of 65.4 ± 4.3 years old) are obtained, including 24 normal subjects (63.3 ± 3.5 years old), 60 osteopenia patients (65.7 ± 4.0 years old), and 34 osteoporosis patients (66.8 ± 5.2 years old). Quantitative CT (QCT) is used to measure the BMD (mg/cm^3) of the L3 lumbar vertebrae of the subjects. The subjects are classified according to the diagnostic criteria for osteoporosis of the lumbar spine QCT established by the International Society of Clinical Bone Density in 2007. The criteria are as shown in Table 1.

Data collection

The MR equipment used in BOLD magnetic resonance experiment is Philips Achieva 3.0 T TX multi-source magnetic resonance with magnetic field strength of 3.0 T [10]. A gradient echo sequence with a deflection angle of 75 degrees is used to obtain T1-weighted and T2* -weighted images of the upper tibia cross-section of the leg. All the images are scanned for 15 min and 2400 images are collected. The time interval for each frame is 0.372 s. The BOLD-MRI experimental procedure of occlusive ischemia is as follows: when cuff relaxes and body is in normal condition, start image acquisition and scanning time is 1 min; start cuff inflation to 50 mmHg contraction, and this stage of scanning lasts for about 5 min; carry out cuff deflation and continue scanning for 9 min to the end. A total of 118 image data samples were collected, and each sample image was 2400 pieces of 176*176-pixel time series images.

The MR equipment used in DCE magnetic resonance experiment is Philips Achieva 3.0 T TX multi-source magnetic resonance with magnetic field intensity of 3.0 T. The L3 vertebral plane of lumbar spine is scanned by T1 weighted gradient echo sequence. Before scanning, injection of contrast agent before elbow is stopped 1 min after the beginning of scanning. Tomography duration is 8.4 min, the interval is 0.88 s, and a total of 544 images are scanned. The imaging parameters were TR/TE = 8.1/3.4 ms, a = 30, FOV (Field of View) = 18 cm, and the pixel resolution was 320*320.

Data processing and analysis based on ROI

Image pre-processing technology is used to complete BOLD image pre-processing such as image denoising, image registration, image enhancement and so on. Then, three tissues of tibialis, soleus and gastrocnemius are selected manually as regions of interest (ROI). It is measured for several times and the mean values are taken to obtain the characteristic signal-time curves of three ROI regions. In order to solve the comparability problem between different tissues of different subjects, the extracted feature signals are normalized, as shown in Formula (1):

$$S_i = \frac{X_i}{X_{baseline}} \tag{1}$$

In Formula (1), S_i is the relative signal value at the moment of i, X_i is the BOLD signal value at the moment of i, and $X_{baseline}$ is the mean of BOLD signal at resting state (the first minute), which is the initial value of BOLD signal at normal state of the subjects and can be used as a characteristic parameter.

After DCE image acquisition, the image is preprocessed according to the preceding steps, and then the bone marrow region is selected as ROI manually to obtain the ROI mean signal-time curve of the bone marrow region.

Feature parameter extraction

The BOLD signal is filtered using Butterworth low pass filter (Fig. 1), and then the slope of each point is calculated. After that, the experimental process is divided into two periods: time period 1: before cuff deflation and time period 2: after cuff deflation. In time period 1, the minimum slope is extracted. By observing the time curve of characteristic signal, it can be judged that the point should be located in the rapid decline stage of BOLD signal. According to the minimum slope point, the inflection point can be found forward, and then the feature point 1 can be determined. Search for the maximum slope point in period 2. Find the inflection point forward according to the maximum slope point, that is, feature point 2. Find the

Table 1 Diagnostic criteria for osteoporosis

Types	BMD (mg/cm^3)
Normal	≥120
Osteopenia	80–120
Osteoporosis	≤80

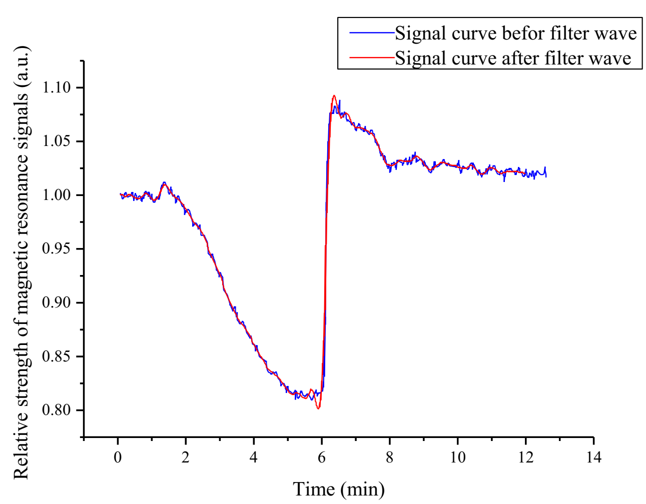

Fig. 1 Butterworth low pass filtering results

Table 2 Meaning of each characteristic parameter

BOLD characteristic parameter		Meaning
BOLD	Baseline	Mean value of T2* signal in resting state without normalization
	MIV (Maximum Inspiratory Volume)	Relative minimum value of signal
	HPV (HPV)	Relative peak value of signal
	Slope	Slope between signal peak and valley
	THIM (Transferring Haemopoietic Inductive Microenvironment)	Time for signal half reduction
	EV (Enterovirus)	Relative average value of end-stage signal in restored state
DCE	A	Total volume of contrast agent in tissue
	kep	Rate constants of diffusion of contrast agents from gap space to plasma
	kel	Change rate of contrast concentration reduction in central indoor
	MaxEn	Relative maximum signal enhancement
	MaxSlope	Maximum rise slope
	AUC (Area under Concentration-Time Curve)	Area under concentration-time curve

inflection point backward, that is, feature point 3. Six characteristic parameters are extracted from BOLD signals. The meanings of each characteristic parameter are shown in Table 2.

Quantitative parameters A, kep and kel are obtained by least square fitting of ROI mean signal-time curve in bone marrow region. The characteristic parameters of the fitting curve are MaxEn, MaxSlope and AUC (Area under concentration-time curve), and MaxSlope is the slope between 90 and 10% of the maximum peak signal of. Table 2 shows the meaning of each parameter.

Data analysis

The correlation analysis method is used to analyze the correlation between the characteristic parameters and between characteristic parameters and BMD. The correlation analysis is a quantitative analysis method. Single factor ANOVA (analysis of variance) analysis is used to compare whether there are significant differences among groups. In this experiment, IBMSPSS 19.0 software is used for statistical analysis. The parameters are expressed as mean ± standard deviation. Finally, taking the skeleton, bone marrow and surrounding muscle tissue as a whole, and using the vascular system as a link, a logistic regression model for osteoporosis is constructed.

Results and discussion

Correlation analysis of BOLD characteristic parameters

As shown in Table 3, Pearson correlation analysis between BOLD characteristic parameters and bone mineral density in the same muscle group is performed by bilateral test. It can be seen that the correlation between BOLD characteristic parameters and bone mineral density is not significant ($P > 0.05$). The P value of THIM parameter of gastrocnemius muscle is less than 0.1, which is close to the statistical significant level. Considering the insufficiency of sample size, it is considered that THIM parameter of gastrocnemius muscle may have a weak correlation with BMD.

Table 3 Correlation between bold characteristic parameters and BMD

Muscle groups		Baseline	Slope (a.u./min)	THIM (min)	HPV	MIV	EV
Tibialis	Correlation coefficient	−0.060	0.078	−0.038	−0.028	−0.033	0.081
	P	0.519	0.399	0.685	0.763	0.724	0.385
Solues	Correlation coefficient	0.002	0.141	−0.147	0.038	−0.124	−0.014
	P	0.983	0.129	0.112	0.686	0.181	0.884
Gastroc	Correlation coefficient	0.061	0.059	−0.155	−0.059	0.010	−0.020
	P	0.512	0.527	0.094	0.526	0.914	0.823

Table 4 ANOVA of age in different BMD groups

Groups	BMD	Age (years)
Normal ($n = 24$)	139.65 ± 13.61	62.3 ± 2.8
Osteopenia ($n = 60$)	98.33 ± 10.95	65.4 ± 4.2
Osteoporosis ($n = 34$)	59.82 ± 14.21	68.7 ± 6.4
P	0.000	0.000

Correlation between age and BMD

Pearson correlation analysis shows that there is a strong correlation between age and BMD in 118 subjects. Pearson correlation coefficient is - 0.48 and P value is 0.000. The results of ANOVA of different BMD groups, as shown in Table 4, show that there are significant differences in age distribution among different BMD groups ($P = 0.000$). In the sample population, the average age of osteoporosis group is higher than that of osteopenia group and normal group in turn. This will interfere with the analysis of the relationship between BMD and BOLD signal quantization parameters. The reason is that there are significant differences in average age between different BMD groups, which will make it impossible to distinguish between changes in parameters caused by differences in BMD or changes caused by differences in age. In order to control variables and make the experiment become a single factor (BMD factor) experiment, it is necessary to exclude the age factor in the analysis based on BMD group.

ANOVA between groups based on BMD

In order to eliminate the interference caused by the age factor of the subjects, some subjects are selected from the subjects as the data source for the experimental analysis. The principle of selection is to select the older subjects from the normal population and the younger subjects from the osteoporosis patients. Finally, 75 cases of sample data are obtained (mean age 63.7 ± 2.7 years old), including 16 normal subjects (63.2 ± 3.0 years old), 42 osteopenia patients (63.8 ± 2.6 years old), and 17 osteoporosis patients (64.0 ± 2.8 years old). Statistical method shows that there is no significant difference in age distribution among different BMD groups. The statistical results of ANOVA analysis of characteristic parameters in different muscle regions among individuals with different BMDs are shown in Table 5.

Table 6 Independent sample T test results of osteoporosis group and normal BMD group

Groups	Baseline	Slope (a.u./min)	THIM (min)	HPV	MIV	EV
Tibialis	0.581	0.041	0.384	0.192	0.625	0.152
Solues	0.384	0.184	0.061	0.532	0.054	0.433
Gastroc	0.456	0.816	0.606	0.029	0.619	0.093

In the BOLD blocking ischemia experiment, there are three stages: the first stage is cuff relaxation. When the muscle is resting, the characteristic parameter related to this stage is Baseline, which indicates the level of muscle oxygen metabolism in normal state; the second stage is cuff tightening, muscle is in ischemia state, and blood flow is blocked and has no input or output. Muscle tissue metabolism can only consume oxygen stored by itself, and the characteristic parameters related to this stage are THIM and MIV; the third stage is muscle reactive congestion, muscle blood recirculates, blood oxygen content rises, and the characteristic parameters related to this stage are HPV, Slope and EV.

In Table 5, the Slope parameters of tibialis anterior muscle BOLD signal show significant difference. From normal bone mass to bone mass reduction and then to osteoporosis patients,

Table 5 ANOVA results of characteristic parameters among different BMD groups

Groups		Baseline	Slope (a.u./min)	THIM (min)	HPV	MIV	EV
Tibialis	Normal	192.4 ± 61.3	1.278 ± 0.514	2.212 ± 0.514	1.086 ± 0.073	0.771 ± 0.060	1.032 ± 0.104
	Osteopenia	187.5 ± 74.1	1.070 ± 0.470	1.856 ± 0.727	1.055 ± 0.057	0.743 ± 0.084	0.990 ± 0.073
	Osteoporosis	192.4 ± 61.3	0.893 ± 0.474	1.983 ± 0.910	1.057 ± 0.050	0.758 ± 0.088	0.996 ± 0.051
	P Value	0.851	0.047	0.260	0.211	0.460	0.165
Solues	Normal	157.5 ± 48.4	1.080 ± 0.247	1.947 ± 0.350	1.063 ± 0.053	0.560 ± 0.078	0.992 ± 0.064
	Osteopenia	149.5 ± 50.6	1.014 ± 0.287	2.109 ± 0.513	1.084 ± 0.049	0.612 ± 0.110	1.015 ± 0.051
	Osteoporosis	141.6 ± 54.1	0.962 ± 0.247	2.332 ± 0.721	1.073 ± 0.031	0.629 ± 0.115	1.008 ± 0.045
	P Value	0.674	0.464	0.124	0.311	0.144	0.341
Gastroc	Normal	148.7 ± 45.0	0.634 ± 0.231	2.041 ± 0.527	1.027 ± 0.054	0.711 ± 0.067	0.974 ± 0.063
	Osteopenia	143.0 ± 52.6	0.620 ± 0.233	2.010 ± 0.773	1.040 ± 0.077	0.718 ± 0.123	0.963 ± 0.116
	Osteoporosis	135.9 ± 52.1	0.652 ± 0.208	2.174 ± 0.887	1.065 ± 0.042	0.560 ± 0.178	1.010 ± 0.056
	P Value	0.768	0.888	0.756	0.193	0.744	0.236

Table 7 ANOVA results of characteristic parameters between muscle groups (gastrocnemius)

Groups	Baseline	Slope (a.u./min)	THIM (min)	HPV	MIV	EV
Tibialis	196.5 ± 71.7	1.051 ± 0.507	1.950 ± 0.710	1.063 ± 0.062	0.759 ± 0.082	0.998 ± 0.076
Solues	155.5 ± 50.5	0.978 ± 0.294	2.108 ± 0.588	1.080 ± 0.058	0.619 ± 0.114	1.012 ± 0.056
Gastroc	147.2 ± 48.9	0.637 ± 0.233	2.068 ± 0.708	1.042 ± 0.062	0.709 ± 0.107	0.969 ± 0.093
P Value	0.000	0.000	0.165	0.000	0.000	0.000

the Slope values gradually decrease, reflecting the recovery rate of blood oxygen metabolism during the reactive hyperemia of the leg. In other words, with the decrease of BMD, the time for BOLD signal returning to peak value becomes longer. Oxygen metabolism ability of osteoporosis patients is weaker than that of normal people. The possible reasons are low capillary density in osteoporosis patients resulting in relatively low blood volume or low myoglobin content, thus leading to lower oxygenation status than that of normal people. Both of these conditions may lead to a significant decrease in Slope value. No significant statistical difference is found in other parameters.

As shown in Table 6, except osteopenia group, independent sample T test results between normal group and osteoporosis group are obtained. The values in the table are *P* values of comparison between the two groups. As can be seen from the table, there is a significant difference in HPV of gastrocnemius ($P < 0.05$), and HPV value increases with the decrease of BMD. There have been studies comparing the results of BOLD signals of the elderly (64.0 ± 6.4 years old) with that of the young (30.3 ± 6.5 years old). It is found that the peak time of the reactive hyperemia in the elderly is longer than that in the young (Slope value decreases, and the peak level of HPV is higher). Age is excluded from the experimental interference factors, which can explain that the effect of osteoporosis on blood oxygen metabolism may be similar to the mechanism of age on blood oxygen metabolism.

According to the experimental results, it can be inferred that the capillary density in skeletal muscle of patients with osteoporosis is lower than that of normal people. The decrease of capillary density will lead to the decrease of blood volume, and consequently the blood perfusion storage in muscle will decrease. HPV represents that the total blood content and oxygen saturation in muscle will also decrease. However, contrary to the fact, HPV value of the patients with osteoporosis and the elderly is higher than that of the normal people and young people. It is inferred that there is a compensatory mechanism of blood oxygen metabolism. Under normal conditions, the blood oxygen metabolism of osteoporosis patients is maintained at a lower level, and the oxygen content of myoglobin transport and storage is lower than that of the normal people. This can be confirmed by the decrease of BMD from Baseline. Under normal conditions, namely reactive hyperemia stage, myoglobin transport and storage capacity of oxygen increases, so that the ratio of BOLD signal, namely HPV value, is higher than that of normal people.

Table 8 Pearson correlation analysis between DCE characteristic parameters and BMD

	MaxEn	MaxSlope	AUC	A	kep	kel
BMD	0.35	0.19	0.25	0.35	−0.03	−0.01
P value	0.00	0.05	0.00	0.00	0.71	0.93

ANOVA between muscle groups

From Table 7, it can be seen that the parameters Baseline, Slope, HPV, MIV and EV show significant differences in different muscle groups ($P < 0.05$), which is related to the composition of muscle fibers in different muscles. The soleus muscle is a slow muscle, which mainly contains type I muscle fibers. Its myoglobin content and capillary density are high and its blood volume and total oxygen content are high. Therefore, the BOLD signal value is high and its oxygen metabolism ability is strong. Baseline, Slope and HPV are higher than gastrocnemius muscle. The gastrocnemius muscle is a fast muscle. The type of muscle fibers is composed of type II muscle fibers. The capillaries and myoglobin content are relatively low, resulting in low blood volume and total oxygen content. The BOLD signal value of gastrocnemius muscle is relatively small and its oxygen metabolism ability is weaker than that of tibialis anterior muscle and soleus muscle.

DCE characteristic parameter analysis

From Table 8, it is seen that there is a significant linear relationship between the parameters MaxEn, MaxSlope, AUC, A, A*kep and BMD ($P < 0.05$), which indicates that these characteristic parameters of DCE can be used as a characteristic variable of BMD to reflect the BMD situation. Table 9 shows the ANOVA analysis of characteristic parameters of different BMD groups. Among them, the parameters Max En and A show significant differences among different groups. Both parameters decrease significantly with the decrease of BMD [11]. Among them, parameter A reflects the volume of blood in bone marrow, including blood vessels (arterioles, capillaries and venous sinuses) and extravascular space. However,

Table 9 ANOVA analysis of DCE characteristic parameters in different bone density groups

Groups	MaxEn	MaxSlope	AUC	A	kep	kel	A*kep
Normal	0.32 ± 0.08	1.34 ± 0.44	0.28 ± 0.10	0.35 ± 0.08	3.87 ± 1.05	0.07 ± 0.01	1.34 ± 0.41
Osteopenia	0.27 ± 0.07	1.17 ± 0.51	0.28 ± 0.10	0.29 ± 0.07	3.90 ± 1.38	0.07 ± 0.01	1.17 ± 0.59
Osteoporosis	0.24 ± 0.05	1.05 ± 0.34	0.22 ± 0.09	0.27 ± 0.05	3.97 ± 1.28	0.07 ± 0.02	1.05 ± 0.34
P Value	0.001	0.145	0.075	0.001	0.959	0.661	0.145

because the age of different bone mineral density tissues has significant differences, it is not easy to judge whether the decrease of bone marrow volume is caused by osteoporosis or by the increase of age, which remains to be further studied and analyzed.

Logistic regression model of osteoporosis

In order to screen variables for subsequent multivariate logistic regression analysis, it is necessary to exclude independent variables without statistical significance. Firstly, one-way ANOVA for variables is carried out. One-way ANOVA of independent variables is shown in Table 10.

Table 10 One-way ANOVA of independent variables

Number	Variables	*P* value
1	Baseline_TIB	0.752
2	Slope_TIB	0.047
3	THIM_TIB	0.426
4	HPV_TIB	0.828
5	MIV_TIB	0.624
6	EV_TIB	0.265
7	Baseline_SOL	0.657
8	Slope_SOL	0.299
9	THIM_SOL	0.410
10	HPV_SOL	0.364
11	MIV_SOL	0.464
12	EV_SOL	0.341
13	Baseline_ GAS	0.771
14	Slope_GAS	0.370
15	THIM_GAS	0.034
16	HPV_GAS	0.633
17	MIV_GAS	0.530
18	EV_GAS	0.265
19	MaxEn	0.037
20	MaxSlope	0.047
21	AUC	0.156
22	A	0.031
23	kep	0.460
24	kel	0.533
25	A*kep	0.491
26	Age	0.097

However, variables without statistical significance in one-way ANOVA may not have statistical significance in multivariate analysis, so the *P* value index is relaxed, and variables with $P < 0.1$ are selected into logistic regression analysis. Variables with *P* value less than 0.2 are Slope_TIB, THIM_GAS, MaxEn, MaxSlope, A, and Age [12].

Table 11 is a table of correlation analysis among six independent variables, from which it can be seen that A, maxEn and maxSlope have significant strong correlation ($P = 0.000$, correlation coefficient > 0.6). In order to eliminate the collinearity among independent variables, the relationship among three variables and their physiological significance are taken into account, and parameters MaxEn and MaxSlope are eliminated. The four independent variables of logistic regression analysis are Age, Slope_TIB, THIM_GAS and A.

In order to make the experimental data of different experiments or different measurement units comparable, each parameter is standardized by standard deviation standardization method.

$$y_i = \frac{x_i \, \overline{x}}{SD} \tag{2}$$

In Formula (2), y_i denotes the parameters calculated by the new definition, $\overline{x}$ denotes the mean values of the parameters in the normal BMD group, and *SD* denotes the standard deviation of the parameters in the normal BMD group. y_i can be used to represent the number of standard deviations from the normal population, which can more intuitively reflect the significance of the parameter values.

The results of logistic stepwise regression analysis are shown in Table 12. Among the four parameters, there are three variables with $P < 0.05$, respectively Age, Slope_TIB and A. The Logistic regression equation for osteoporosis is shown in Formula (3) and Formula (4):

$$Logit(BMD = 0) = 2.370 + 0.485Age - 0.6Slope\_TIB - 0.545A \tag{3}$$

$$Logit(BMD = 1) = 5.400 + 0.485Age - 0.6Slope\_TIB - 0.545A \tag{4}$$

The likelihood ratio test of regression model is conducted and it has statistical significance ($\chi^2 = 18.481$, $P < 0.001$).

Table 11 Analysis of correlation among independent variables

		Age	Slope_TIB	THIM_GAS	A	MaxEn	MaxSlope
Age	Correlation coefficient	1	−0.028	0.007	−0.100	−0.107	−0.144
	P		0.820	0.955	0.411	0.379	0.234
Slope_TIB	Correlation coefficient	−0.028	1	−0.099	0.050	0.060	0.472
	P	0.820		0.422	0.686	0.627	0.099
THIM_GAS	Correlation coefficient	0.007	−0.099	1	−0.081	−0.069	0.419
	P	0.955	0.422		0.507	0.573	0.603
A	Correlation coefficient	−0.100	0.050	−0.081	1	0.997	0.603
	P	0.411	0.686	0.507		0.000	0.000
MaxEn	Correlation coefficient	−0.107	0.060	−0.069	0.603	1	0.652
	P	0.379	0.627	0.573	0.000		0.000

Parallel line test of the model is carried out and the test result is $P > 0.05$. The regression equation is parallel to each other, which can use ordered multi-classification logistic regression. From the logistic regression equation, it is seen that parameters Age, Slope_TIB and A have independent effects on BMD. In the previous single factor analysis, it is also found that AGE, Slope_TIB, A and other parameters are significantly different in different BMD groups. However, the confounding effects of other factors and their interactions cannot be excluded. Multivariate logistic regression analysis can be used to evaluate the independent role of factors studied for osteoporosis production. Age has a *P* value of 0.097 in one-way ANOVA and an OR value shows significant effect in multivariate analysis, which is 1.624, indicating that age is a risk factor for osteoporosis. With age increasing by one standard deviation unit (3.2 years old), the risk of osteoporosis is 1.624 times as high as before, which is consistent with the actual situation. The OR values of Slope_TIB and blood perfusion parameter A of bone marrow are less than 1, which indicates that Slope_TIB and A are protective factors for osteoporosis. The parameter A represents the volume of blood in bone marrow including the space of blood vessels (arterioles, capillaries and venous sinuses) and the extravascular space, and the decrease of volume of blood in bone marrow will cause osteoporosis. The probability of osteoporosis is 1.8 times as high as before for every standard deviation of parameter A. Parameter Slope_TIB reflects the ability of oxygen metabolism of tibial anterior muscle in skeletal muscle. The bigger the parameters are, the higher the oxygen perfusion reserve of muscle in reactive hyperemia stage is. The later the oxygen saturation is reached, the better the oxygen metabolism ability of blood is. It shows that the decrease of oxygen metabolism ability of muscle is also one of the important factors causing osteoporosis. The probability of osteoporosis is 1.72 times as high as before for every standard deviation reduction in the value of parameter Slope_TIB.

Conclusion

A set of analysis methods of weighted sequence image processing and analysis, ROI analysis and characteristic parameter graph of magnetic resonance are established to obtain the information of skeletal muscle oxygen metabolism function. Then, combined with the physiological parameters of bone marrow blood perfusion obtained by DCE-MRI experiment, the different characteristic parameters obtained by BOLD-MRI and DCE-MRI are independent variables. Multivariate logistic regression analysis is carried out for dependent variables among different BMD groups, and it is used to obtain the regression model of the influencing factors of osteoporosis. This study suggests that there is a relationship between skeletal muscle oxygen metabolism function and BMD, and that chronic muscle vascular function may deteriorate in patients with osteoporosis. It is also found that age, bone marrow volume and gastrocnemius muscle oxygen metabolism have significant independent effects on osteoporosis.

Table 12 Multivariate logistic regression analysis of osteoporosis

Variables	β	SE	Wald	*P*	OR	95% confidence interval
AGE	0.485	0.253	3.619	0.047	1.624	1.012–2.686
Slope_TIB	−0.600	0.262	5.247	0.022	0.549	0.329–0.919
THIM_GAS	0.357	0.356	2.627	0.105	1.429	1.000–2.886
A	−0.545	0.249	4.522	0.033	0.580	0.368–0.96

The relationship between osteoporosis and blood circulation function is qualified, which makes up for the gap in the study of the physiological mechanism of the relationship between osteoporosis and blood circulation function in China.

Compliance with ethical standards

Conflict of interest Author Xiaoming Qiu declares that he has no conflict of interest. Author Yufei Fu declares that he has no conflict of interest. Author Jiao Chen declares that he has no conflict of interest. Author Yu Ye declares that he has no conflict of interest. Author Zhen Wang declares that he has no conflict of interest. Author Xianfang Ming declares that he has no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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