TECHNICAL REPORT

ISO/TR 16379

First edition
2014-03-01

Tissue-engineered medical products — Evaluation of anisotropic structure of articular cartilage using DT (Diffusion Tensor)-MR Imaging

Produits médicaux à base de tissus — Évaluation de la structure anisotrope du cartilage articulaire en utilisant l'imagerie en tenseur de diffusion (IRM-TD)

Reference number
ISO/TR 16379:2014(E)

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Published in Switzerland

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Foreword

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The committee responsible for this document is ISO/TC 150, *Implants for Surgery*, Subcommittee SC 7, *Tissue-engineered Medical Products*.

Introduction

Structural evaluation of articular cartilage with conventional diagnostic technologies is challenging, and Nihon University has developed technologies (see Reference [1]) and collected relevant data for *in vivo* evaluation of articular cartilage structure by means of diffusion tensor magnetic resonance imaging (DT-MRI) using 1,5 Tesla or 3 Tesla MRI equipment employed for treatment in hospital settings. These data are released in this Technical Report prepared for reference in treatment settings.

This work is part of "Development of Cartilage Observation and Evaluation Technologies for Regenerative Medicine Processes", an activity managed by the University under "Development of Evaluation Technology for Early Introduction of Regenerative Medicine", a project contracted by the New Energy and Industrial Technology Development Organization (NEDO) to the National Institute of Advanced Industrial Science and Technology (AIST) and its Technology Research Association of Medical Welfare Apparatus.

Tissue-engineered medical products — Evaluation of anisotropic structure of articular cartilage using DT (Diffusion Tensor)-MR Imaging

1 Scope

This Technical Report has been prepared for evaluation of therapeutic courses for articular cartilage disease and summarizes results from structural evaluation of knee joint cartilage by diffusion tensor imaging, an MRI applied technology allowing non-invasive observation of soft tissue morphology *in vivo*.

This Technical Report is intended for use in areas such as regenerative medicine for knee joint cartilage disease.

After *in vivo* transplant of cartilage cells or tissue as a regenerative treatment, longitudinal diagnosis is needed to assess regeneration as articular cartilage, but arthroscopes used primarily for this purpose are invasive and also do not allow evaluation of structure by simple observation of surfacial characteristics. Radiography and CT do not visualize articular cartilage and also entail the problem of exposure. Collagen fibres, the primary component of articular cartilage, have a surfacial layer parallel to the articular surface to serve a lubricating function for the articular surface, a middle layer with a randomized structure to distribute loads, and deep layers oriented vertically to support loads. The anisotropy of this three-layer structure is a characteristic feature of hyaline cartilage structures and a mechanism demonstrating a lubricating function for articular cartilage. We can then ask whether articular cartilage can be assessed by evaluating the anisotropy of collagen.

MRI techniques allow non-invasive visualization of soft tissue form and function *in vivo*, and DT-MRI conveys the direction of water molecule motion. In fibrous tissues, the direction of water molecule motion is restricted to the direction of fibre orientation; consequently, the direction of water molecule motion matches that of fibre orientation. The use of DT-MRI therefore does allow evaluation of collagen fibre orientation and anisotropy in articular cartilage.

DT-MRI is thus used to observe articular cartilage anisotropy data for use as standardized data in longitudinal diagnosis following transplant of articular cartilage as a regenerative treatment.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
diffusion tensor
DT
tensor expressing the orientation and magnitude of diffused proton signals

2.2
sequence
protocol for performance of MRI

2.3
spin-echo echo-planar imaging
SE-EPI
method of high-speed imaging in which gradient fields are flipped continuously at high speed to produce echoes continuously by means of a spin-echo pulse sequence

2.4
field of view
FOV
width and height of an imaged region (expressed in cm or mm)

2.5
matrix
pixel resolution for acquisition of MR signals in a field of view

2.6
echo time
TE
time after RF pulse application until an echo is produced

[SOURCE: JIS K 3611]

2.7
radio frequency pulse
RF pulse
short duration, high-frequency electromagnetic wave in pulse form

[SOURCE: JIS K 3611]

2.8
repetition time
TR
time interval for repetition of the basic unit of magnetic resonance pulse sequences

[SOURCE: JIS K 3611]

2.9
slice thickness
thickness of the imaging plane

2.10
number of averages
NA
number of times an identical MR signal is repeated

2.11
b value
maximum value of the parameter indicating level of diffusion weighting

2.12
motion probing gradient
MPG
gradient field applied to detect diffusion

2.13
parallel imaging
high-speed imaging method making use of the difference in sensitivities provided by multiple coils

2.14
fractional anisotropy
FA
number indicating level of structural anisotropy

2.15
mean diffusivity
MD
mean of diffusion coefficients along the three primary axes of a diffusion tensor

2.16
signal-to-noise ratio
SNR
value expressing the proportion of signal to noise; greater values indicate higher image quality

2.17
voxel
three-dimensional cuboid representing the minimum unit comprising a three-dimensional image

3 Principle

In the regeneration medicine for artificial cartilage, it is important to evaluate whether the implanted tissues regenerate as an artificial cartilage with time. However, an arthroscope is invasive and only monitors the surface texture of articular cartilage. X-ray and CT cannot project the cartilage tissue and have an exposure problem.

An articular cartilage has anisotropy by differential orientation of collagen fibra to exert a lubrication property as a joint. In the superficial layer, collagen fibra is oriented to parallel on joint surface. Next, in the middle layer, collagen fibra was in random for distribution of loading and oriented vertically in deep layer. Such three-layer structure is a feature of articular cartilage, which is based on the biomechanical property of articular cartilage. Thus, it is possible to evaluate whether or not the articular cartilage by observation of the anisotropy structure.

In DT-MRI, in MRI techniques, it is possible to know the direction of proton movement. In fibrotic tissues, as the direction of water molecule movement is limited along the orientation of collagen fibro, the fibro direction is consistent with the direction of proton movement. Therefore, the direction of collagen structure can be evaluated with DT-MRI.

In this draft, DT-MRI data obtained from healthy male by using several MR devices shows for use as reference data to evaluate the process after regenerate treatment of articular cartilage.

4 Diffusion tensor magnetic resonance imaging (DT-MRI) data observation in articular cartilage

4.1 DT-MRI measurement process

The process shown in the flowchart in Figure 1 is used for acquisition, measurement, and observation of data to evaluate articular cartilage structure. This Technical Report envisions that different models of MRI equipment are used in different hospital facilities, and thus observational data are shown for three types of MRI apparatus produced by different manufacturers. Table 1 presents the MRI apparatus, signal-receiving coils, and imaging parameters used in observation.

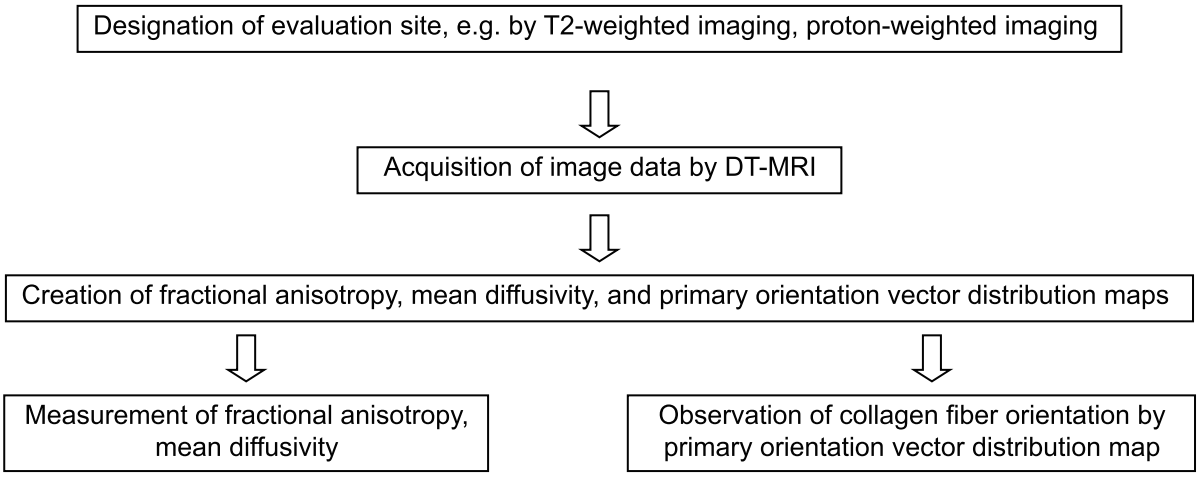

Figure 1 — DT-MRI data measurement process

Table 1 — MRI apparatus, signal-receiving coils, and imaging parameters used in DT-MRI

Imaging facility	Kyoto University Institute for Frontier Medical Sciences	Nihon University School of Dentistry at Matsudo Hospital	Hiroshima University Hospital
Apparatus (Manufacturer)	SONATA 1,5T (Siemens)	Achieva 1,5T (Philips)	Signa Excite 3T (General Electric)
Signal-receiving coil	4 ch flex array	8 ch sense knee	Lower extremity
Sequence	SE-EPI	SE-EPI	SE-EPI
FOV [mm]	192 × 192	150 × 150	128 × 128
Matrix	192 × 192	144 × 142	128 × 128
TR [ms]	2 200	2 200	2 200
TE [ms]	70	68	68
Slice thickness [mm]	3	5	5
Number of averages	24	20	12
b-value	600	600	400
No. MPG axes	6	6	6,15
Parallel imaging	GRAPPA[a]	SENSE[b]	n/a
Image slice	Sagittal plane	Sagittal plane	Sagittal plane
Pixels	384 × 384	400 × 400	256 × 256

[a] Generalized rapid acquisition with partially parallel acquisition.

[b] Sensitivity encoding.

4.2 Notes on setting of DT-MRI imaging parameters for articular cartilage

4.2.1 Imaging resolution

The resolution at which MR signals are acquired corresponds to a voxel size determined by matrix and slice thickness. Larger voxel sizes correspond to higher SNR, which also increases data reliability. Conversely, smaller voxel sizes increase resolution but decreased SNR of MR signals, which decreases data reliability.

Because articular cartilage has a three-layer structure with differing collagen fibre orientations (see Reference [2]), the matrix and slice thickness parameters used for this Technical Report were selected to allow acquisition of three-layer data.

4.2.2 Repetition time

Longer TR increases the number of slices in an image but lengthens imaging time. The parameter in this Technical Report was selected based on Reference [1].

4.2.3 Number of averages

A greater number of signal averages raises SNR and also increases data reliability but lengthens imaging time. The parameter in this Technical Report was selected based on Reference [1].

4.2.4 b-value

Higher b-values lengthen TE, which might lead to under-representation of diffusivity. Conversely, lower b-values can lead to over representation of diffusivity, and this parameter shall be set with consideration for the imaging target. The parameter in this Technical Report was selected based on Reference [1].

4.2.5 Motion probing gradient (MPG)

MPG shall be applied in a minimum of six directions to determine diffusion tensors. As MPG is applied to more axes, more complex structures can be analysed, but imaging time lengthens. But for application of MPG to equal numbers of axes, a higher static field intensity of the MRI apparatus will shorten imaging time. In consideration of the imaging times envisioned in hospital use, this Technical Report compares measurement data for imaging performed in six directions with an apparatus having a 1,5 T static field intensity, and in six directions and 15 directions with an apparatus having a 3 T static field intensity.

4.2.6 Parallel imaging

Imaging time can be shortened by application of parallel imaging. Signal-receiving coil is required for application of parallel imaging.

4.3 Measurement indices for structural evaluation of articular cartilage by DT-MRI

4.3.1 DT-MRI imaging slices and data measurement sites

A measurement slice is selected for acquisition of DT-MRI imaging data on articular cartilage. In a coronal slice of the knee joint as shown in Figure 2, DT-MRI imaging is performed in the sagittal plane at the location most inferior to the lateral condyle of the femur, and the image data acquired are used to an create anisotropy distribution image and a mean diffusivity distribution graph, and fractional anisotropy and mean diffusivity are measured. The measured data are graphed, with the horizontal axis representing depth from the cartilage surface.

But as shown in Figure 3, depth from the cartilage surface is a relative measure relating the pixel centre where data are measured to the thickness of the cartilage concerned. [See the following Formula (1)]

$$\mathrm{ND} = \frac{D}{T} \times 100\% \tag{1}$$

where

ND is the depth from surface (%);

D is the distance to pixel centre of data measurement (mm);

T is the cartilage thickness (mm).

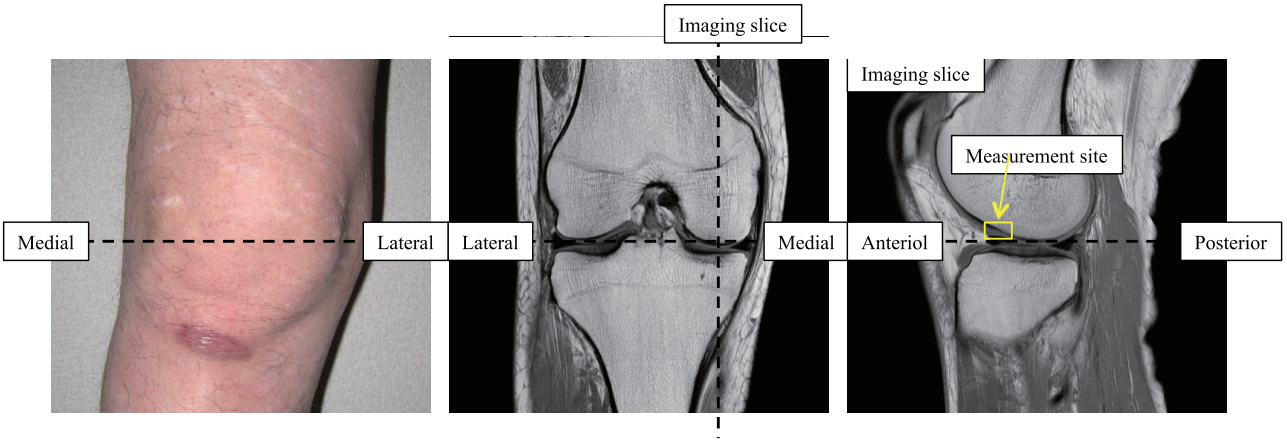

Figure 2 — DT-MRI imaging slice and data measurement site

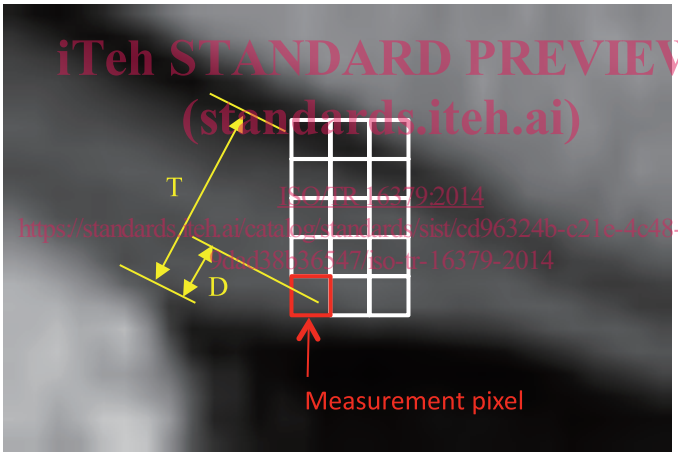

Figure 3 — Pixel intensity measurement site and depth from cartilage surface

NOTE Enlargement of measurement site at right in Figure 2.

4.3.2 Measurement of fractional anisotropy

4.3.2.1 Purpose of measurement

Fractional anisotropy is measured to evaluate the strength of structural anisotropy corresponding to collagen fibre orientation in articular cartilage.

4.3.2.2 Measurement method

The knee joint is imaged by DT-MRI, an anisotropy distribution image of the imaging slice is created from the image data acquired, and the fractional anisotropy of the articular cartilage depicted is measured. The value of fractional anisotropy is a measurement of the value at three pixels parallel to the femoral aspect of the cartilage surface in the fractional anisotropy distribution diagram, and five pixels

