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Original Article

Determination of Residual Stress with Diffusion MR Method in Cortical and Trabecular Sections of Human Vertebral Bone Tissue

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ABSTRACT

Objective: The aim of this study was to develop a new method for the determination of residual stress by measuring diffusion coefficient in human vertebral bone tissue using the diffusion MRI method.

Methods: For this study, 75 healthy individuals were recruited and divided into three groups. There were 25 individuals in each group. The age group consists the following: group 1, 15-20; group 2, 40-50; and group 3, 60-70. The vertebrae images of subjects were taken by diffusion MRI. Diffusion coefficient of cortical and trabecular regions was measured on these images, and the results were compared using the Kruskal–Wallis statistical method. Bone densitometry of all subjects was measured, and groups were compared using ANOVA.

Results: The cortical and trabecular diffusion coefficients were compared in groups 1-3. Both diffusion parameters were significantly decreased in groups 1-3. This indicates a decrease in diffusion with increasing age. In the measurements performed with X-ray densitometry, dual energy X-ray absorptiometry (DXA) and Crush values were found to be increased significantly. No significant change was observed in bone mineral content (BMC), bone mineral density (BMD), T, and Z values. Cortical and trabecular diffusion coefficients were decreased with age. BMD and BMC values did not change, but DXA and Crush values were observed to increase with age. Although BMD and BMC values did not change, diffusion reduction may be associated with increasing age.

Conclusion: The results of this study indicate that residual stress that causes nanocrush and later fragility in bone tissue can be determined by measuring diffusion coefficient through the diffusion MR method.

Keywords: Residual stress, vertebral bone, diffusion coefficient, diffusion MR

INTRODUCTION

Stress occurring in materials without any application of external force is defined as residual stress. Residual stress occurs in the natural processes of the material. It occurs during the natural life cycle in the bone tissue and increases the fragility of the bone. The presence of residual stress in bone tissue was reported by Tadano and Okashi.[1] Yamada and Tadano[2] have measured residual stress in bone tissue using the X-ray diffraction method.

In all of the residual stress measurement techniques, the measured samples are taken into the measurement medium in small pieces, and the measurement is made. These methods cannot make the measurement on live tissue. The cortical bone has a complex structure shaped by collagen matrix and mineral particles such as hydroxyapatite. Hydroxyapatite (HAp) in the bone tissue has a hexagonal crystal structure, and X-ray scattering can be used to measure the interplanar spacing of HAp crystals.[3–8]

When the bone tissue is deformed, the variation of the lattice planes of the HAp crystals always changes proportionally. The distance between the lattice planes of the HAp crystals was shown to vary proportionally to the deformation of the bone tissue.[6] HAp crystal tension can be calculated by the deformation of interplanar spacing.[3,7]

Live tissues respond to mechanical stress through potential changes in volume and growth.[9] Measurements by X-ray diffraction in rabbit tibiofibular showed residual stress of 0.1 MPa even in the natural posture.[10] Tanaka and Adachi[11] reported a 2 MPa residual stress in the natural position in cattle coccygeal vertebrae.

According to the results of the study, it is possible to measure residual stress levels that increase the fragility of human vertebral bone tissue in vivo by the diffusion MR method. Known methods for measuring residual stress only measure in vitro. This study will be a new method in this subject.

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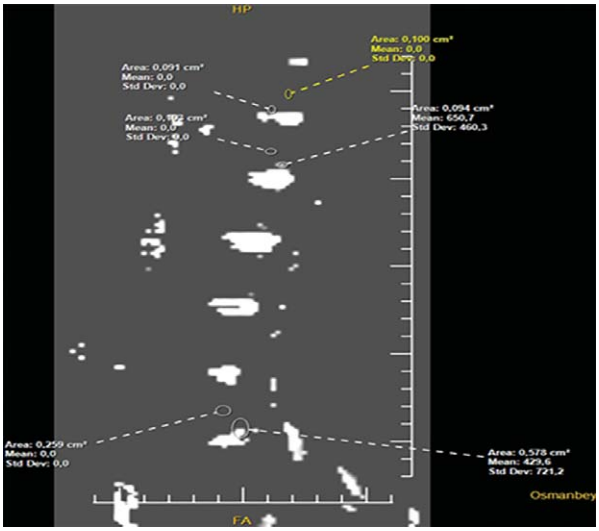
Figure 1. Measurement of diffusion coefficient in vertebra in diffusional MR.



According to the current literature, residual stress in the vertebral bone tissue is measured by in vitro methods, mainly by the X-ray diffraction method. It is not possible to measure living tissue in vivo. This study aims to determine the residual stress measurement in living tissue with the diffusion coefficient.

METHODS

For this study, a total of 75 healthy subjects (individuals) without any bone problems were selected and divided into three groups with 25 individuals in each group. Subjects were divided based on the age group: group 1, 15-20; group 2, 40-50; and group 3, 60-70. The subjects were not administered any drugs, and the vertebrae images were taken by diffusion MRI (Siemens Senfoni 1.5T). Diffusion coefficients of the same regions were measured on these images, and the results were compared with the appropriate statistical method (Kruskal–Wallis). In addition, bone densitometry of all subjects was measured, and groups were compared using ANOVA (Figure 1).

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

All procedures in this study involving human participants were performed in accordance with the Ethical Standards of the Institutional Review Board and National Research Committee with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Ethical committee approval was received from the Medical Faculty Ethics Committee of Harran University (April 1, 2016, No. 03-12).

Main Points

- Residual stress is a phenomenon that causes cracks in bone tissue and subsequent fractures.
- Residual stress cannot be measured in living bone tissue using current methods.
- In this study, a method has been developed to measure residual stress in living bone tissue using the diffusion MR method.

RESULTS

Diffusion MR images of cortical and trabecular sections of C2, C7, T1, T12, L1, and L5 vertebrae were taken for the age groups of 15-20 (group 1), 40-50 (group 2), and 60-70 (group 3). Diffusion measurements were made in these sections. The k and m diffusion values were determined in these vertebrae of each group. C2, C7, T1, T12, L1, and L5 vertebrae of k and m diffusion MR values were compared with groups 1-3. In addition, group 1 and group 2, group 1 and group 3, and group 2 and group 3 were compared with each other separately (Tables 1 and 2).

For each sample, dual energy X-ray absorptiometry (DXA), Crush, bone mineral content (BMC), bone mineral density (BMD), T, and Z values were measured (Table 3). These values were also compared between groups. In the 60-70 age group, it was found that the crush value, which is an indicator of fragility, had increased significantly according to the DEXA measurements (8.23), and also the Z score result was found to have decreased significantly in the older age group (–1.06), compared with groups 1 and 2, which were not significant.

DISCUSSION

The presence of residual stress in bone tissue was reported by Tadano and Okashi.[1] Yamato and Tadano[2] measured residual stress in bone tissue by the X-ray diffraction method.

The cortical bone has a complex structure shaped by collagen matrix and mineral particles such as HAp. HAp in the bone tissue has a hexagonal crystal structure, and X-ray scattering can be used to measure interplanar spacing of HAp crystals.[3–8]

When the bone tissue is deformed, the variation of the lattice planes of the HAp crystals always changes proportionally. The distance between the lattice planes of the HAp crystals was shown to vary proportionally to the deformation of the bone tissue.[6] HAp crystal tension can be calculated by deformation of interplanar spacing.[3,7]

Live tissues respond to mechanical stress through potential changes in volume and growth.[9] Measurements by X-ray diffraction in rabbit tibiofibular showed residual stress of 0.1 MPa even in the natural posture.[10] Tanaka and Adachi[11] reported a 2 MPa residual stress in the natural position in cattle coccygeal vertebrae.

According to the current literature, residual stress in vertebral bone tissue is measured by in vitro methods, mainly by the X-ray diffraction method. It is not possible to measure living tissue in vivo. This study aims to determine the residual stress measurement in living tissue with the diffusion coefficient.

In the results of the evaluation, diffusion MR images of three different groups were taken, and diffraction coefficients k and m were determined separately in C2, C7, T1, T12, L1, and

Table 1. Measured k Diffusion Values of the C2, C7, T1, T12, L1, and L5 Vertebrae Cortical Sections in Groups 1-3

	Group 1	Group 2	Group 3	*P*
C2	254 ± 160	257 ± 138	197 ± 123	.152
C7	170 ± 164	182 ± 94	108 ± 92	.028
T1	196 ± 135	175 ± 95	156 ± 59	.028
T12	147 ± 25	100 ± 95	106 ± 83	.023
L1	153 ± 75	127 ± 80	78 ± 57	.004
L5	143 ± 29	100 ± 83	65 ± 20	.000

It is observed that k diffusion values in all vertebrates, except C2, decreased significantly with increasing age.
C2, C7: cortical 2 and 7 vertebral bones; T1, T12: thoracal 1 and 12 vertebral bones; L1, L5: lomber 1 and 5 vertebral bones.

Table 2. Measured m Diffusion Values of the C2, C7, T1, T12, L1, and L5 Vertebrae Medullary (Trabecular) Sections in Groups 1-3

	Group 1	Group 2	Group 3	*P*
C2	450 ± 145	344 ± 146	294 ± 152	.022
C7	420 ± 171	317 ± 152	241 ± 160	.010
T1	234 ± 124	312 ± 134	236 ± 176	.014
T12	254 ± 43	182 ± 159	147 ± 93	.042
L1	240 ± 99	212 ± 62	110 ± 92	.000
L5	193 ± 29	185 ± 59	90 ± 37	.000

It is observed that m diffusion values in all vertebrae decreased significantly with increasing age.
C2, C7: cortical 2 and 7 vertebral bones; T1, T12: thoracal 1 and 12 vertebral bones; L1, L5: lomber 1 and 5 vertebral bones.

Table 3. DXA, Crush, BMC, BMD, T, and Z Values Measured in the Vertebrae of Groups 1-3

	Group 1		Group 2		Group 3		
	Mean	SD	Mean	SD	Mean	SD	*P*
DXA	93	12.8	95	12.7	109	23.97	.010
Crush	2.4	2	3.8	0	7.9	4.2	.025
BMC	56	11	60	13	57	14	.610
BMD	0.97	0.13	1.0	0.13	1.06	0.21	.927
T	-0.7	1.2	-0.6	1.1	-0.5	1.7	.864
Z	-0.69	1.2	-0.78	1.1	-1.06	2.05	.029

It is observed that DXA and Crush values increase significantly with age. There was no significant change in BMC, BMD, and T values, but the Z score result was found to be increased significantly in the older age group, compared with groups 1 and 2.
DXA, dual energy X-ray absorptiometry; BMC, bone mineral content; BMD, bone mineral density; T, maximum bone mass; Z, expresses the mean BMD difference of controls in the same gender and age group as the standard deviation of the patient's BMD results.

L5 vertebrae. In all groups, m diffusion coefficient was found to be greater than k diffusion coefficient on average. It was observed that the diffusion coefficients of C2, C7, T1, and T12 vertebrae were decreased in the 60-70 age group subjects, and both the m and k diffusion coefficients were observed to decrease significantly on average in L1 and L5 vertebra cortical in particular. These results indicate that the loading in the lumbar region is greater, resulting in higher residual stress in this region.

In the 60-70 age group, it was found that the crushing value, which is an indicator of fragility, increased significantly according to the DEXA measurements (8.23), and also the Z score result was found to decrease significantly in the older age group (–1.06), compared with groups 1 and 2, which were not significant. It was about –0.69 and –0.78 in the other groups. Full fragility occurs in values smaller than –2.5. There was no significant difference between the groups in terms of BMC and BMD values.

CONCLUSION

Residual stress is a physical factor that occurs in natural life processes and causes nanocracks in bone tissue. The aim of this study was to develop a new method for measuring residual stress in living bone tissue. In this study, we have developed a new method for the measurement of residual stress in live vertebral bone tissue using the diffusion MR method.

Ethics Committee Approval: Ethical committee approval was received from the Medical Faculty Ethics Committee of Harran University (April 1, 2016, No. 03-12).

Informed Consent: Informed consent was obtained from the patients who participated in this study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept - C.S.; Design - C.S.; Supervision C.S.; Resources - C.S, M.A.A.; Materials - C.S, A.D.; Data Collection and/or Processing - C.S, A.D.; Analysis and/or Interpretation - C.S.; Literature Search - C.S; Writing Manuscript - C.S. A.D; Critical Review - C.S, M.A.A

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Conflict of Interest: The authors do not have any financial relationship with Harran University Scientific Research Fund, which is the sponsor of the research. The authors have no conflicts of interest to declare.

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