Diffusion-weighted Magnetic Resonance Imaging of Normal Masticatory Muscles in Apparent Diffusion Coefficient

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Abstract
To evaluate the apparent diffusion coefficient (ADC) values in normal masticatory muscles with magnetic resonance (MR) imaging.

This study was approved by the ethics committee at the authors’ university (EC15-12-009-1). Twenty-seven healthy volunteers (9 men and 18 women; age range, 21–77 years; mean age, 53.7 years) who underwent MRI examination of the TMJ at Nihon University School of Dentistry at Matsudo from November 2015 to January 2017 were included in this study. Diffusion-weighted MR images were acquired using a 1.5 T unit with a b factor of 0 and 1000 s/mm², and ADC maps were generated. The ADC values were measured for healthy masticatory muscles. Regions of interest (ROIs) were drawn to completely include the right and left lateral pterygoid, medial pterygoid, and masseter muscles on a slice demonstrating the largest area of each muscle on the ADC maps.

The mean ADC values of the lateral pterygoid muscles, medial pterygoid muscles, and masseter muscles were 1.21 ± 0.31 × 10⁻³ mm²/s, 1.10 ± 0.25 × 10⁻³ mm²/s, and 1.09 ± 0.23 × 10⁻³ mm²/s, respectively. The ADC values of the lateral pterygoid muscles were significantly higher than those of the medial pterygoid muscles and masseter muscles (*p < 0.05).

The results of this study present the ADC values of the masticatory muscles of healthy subjects in vivo. Data regarding the ADC values for normal masticatory muscles will help facilitate quantitative evaluations of temporomandibular disorders.

Keywords:
diffusion magnetic resonance imaging, healthy volunteers, masticatory muscles

Introduction
Temporomandibular disorders (TMD), which affect the temporomandibular joint (TMJ) and supporting structures, include symptoms such as limited mouth opening, clicking, pain, and tenderness in the pre-auricular area and masticatory muscles (1). However, the etiology of these disorders is multifactorial and remains unknown. The four principal muscles involved in mastication are the medial and lateral pterygoid muscles, temporalis muscles, and masseter muscles. In previous studies, the evaluation of masticatory muscle function during jaw movement has been limited to electromyography (EMG) and palpation (2). Recently, MRI, with its high spatial resolution, has been used in muscular anatomical imaging (3). Furthermore, functional MRI sequences, such as diffusion-weighted imaging (DWI), have been used to study muscular tissue function non-invasively (3).

DWI is able to measure water molecule diffusion and detect tissue microstructure in vivo. The quantitative metric derived from DWI is the apparent diffusion coefficient (ADC) (4), and many qualitative and quantitative DWI analyses have been utilized in numerous studies (5).

However, there are few studies that evaluate the ADC values of normal masticatory muscles. Thus, the purpose of this study was to measure the ADC values in normal masticatory muscles using diffusion-weighted MRI.
Materials and Methods

Subjects
This prospective study was approved by the Institutional Review Board (EC15-12-009-1), and all subjects provided written informed consent prior to the MRI examination. For the basic examination, the masticatory muscles (lateral pterygoid muscles, medial pterygoid muscles, and masseter muscles) of 27 healthy volunteers (9 men and 18 women; mean age, 53.7 years; age range, 21–77 years) who underwent MRI examination to evaluate brain and maxillofacial diseases as outpatients at the radiology department at Nihon University School of Dentistry at Matsudo from November 2015 to January 2017 were included in this study. The exclusion criteria were TMD patients, patients younger than 15 years old, patients with tumors around the TMJ, and imaging studies with severe artifacts. None of the subjects had a documented history of malignant or benign tumors or osteomyelitis. The inclusion criterion for the subjects was general good health. These subjects were diagnosed as healthy based on diagnostic criteria of the American Academy of Orofacial Pain (1).

MR imaging
MR imaging of the TMJ, which included the bilateral medial muscles, lateral pterygoid muscles, and masseter muscles, was performed using a 1.5-Tesla unit (Intera Achieva 1.5T, Philips Medical Systems, Best, The Netherlands) with a 5-channel phased array coil.

The first sequence was DWI, which was obtained using a spin-echo technique. DWI was acquired in the axial plane with the following parameters: TR, 5,800 ms; TE, 69 ms; matrix, 256 × 256; field of view, 28 cm; section thickness, 6.0 mm: intersection gap, 1.4 mm; imaging time, 3 min 29 s; b-values, 0 and 1000s/mm².

Image analysis
The ADC was calculated using the ADC visualize tool implemented in a dedicated off-line workstation (Philips Medical Systems, Best, The Netherlands). The regions-of-interest (ROIs) were manually placed by tracing the contours of the right and left side of the lateral pterygoid muscles, medial pterygoid muscles, and masetter muscles on b = 0 images that demonstrated the maximal area of each muscle in the postural position (Fig. 1). Fascia, blood vessels, and fat were excluded from the ROIs. ROI placement was performed by two oral radiology specialists, independently. ADC values were measured for healthy masticatory muscles, and the effects of gender and age were also analyzed. The temporalis muscles were not clearly demonstrated in many patients, therefore, the ADC of the temporalis muscles was not measured.

Statistical analyses
The relationship between the masticatory muscles and ADC values of each muscle were analyzed using the Kruskal-Wallis test. These analyses were performed using the statistical package SPSS, version 21.0 (SPSS Japan, Tokyo, Japan). *P-values < 0.05 were considered statistically significant.

Results
The ADC values of the lateral pterygoid muscles were significantly higher than those of the medial pterygoid and masseter muscles (*p<0.05) (Fig. 2). The mean ADC values of the lateral pterygoid, medial pterygoid, and masseter muscles were 1.21 ± 0.31 × 10⁻³ mm²/s (mean ADC ± SD), 1.10 ± 0.25 × 10⁻³ mm²/s, and 1.09 ± 0.23 × 10⁻³ mm²/s, respectively.

The comparison of ADC values of the masticatory muscles between healthy men and women volunteers (Table 1). The ADC values of the men and women with regard to the lateral pterygoid muscles in healthy volunteers were 1.17 ± 0.25 × 10⁻³ mm²/s and 1.19 ± 0.32 × 10⁻³ mm²/s, respectively. The ADC values of the medial pterygoid muscles in healthy men and women volunteers were 1.08 ± 0.24 × 10⁻³ mm²/s and 1.11 ± 0.25 × 10⁻³ mm²/s, respectively. The ADC values of the massetter muscles in healthy men and women volunteers were 1.06 ± 0.24 × 10⁻³ mm²/s and 1.11 ± 0.23 × 10⁻³ mm²/s, respectively. There was no relationship among the ADC values of the masticatory muscles with regard to sex.

The ADC values of healthy volunteers according to age groups by decade (Table 2). There was no relationship among the ADC values of the masticatory muscles with respect to each age group.

Discussion
In this study, we measured the diffusion coefficients of normal masticatory muscles using diffusion-weighted MRI. The ADC values of the lateral pterygoid muscles were significantly higher than those of the medial pterygoid muscles and those of the massetter muscles.
Only a few studies have examined the DWI of masticatory muscles (6). DWI has become more widespread, on other hand the relative value of DWI sequences (7, 8).

Muscles can be divided into three types, striated muscles, smooth muscles, and cardiac muscles. The masticatory muscles are striated muscles, as are the dorsi flexor and spinal column erector muscles. Concretely, Yanagisawa O et al reported that the ADC$^{b=0}$ and ADC$^{b=50-700}$ values were $2.64 \times 10^{-3}$ mm$^2$/s and $1.44 \times 10^{-3}$ mm$^2$/s in the ankle dorsiflexors and $3.02 \times 10^{-3}$ mm$^2$/s and $1.49 \times 10^{-3}$ mm$^2$/s in the erector spinae muscles, respectively. The study results of healthy volunteers revealed that the mean ADC values of the normal ankle dorsiflexors and erector spinae muscles were significantly higher than those of the masticatory muscles in healthy volunteers. The difference in ADC values between the masticatory muscles and muscles of the foot (ankle dorsiflexors, erector spinae muscles) may be attributed to differences in the composition of the muscle architecture (10), as the muscles of the feet and masticatory muscles are functionally different.
Fig. 2. Comparison the ADC values of the masticatory muscles in healthy volunteers
The ADC values of the lateral pterygoid muscles were significantly higher than those of
medial pterygoid muscles and masseter muscles (*p<0.05).
The mean ADC values of the lateral pterygoid, medial pterygoid, and masseter muscles
were 1.21±0.31×10⁻³ mm²/s (mean ADC±SD), 1.10±0.25×10⁻³ mm²/s, and 1.09±
0.23×10⁻³ mm²/s, respectively.

Table 1. Comparison of the ADC of the masticatory muscles between healthy men and
women volunteers
Values are shown as mean ± S.D. (×10⁻³ mm²/s).
There was no relationship among the ADC values of the masticatory muscles with regard
to sex.

<table>
<thead>
<tr>
<th></th>
<th>lateral pterygoid muscles</th>
<th>medial pterygoid muscles</th>
<th>masseter muscles</th>
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</thead>
<tbody>
<tr>
<td>men(n=9)</td>
<td>1.17±0.25</td>
<td>1.08±0.24</td>
<td>1.06±0.24</td>
</tr>
<tr>
<td>women(n=18)</td>
<td>1.19±0.32</td>
<td>1.11±0.25</td>
<td>1.11±0.23</td>
</tr>
</tbody>
</table>

Table 2. The ADC values with healthy volunteers (lateral pterygoid muscles, medial
pterygoid muscles and masseter muscles) according to age groups
Values are shown as mean ± S.D. (×10⁻³ mm²/s).
There was no relationship among the ADC values of the masticatory muscles with respect
to each age group.

<table>
<thead>
<tr>
<th>age groups</th>
<th>lateral pterygoid muscles</th>
<th>medial pterygoid muscles</th>
<th>masseter muscles</th>
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<tbody>
<tr>
<td>20-29(n=4)</td>
<td>1.13±0.27</td>
<td>1.08±0.24</td>
<td>1.14±0.30</td>
</tr>
<tr>
<td>30-39(n=2)</td>
<td>1.22±0.42</td>
<td>0.98±0.33</td>
<td>1.09±0.18</td>
</tr>
<tr>
<td>40-49(n=3)</td>
<td>1.10±0.30</td>
<td>1.01±0.26</td>
<td>1.02±0.26</td>
</tr>
<tr>
<td>50-59(n=6)</td>
<td>1.11±0.29</td>
<td>1.21±0.21</td>
<td>1.14±0.22</td>
</tr>
<tr>
<td>60-69(n=8)</td>
<td>1.14±0.28</td>
<td>1.14±0.26</td>
<td>1.07±0.24</td>
</tr>
<tr>
<td>70-79(n=4)</td>
<td>1.20±0.26</td>
<td>1.15±0.22</td>
<td>1.10±0.22</td>
</tr>
</tbody>
</table>
The ADC values of the masticatory muscles in healthy women volunteers were higher than those of men volunteers. However, there was no relationship found among the ADC values of the masticatory muscles in terms of sex. These sex differences may be attributed to differences in the motor units and constituent muscle fibers between men and women. Furthermore, these findings showed that water molecules within the muscles diffused more easily in women subjects than in men subjects.

On the other hand, Galbán et al. used DWI to show that DWI of the skeletal muscles generally decreased with aging. However, this was not shown in our study. We speculate that the masticatory muscles might become less fatigued than the muscles of the feet as they only control mandibular movements for mastication and are involved in speech and facial expressions.

Our results suggest that the difficulties in using palpation alone to study temporomandibular disorders may be circumvented by employing the ADC values as an alternative method for studying masticatory muscles.

However, our study has some limitations. First, this study group included a small number of patients. Second, we were not able to evaluate the temporalis muscles with low image resolution on DWI. Thus, we were not able to measure the ADC values in patients with severe image distortions from susceptibility artifact.

Conclusion
The ADC values of the lateral pterygoid muscles were significantly higher than those of the median pterygoid muscles and masseter muscles. Data concerning the ADC values for normal masticatory muscles may facilitate the quantitative evaluation of TMDs.

Acknowledgments
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References