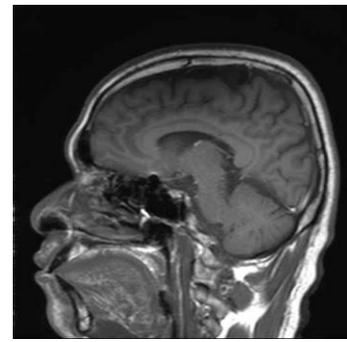




筑波大学
University of Tsukuba



My brain

Compact/Mobile MRIの過去・現在・未来

巨瀬勝美

筑波大学数理物質系 物理工学域

第18回NMRマイクロイメージング研究会(2014-8-11)

講演の内容

1. はじめに

2. Compact/Mobile MRIの誕生と概要

3. 人体局所用MRI

踵骨骨密度測定用MRI, 指骨骨微細構造計測用MRI

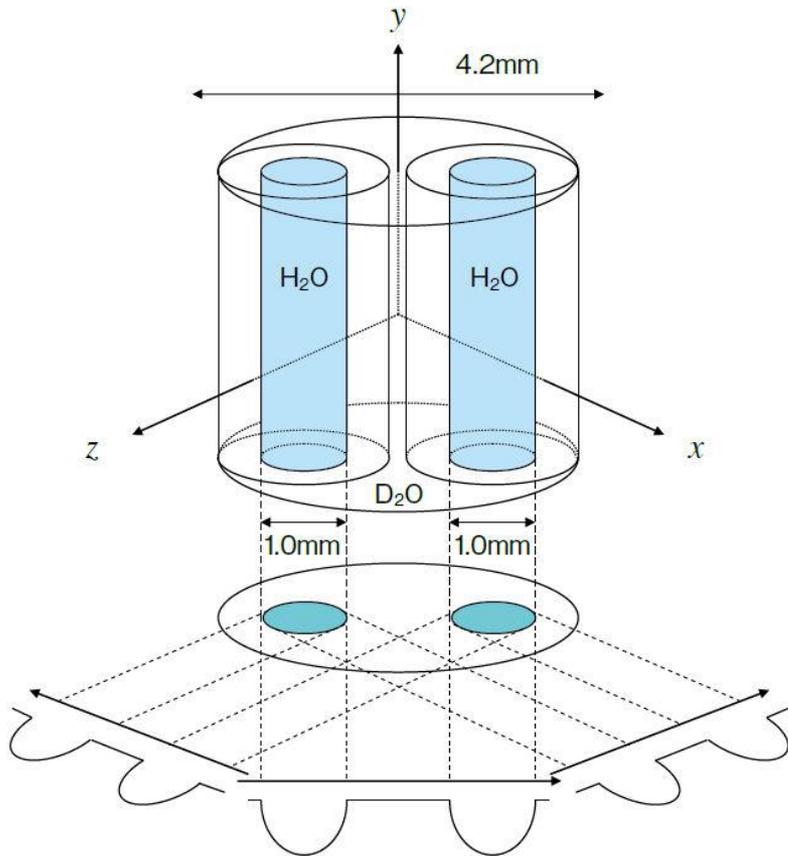
関節リウマチ診断用MRI, 小児骨年齢計測用MRI

4. 植物計測用MRI

梨果実計測用MRI, 梨枝計測用MRI, 樹木計測用MRI

5. むすび

MRIの発見: 1973年



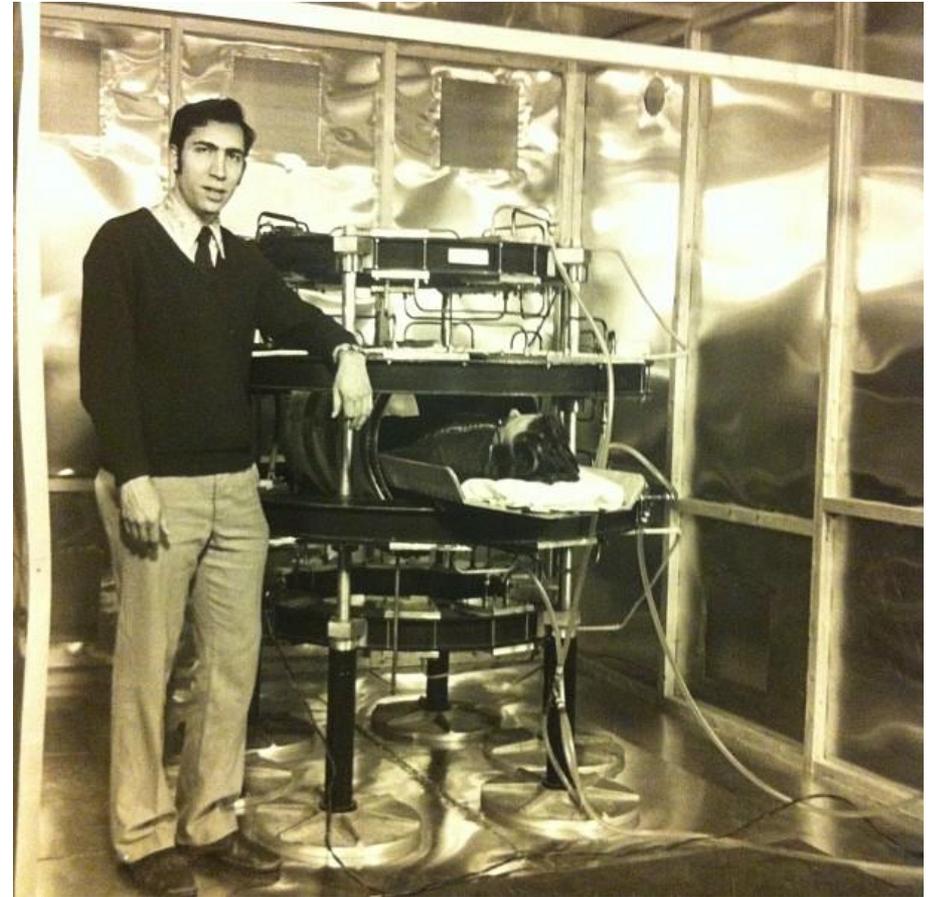
State University of New York at Stony Brook

Varianの60MHzのNMR分光計を用いて5mm管で行われた。
キャピラリの周囲に D_2O が充填してある

全身用(WB)MRIの実用化:1980年



テレタイプとミニコンピュータ



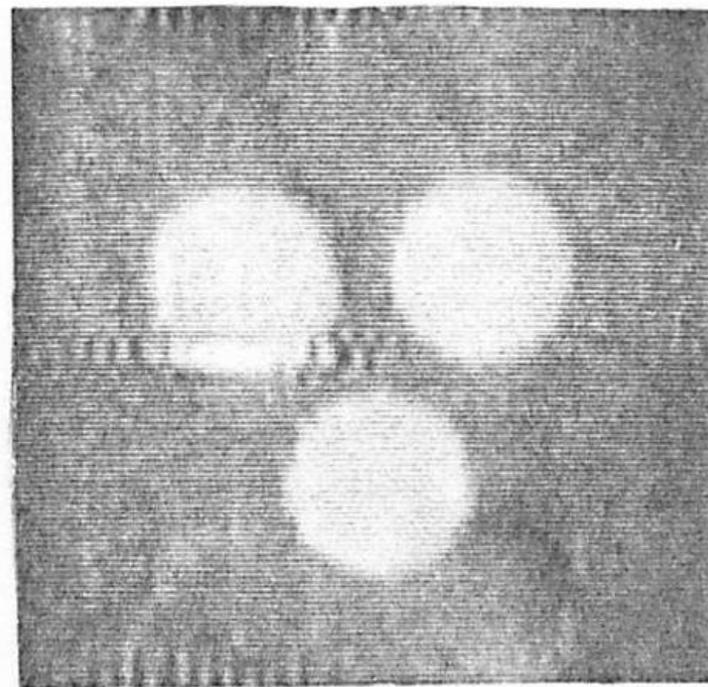
Spin warp法を用いた0.04Tでの撮像

Aberdeen大学のEdelsteinらが、**最初にゴールにたどり着いた。**

実験室におけるMRIの構築: 1981年～



東大物性研安岡研究室(1984年1月)



180°EPIを用いたファントム像:
64x64画素. 0.7T鉄芯電磁石で
撮像(1985年12月)

Unixミニコンを用いた研究用MRIの構築とEPI像の取得

最初の商用WB-MRI: 1982~3年



開発チーム
(東芝中央病院)



自作のRFコイルで
撮像したデジタル像

0.15Tの常伝導磁石を用いて世界初の製品を発売

WB-MRIの現状(2014年)



超伝導磁石を用いたMRI(東芝MS)



永久磁石を用いたMRI(日立メディコ)

世界全体で約20,000台が使われており、毎年2,000台が販売されている。年間の装置市場は、約40億ドルと言われている。

Non-medical applications of NMR imaging?

MRIの可能性を活かした、さまざまな応用研究

→ WB-MRIは、高価で広い設置スペースを必要とする

Solution!



小動物用MRI



NMR分光計+グラジエントプローブ

これらでも対応できない広範な応用: Compact/Mobile MRI

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関節リウマチ診断用MRI, 小児骨年齢計測用MRI

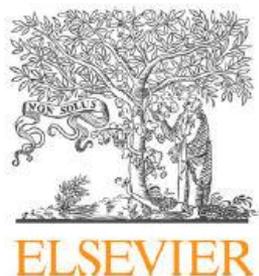
4. 植物計測用MRI

梨果実計測用MRI, 梨枝計測用MRI, 樹木計測用MRI

5. むすび

Compact/Mobile MRIとは？(1)

Progress in Nuclear Magnetic Resonance Spectroscopy 76 (2014) 1–60



Contents lists available at [ScienceDirect](#)

Progress in Nuclear Magnetic Resonance Spectroscopy

journal homepage: www.elsevier.com/locate/pnmrs

Low-field permanent magnets for industrial process and quality control

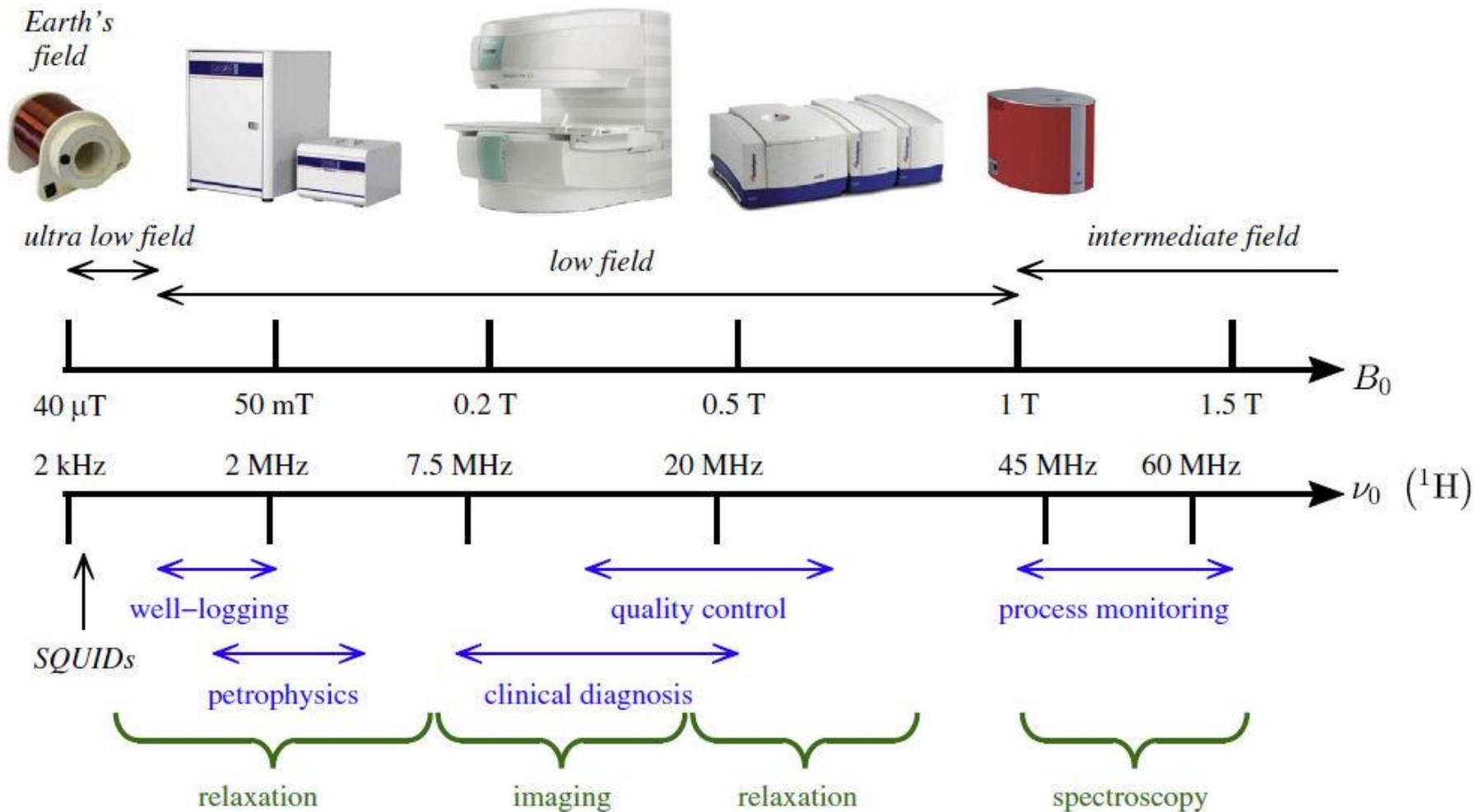
J. Mitchell^{a,b}, L.F. Gladden^{a,*}, T.C. Chandrasekera^a, E.J. Fordham^b

^aDepartment of Chemical Engineering and Biotechnology, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, United Kingdom

^bSchlumberger Gould Research, High Cross, Madingley Road, Cambridge CB3 0EL, United Kingdom

SchlumbergerとCambridge大学のグループによるレビュー
586個の文献を引用した60ページのレビュー論文(3論文引用)

Compact/Mobile MRIとは？ (2)



Low fieldとは、10mT(100G)から1Tまでと規定：永久磁石での発生に適する

Compact/Mobile MRIとは？ (3)

**CHEMICAL
REVIEWS**

Review

pubs.acs.org/CR

Miniaturization of NMR Systems: Desktop Spectrometers, Microcoil Spectroscopy, and “NMR on a Chip” for Chemistry, Biochemistry, and Industry

Sergey S. Zalesskiy,[†] Ernesto Danieli,[‡] Bernhard Blümich,^{*,‡} and Valentine P. Ananikov^{*,†,§}

[†]Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Moscow, 119991, Russia

[‡]Institut für Technische Chemie und Makromolekulare Chemie, RWTH Aachen University, Worringerweg 1, D-52074 Aachen, Germany

[§]Department of Chemistry, Saint Petersburg State University, Stary Petergof, 198504, Russia

ロシアとBluemichのグループによるレビュー

328個の文献を引用した**54ページ**のレビュー論文(4論文引用)

Compact/Mobile MRIとは？ (4)

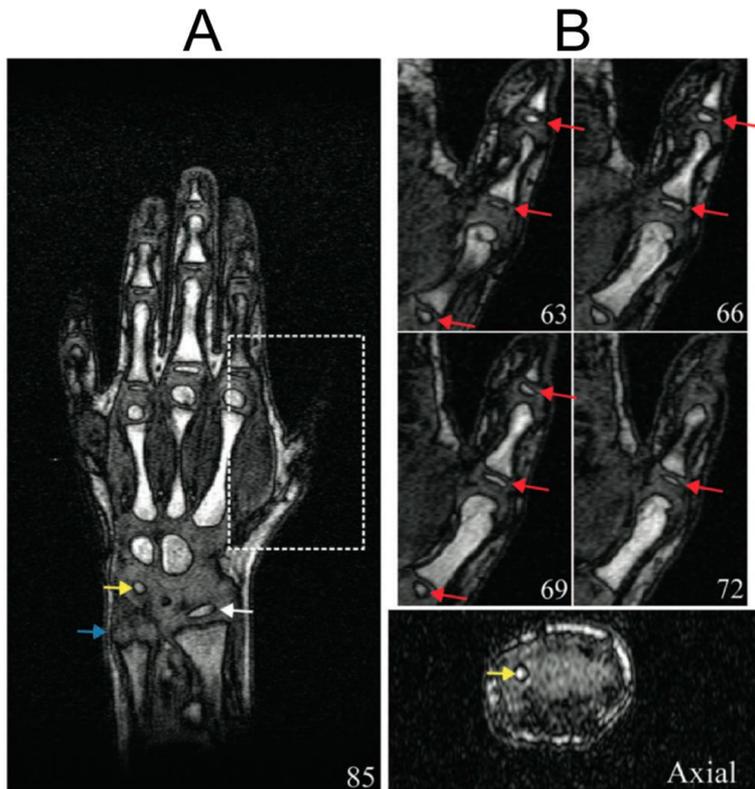


Fig.54

この他に、梨果実の論文に対するコメントがあるが、
小型NMR/MRIに関する一般的なハードウェアの提示はない。

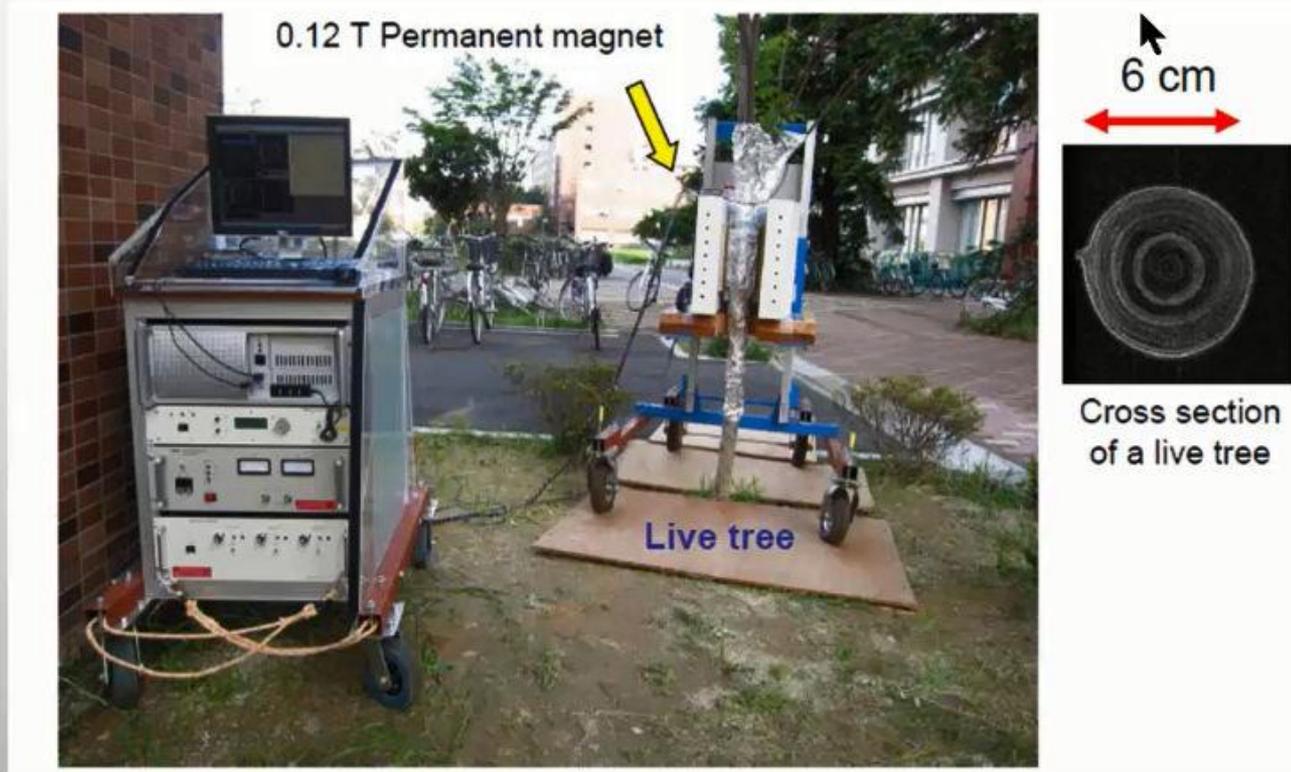
relatively novel idea. Terada and co-workers have demonstrated the use of a compact MRI scanner based on permanent magnets for skeletal age assessment.²⁴⁹

The system works at 0.3 T with a homogeneity better than 50 ppm and a footprint of about 1 m². Hand images of children with spatial resolution better than 500 μ m were obtained in less than 3 min (Figure 54A). From the dimensions of particular bones determined in MR images (red arrows in Figure 54B), the age of the volunteers can be obtained.

Mobile sensors were also used to study small animals in vivo, for example, mice and rats. Kose and co-workers developed a 1 T yokeless permanent magnet with a 9 cm bore, a 3.2 cm in diameter and a 5 cm long solenoid RF coil.²⁵⁰ They recorded images of the whole mouse brain and body with in-plane resolution of about 200 μ m and typical slice thicknesses of 1 mm. Besheer and co-workers used a commercial benchtop MRI

筑波大におけるCompact/Mobile MRI(1)

What do You Want to Build?



Courtesy: Katsumi Kose, PhD, University of Tsukuba

ISMIRM2014でGEの講演者から紹介された我々のシステム. 前年の私の講演からの引用. WB-MRIを見慣れた聴講者から見れば, 新鮮な印象があった.

筑波大におけるCompact/Mobile MRI (2)



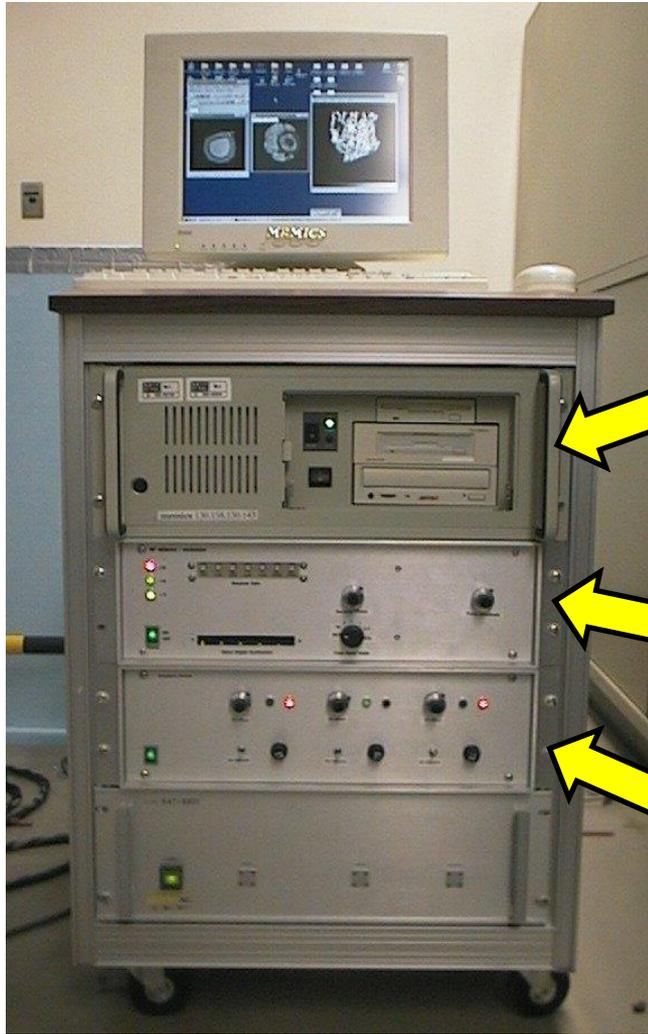
磁石をリフトに載せ、それを電動台車に搭載して、コンソールを牽引する。

ポータブルMRIコンソールの誕生



臨床用MRIの静磁場を借用したMR Microscopyの開発(1998年)

ポータブルMRIコンソールの特徴

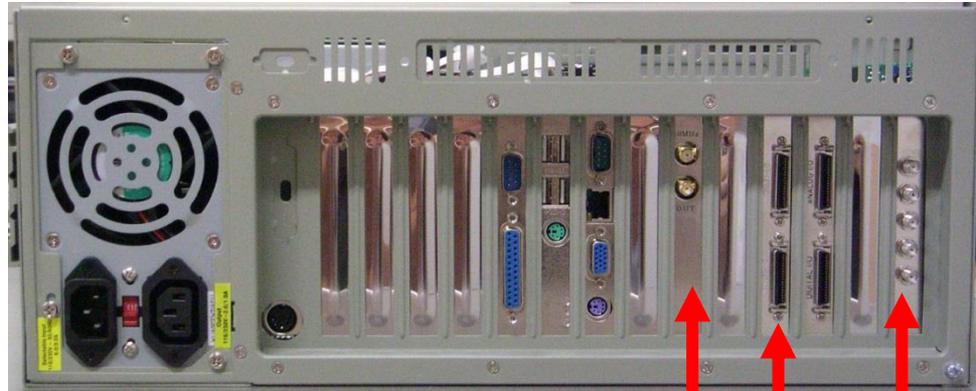


1. 電気系システムが**一体型・可搬型**となっている。
2. PCに**商用の拡張ボード**を挿入することによりシステム構築を容易にしている。
3. RFの**送受信系**を1個のユニットにまとめている。
4. **3CH**のグラジエント電源を1個のユニットにしている。

size: 54 cm(W) x 77 cm(H) x 60 cm(D), weight: **80 kg**, 1998年.

Commercially available extension cards

Industrial
PC



AD
Converter
(**DATEL**)

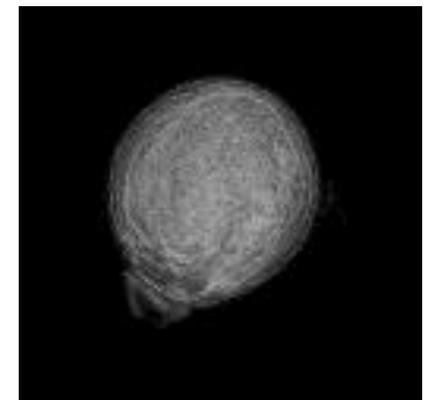
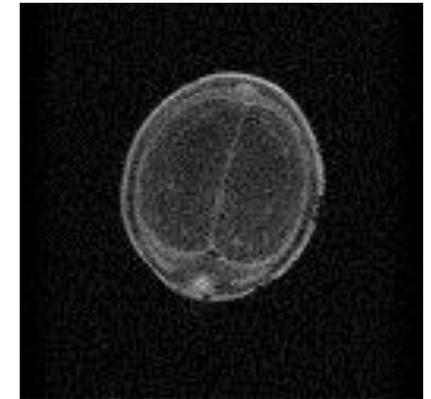
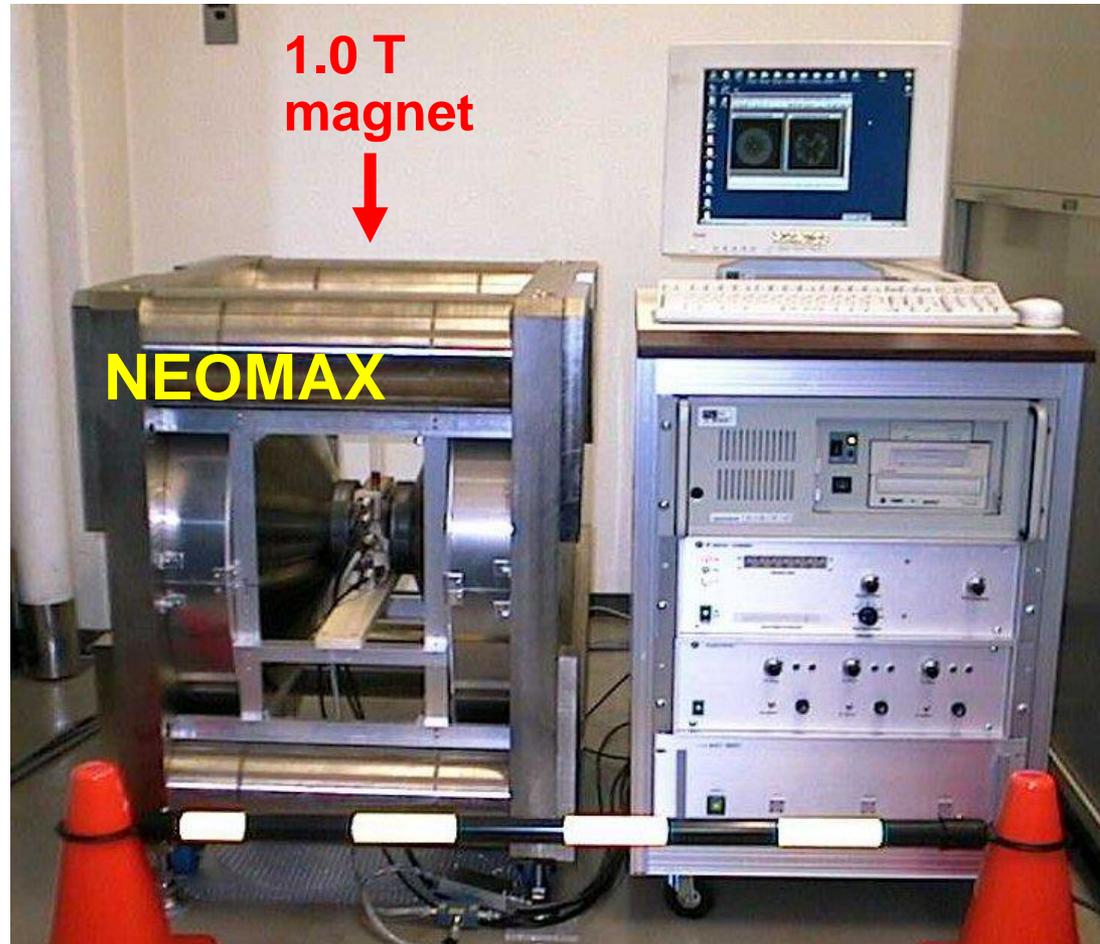
direct digital
synthesizer
(**DST**)



pulse programmer (**mtt**)

- [6] K. Kose, T. Haishi, Development of a flexible pulse programmer for MRI using a commercial digital signal processor board, Spatially Resolved Magnetic Resonance, Edited by P. Blumler, B. Blumich, R. Botto, E. Fukushima, WILEY-VCH, 703-709 (1998).
- [7] K. Kose, T. Haishi, A. Caprihan, E. Fukushima, Real-time NMR imaging systems using personal computers, J Magn Reson **124**, 35-41(1997).

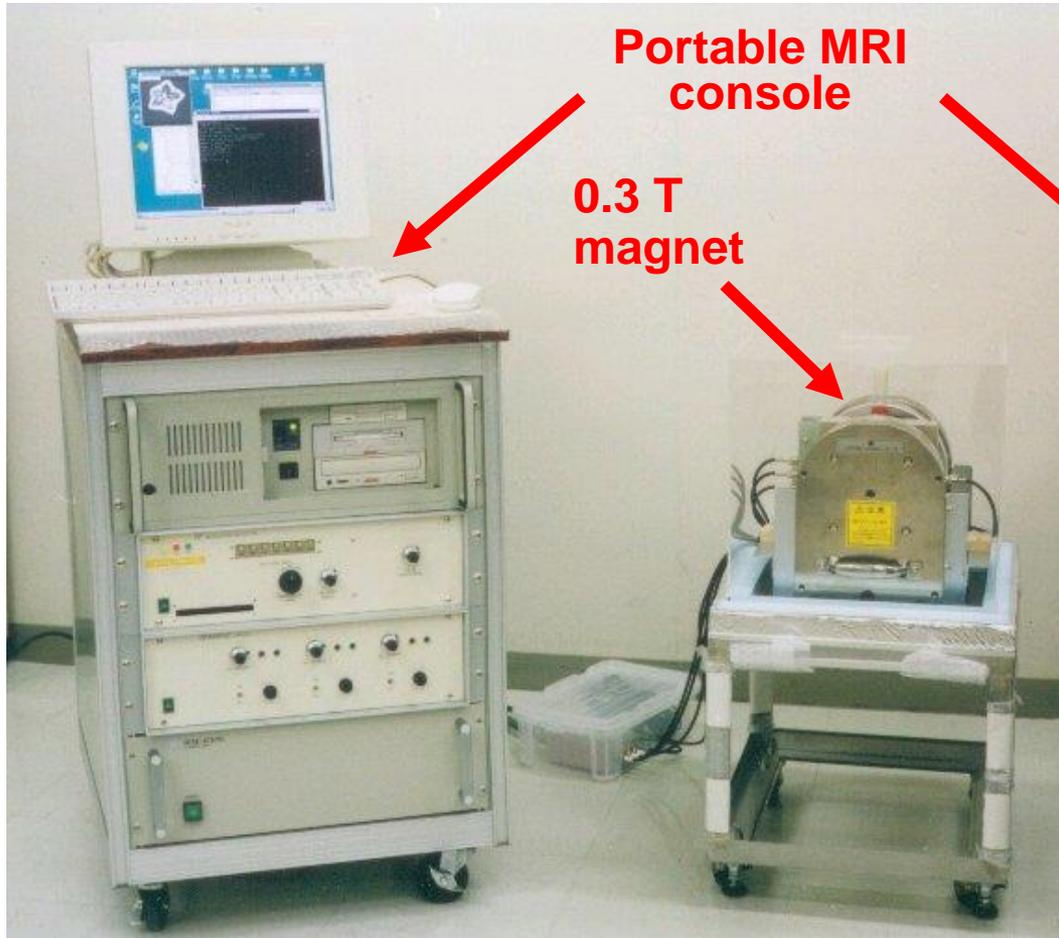
Prototype of Compact/Mobile MRI



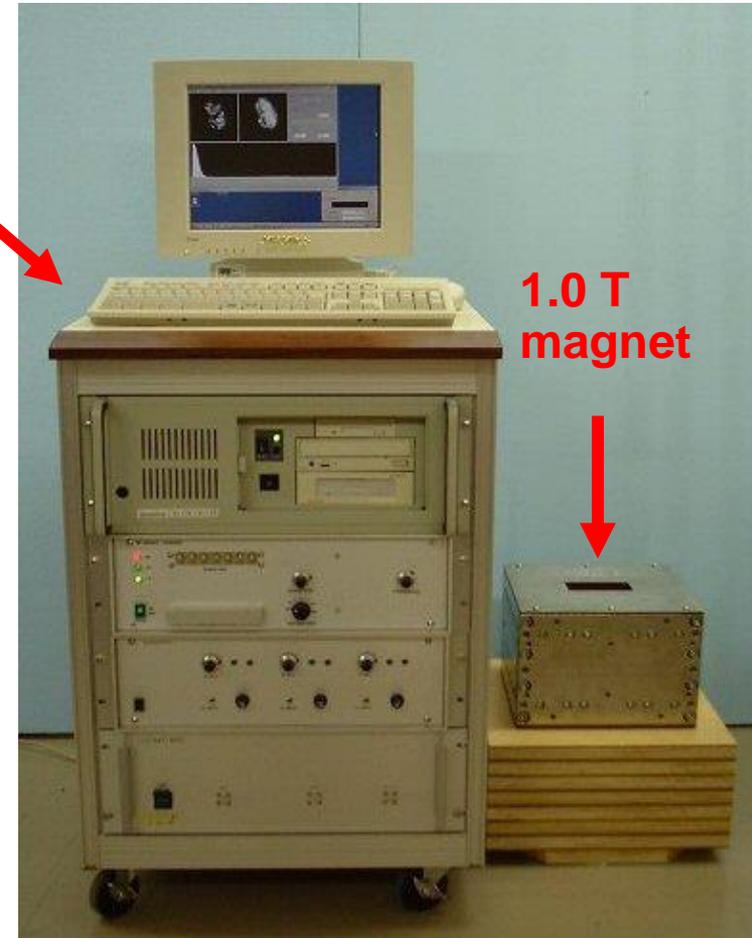
$(50 \mu\text{m})^3$ resolution

Haishi T, Uematsu T, Matsuda Y, Kose K: Development of a 1.0 T MR Microscope using a Nd-Fe-B Permanent Magnet. *Magn Reson Imaging* 2001; 19: 875-880.
(constructed in 1998) (1999 ICMRM-YIA)

Concept Model of Compact/Mobile MRI



Constructed in 1999, formal debut in 2011



Constructed in 2000, formal debut in 2007

Portable MRI console and small permanent magnet

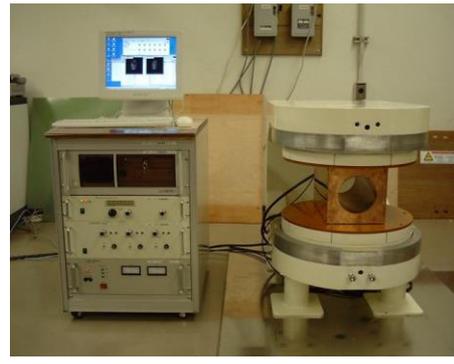
Compact MRI using permanent magnets



1998:MR microscope



1999:Portable MRI



2000:Salmon MRI



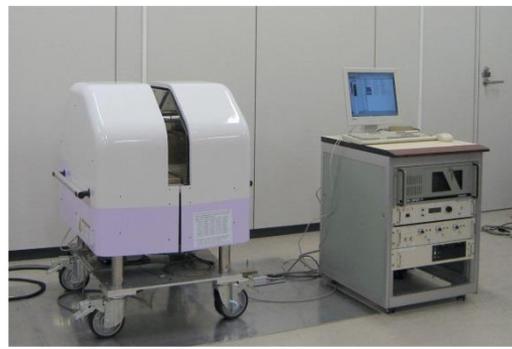
2001:Heel MRI



2003:Mouse MRI



2006:Finger MRI



2006:Wrist MRI



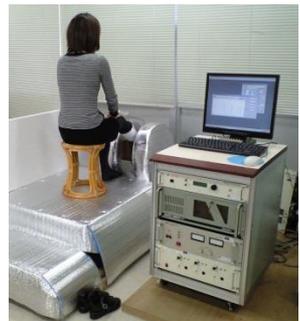
2006:Plant MRI



2006:Cold room MRI



2005:Hand MRI



2008:Heel MRI



2008:Clinical MRI !

Permanent-magnet compact MRI systems

ADVANTAGES:

1. Compactness

Small installation space

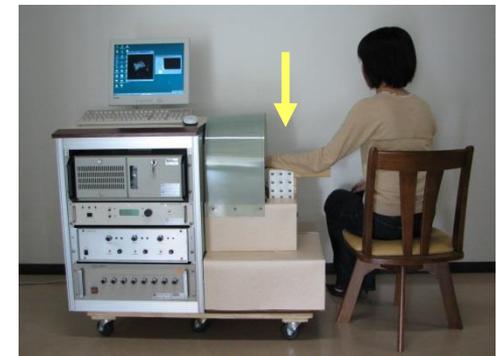
2. Openness

Easy access to the sample

3. Portability

New applications

in **unconventional** environments:
outdoor, low or high temp. room.



Categories of Compact/Mobile MRI

1. 人体局所用MRI

踵骨骨密度計測, 指骨骨微細計測, 橈骨骨微細計測,
関節リウマチ診断用, 小児骨年齢計測用

2. 植物計測用MRI

梨果実計測用, 梨枝計測用, 樹木計測用

3. マウス(小動物)用MRI

マウス・ラット計測用

4. 食品用MRI

鮭雌雄判別用, 食品用

5. 特殊環境用MRI

低温室用, 温度可変型

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関節リウマチ診断用MRI, 小児骨年齢計測用MRI

4. 植物計測用MRI

梨果実計測用MRI, 梨枝計測用MRI, 樹木計測用MRI

5. むすび

人体局所計測用MRI

なぜ人体局所計測用MRIか？

1. 特定用途に最適化したシステムにすることにより、**設置スペース**を小さく、検査効率を向上させ、**システムコストと検査コスト**を節減することができる。

2. オープンスペースで、座った姿勢などで計測することにより、**被験者への負担を軽減**できる。

3. 可搬型にすることにより、**集団検診**などへの利用が可能となる。

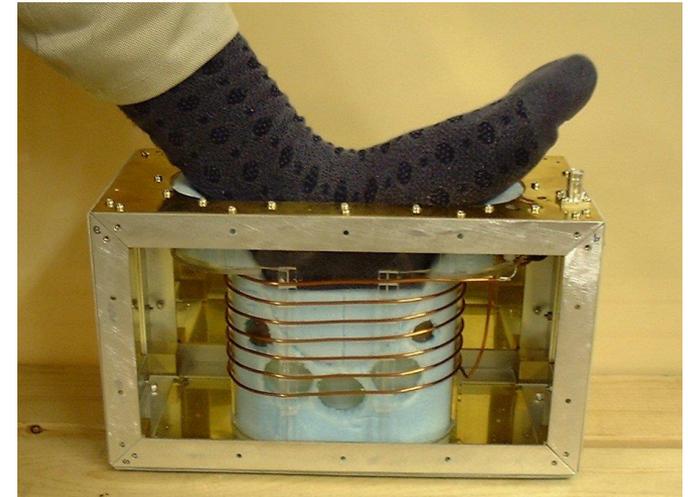
→ WB-MRIでは困難な研究が可能。スルーputtの向上。

踵骨骨密度計測用MRI(1)

Development of a Compact MRI System for Trabecular Bone Volume Fraction Measurements

Katsumi Kose,^{1*} Yoshimasa Matsuda,¹ Takeaki Kurimoto,¹ Seitarou Hashimoto,¹ Yukako Yamazaki,¹ Tomoyuki Haishi,² Shin Utsuzawa,² Hiroshi Yoshioka,³ Shigemasu Okada,⁴ Masaaki Aoki,⁴ and Tsuyoshi Tsuzaki⁴

MRM vol.52
440-444 (2004)

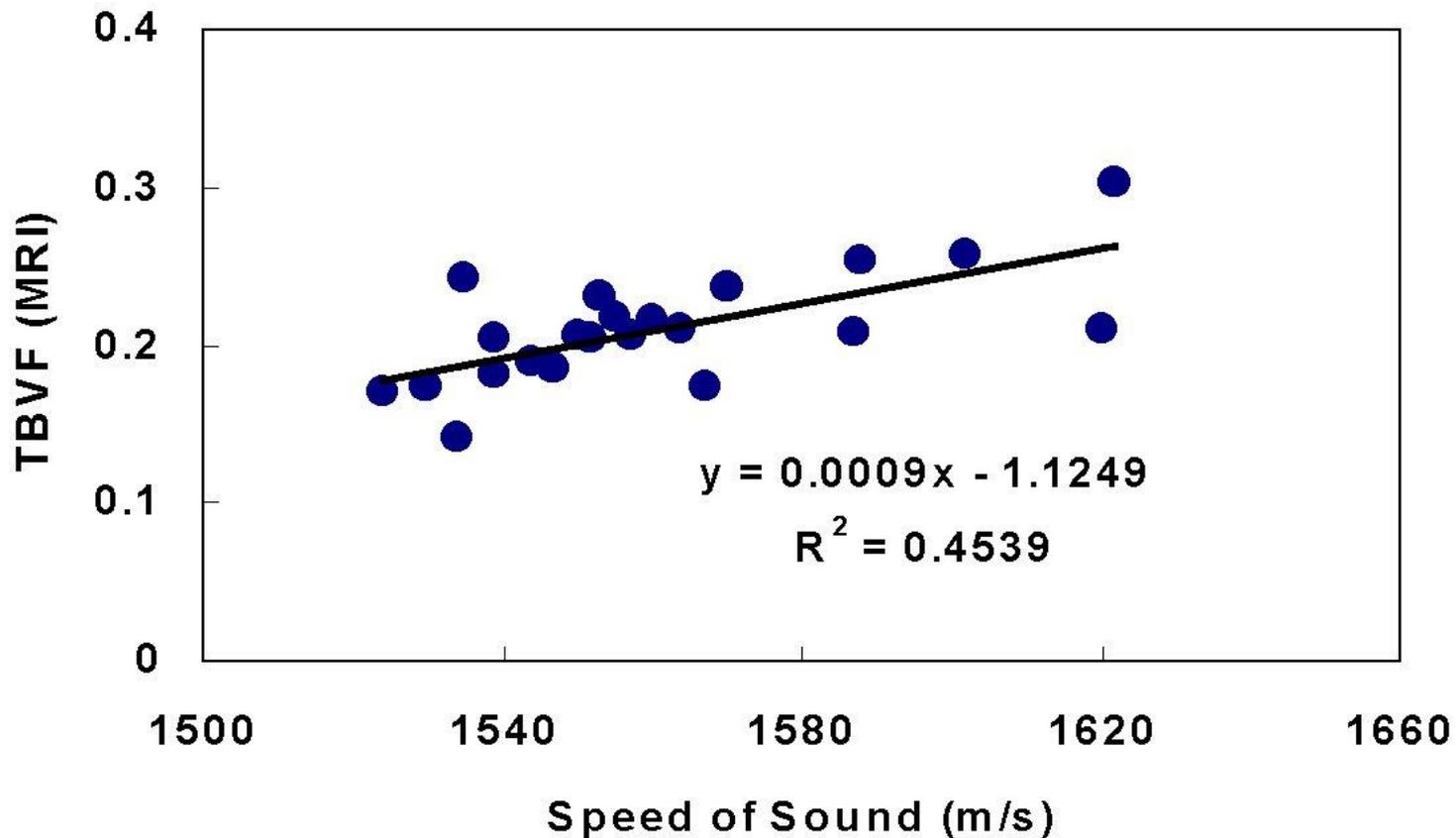


外部標準ファントムと密度標準ファントムを用いてプロトン密度を定量化. 海綿骨密度はそれから算出.

0.2T, 16cmギャップの磁石を使用

踵骨骨密度計測用MRI(2)

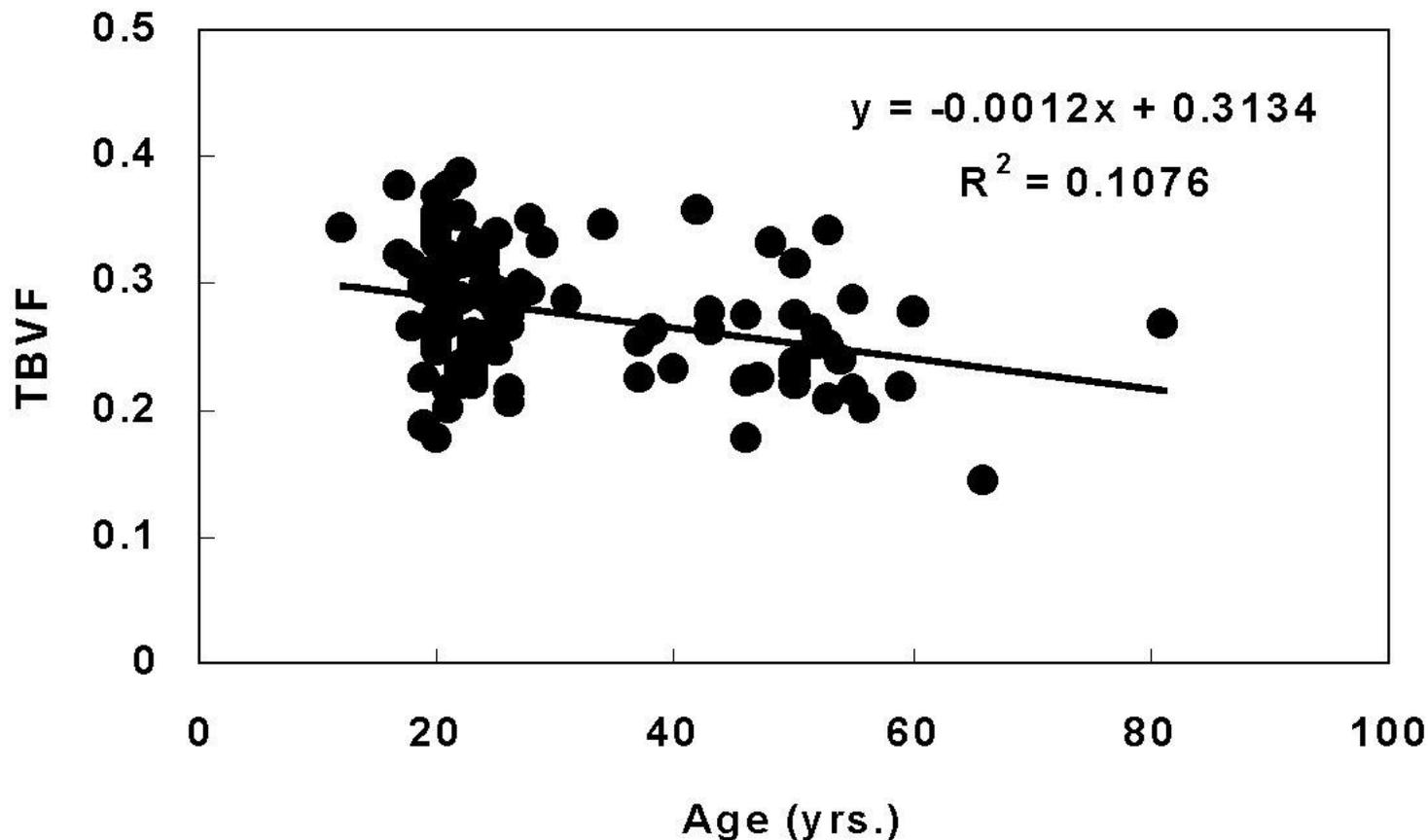
SOS vs TBVF (n=22)



理系女子学生22人(18-23歳)を対象とした計測

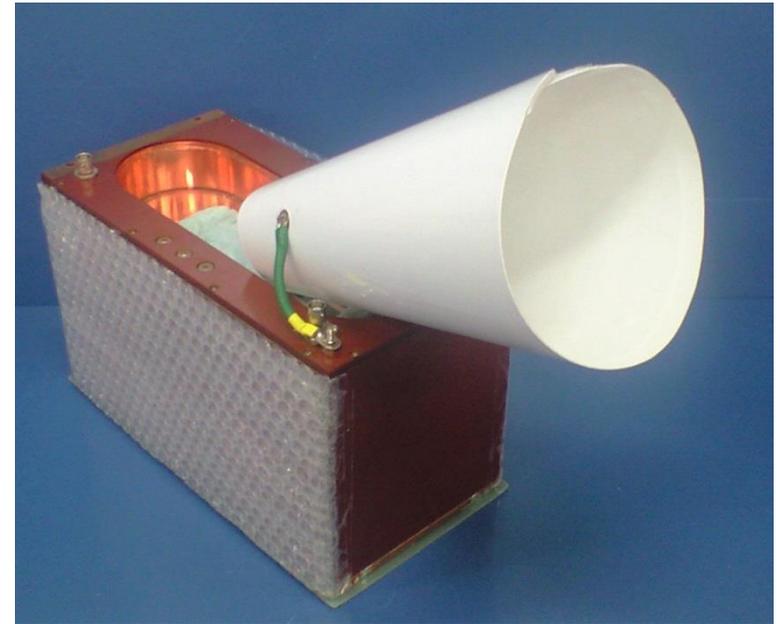
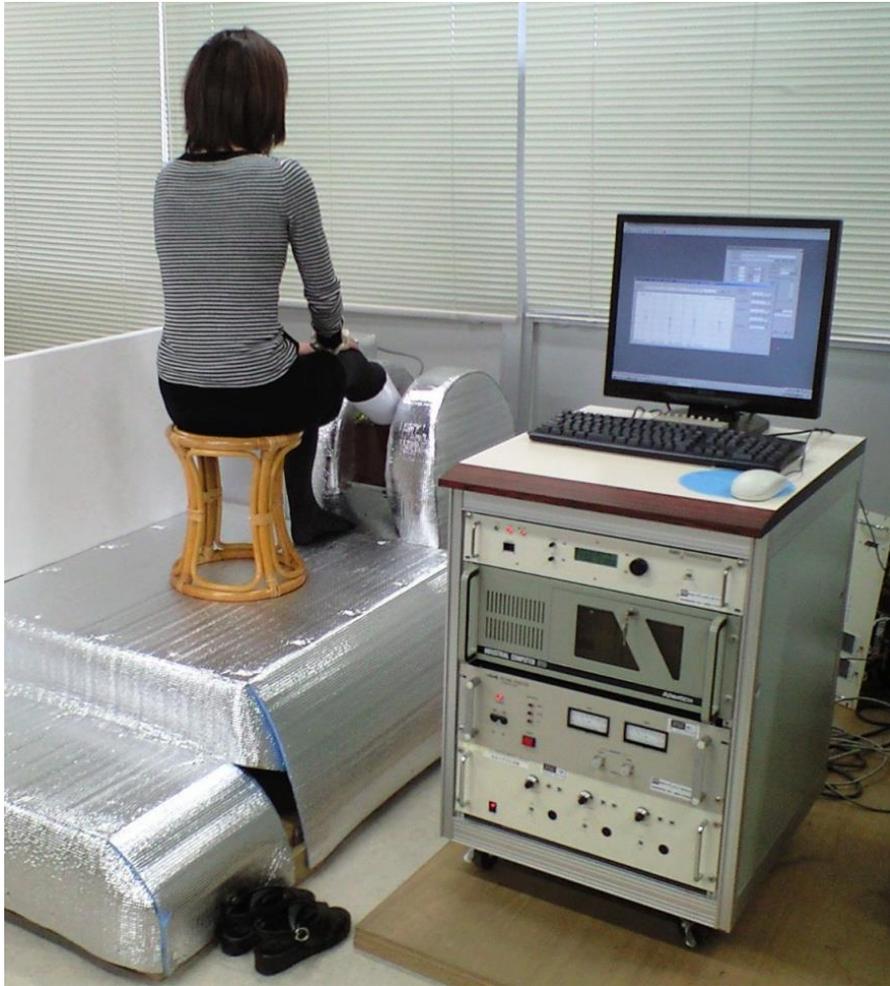
踵骨骨密度計測用MRI(3)

AGE vs TBVF (n=108)



2002年の**学園祭**参加者を対象とした計測(2D)

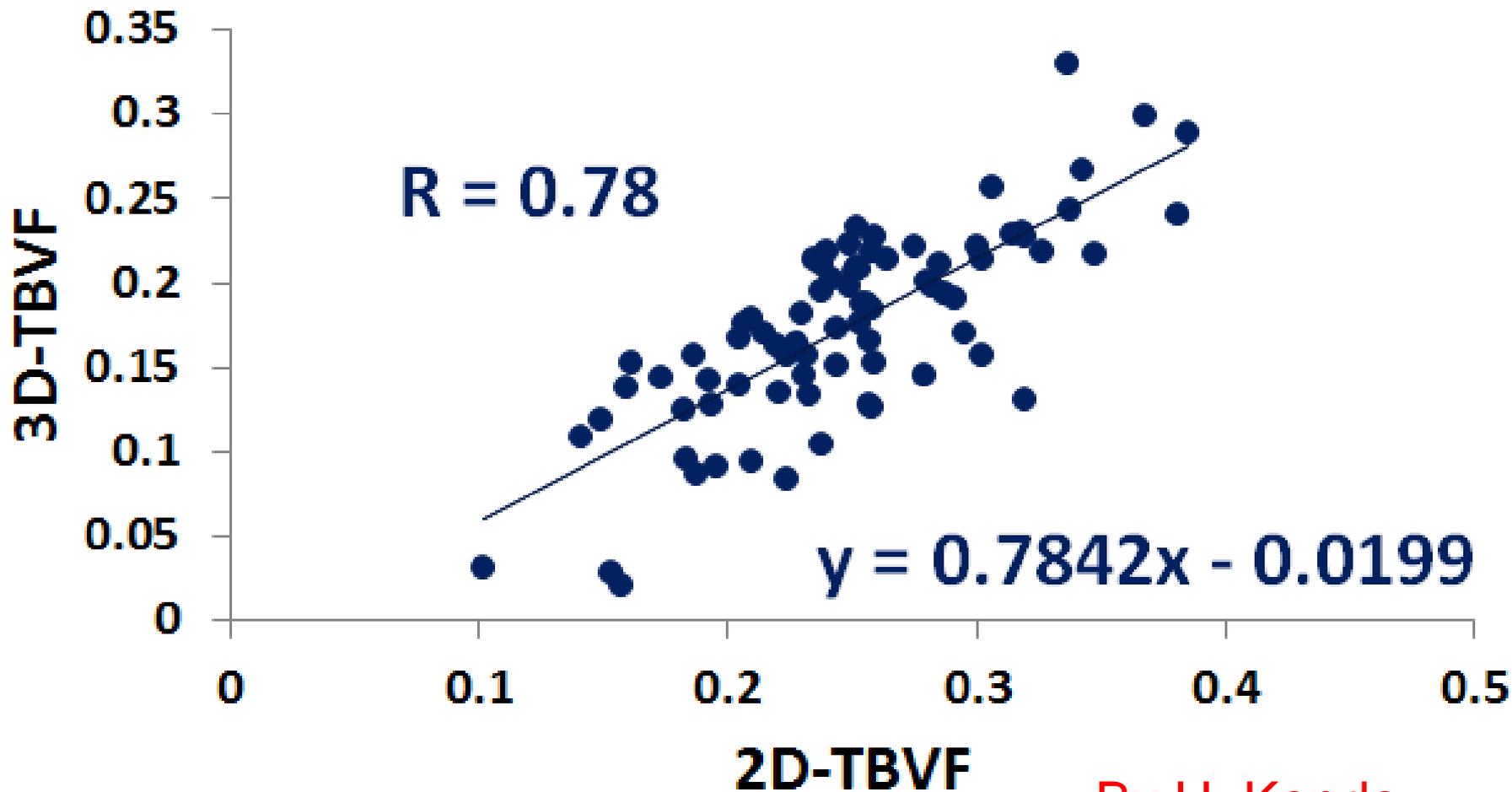
踵骨骨密度計測用MRI(4)



局所シールドを有する
RFプローブ

シールドルーム不要としたシステム. By K. Taniguchi

踵骨骨密度計測用MRI(5)



By H. Kondo

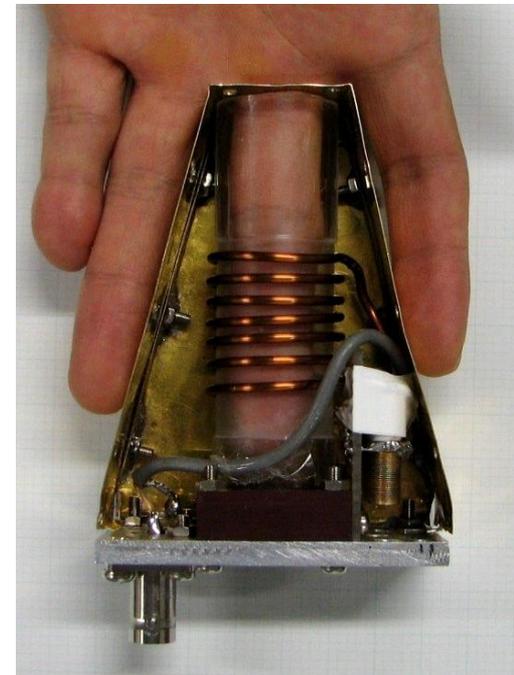
2D中央断面と3D全骨でのTBVFの相関(3Dでは位置決め不要)

指骨骨微細構造計測用MRI(1)

Development of a Compact MRI System for Measuring the Trabecular Bone Microstructure of the Finger

MRM vol.57
272-277 (2007)

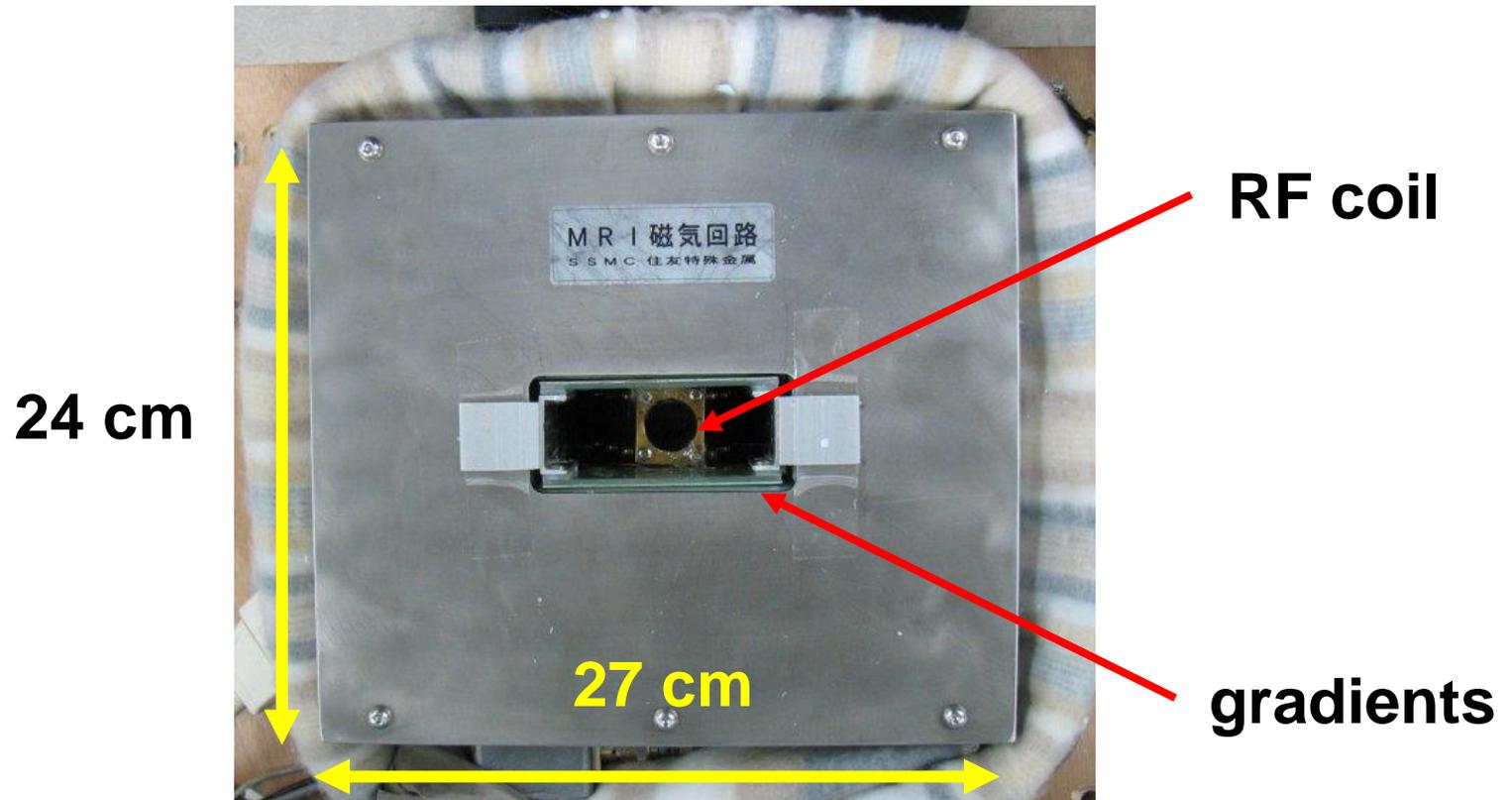
Nachiko Iita, Shinya Handa, Sadanori Tomiha, and Katsumi Kose*



強制回復3DSEを用い、 $160\mu\text{m}$ 立方の3D画像を11分で撮像。

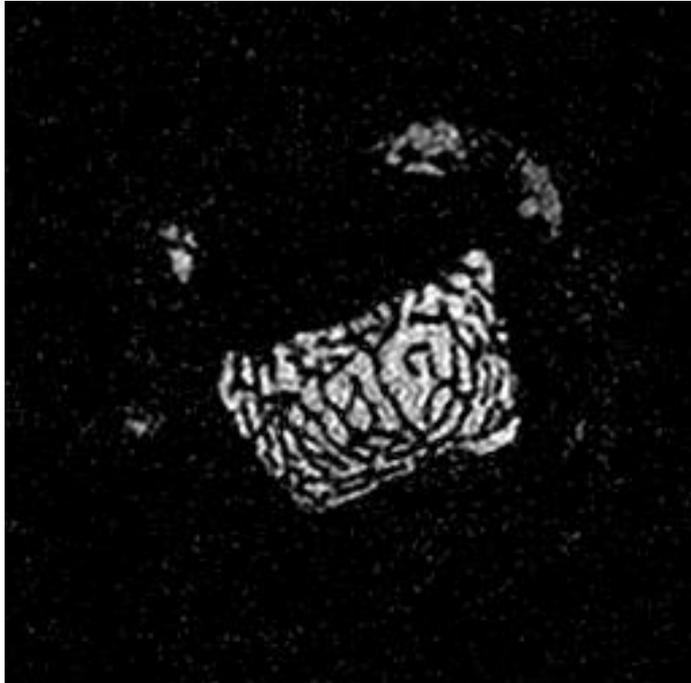
1.0 T, 40mmギャップの磁石を使用(2000年に導入した磁石)

指骨骨微細構造計測用MRI(2)

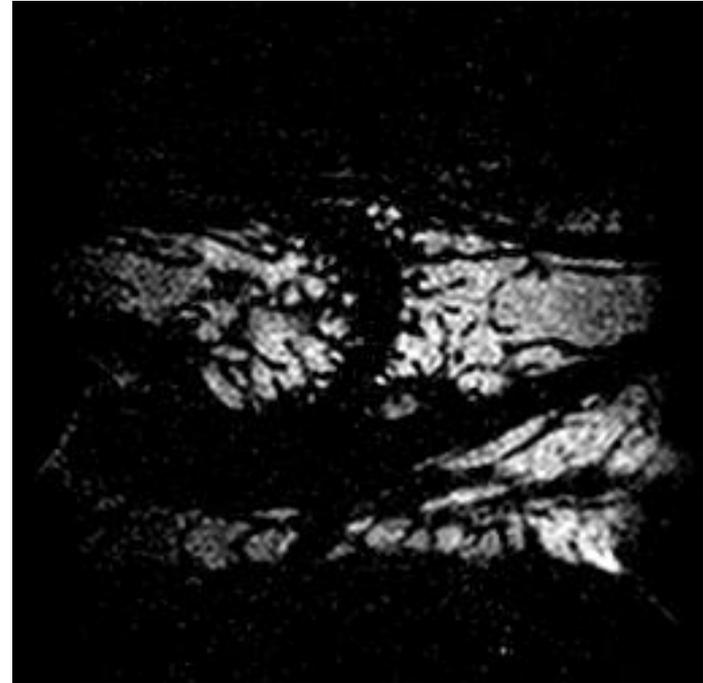


The specification of the magnet; field strength: 1.0 T, gap width: 40 mm, homogeneity: **13 ppm over 13 mm dsv**, size: 27 cm (W) × 24 cm (H) × 18 cm (D), weight: 85kg.

指骨骨微細構造計測用MRI(3)



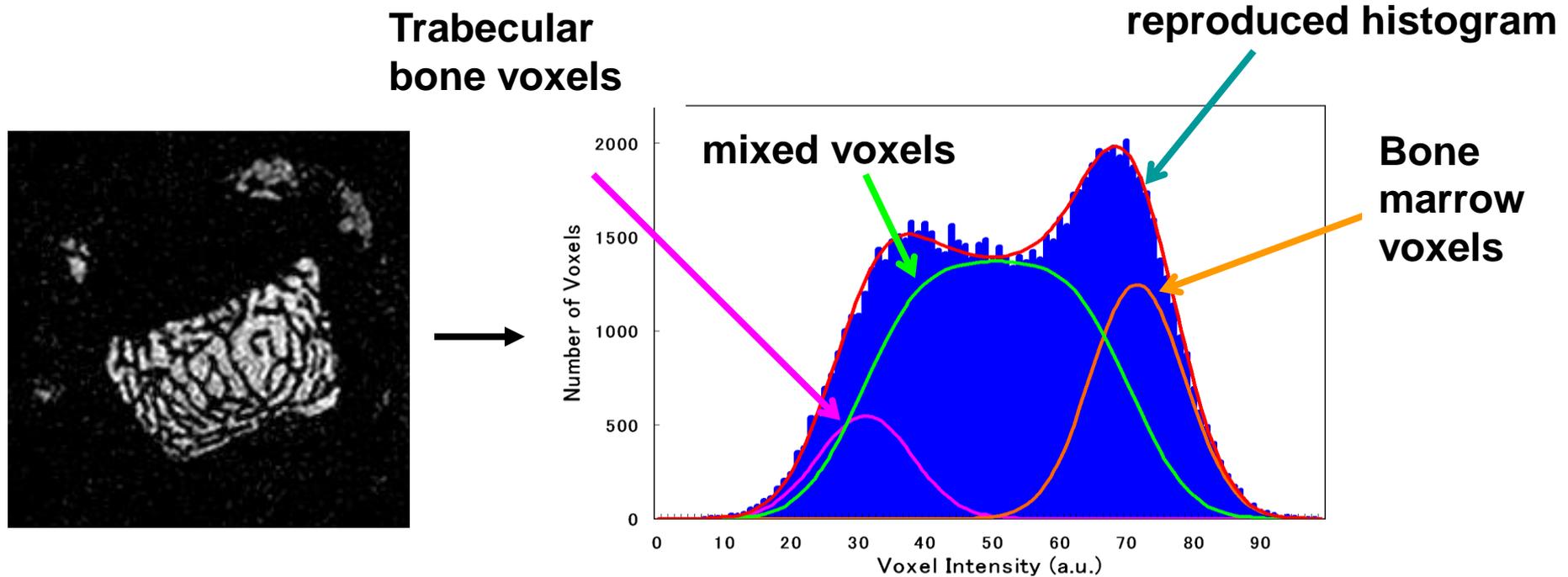
Transverse section



Sagittal section

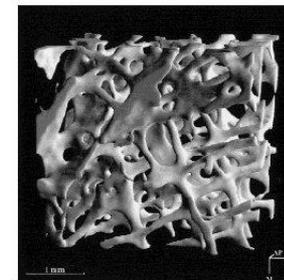
The figures show transverse and sagittal cross-sections selected from a 256^3 voxel 3D image dataset of a middle finger. This dataset was obtained through a zero-filled Fourier interpolation of the 128^3 voxel image. The **voxel size was $(80 \mu\text{m})^3$** .

指骨骨微細構造計測用MRI(4)

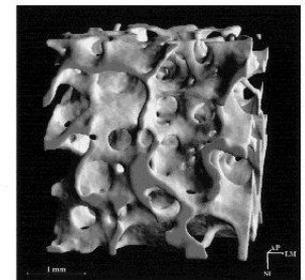


この方法で骨と骨髄の閾値を求め、骨微細構造パラメタをTRI/3DBONEで計算.

Structure model index (SMI) →

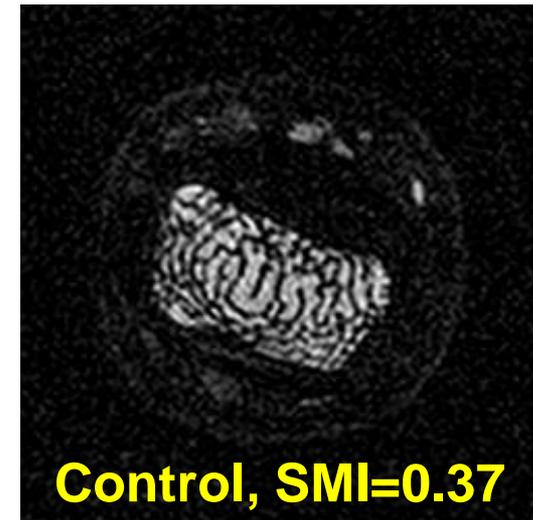
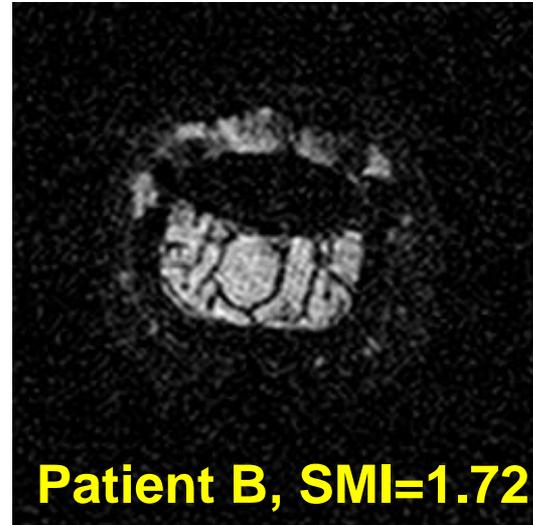
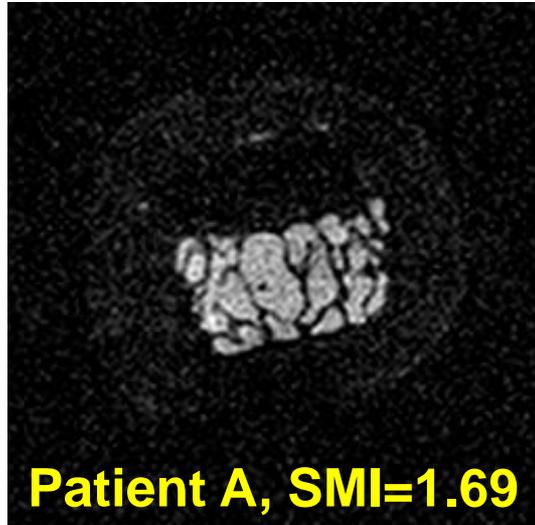


SMI=2.1



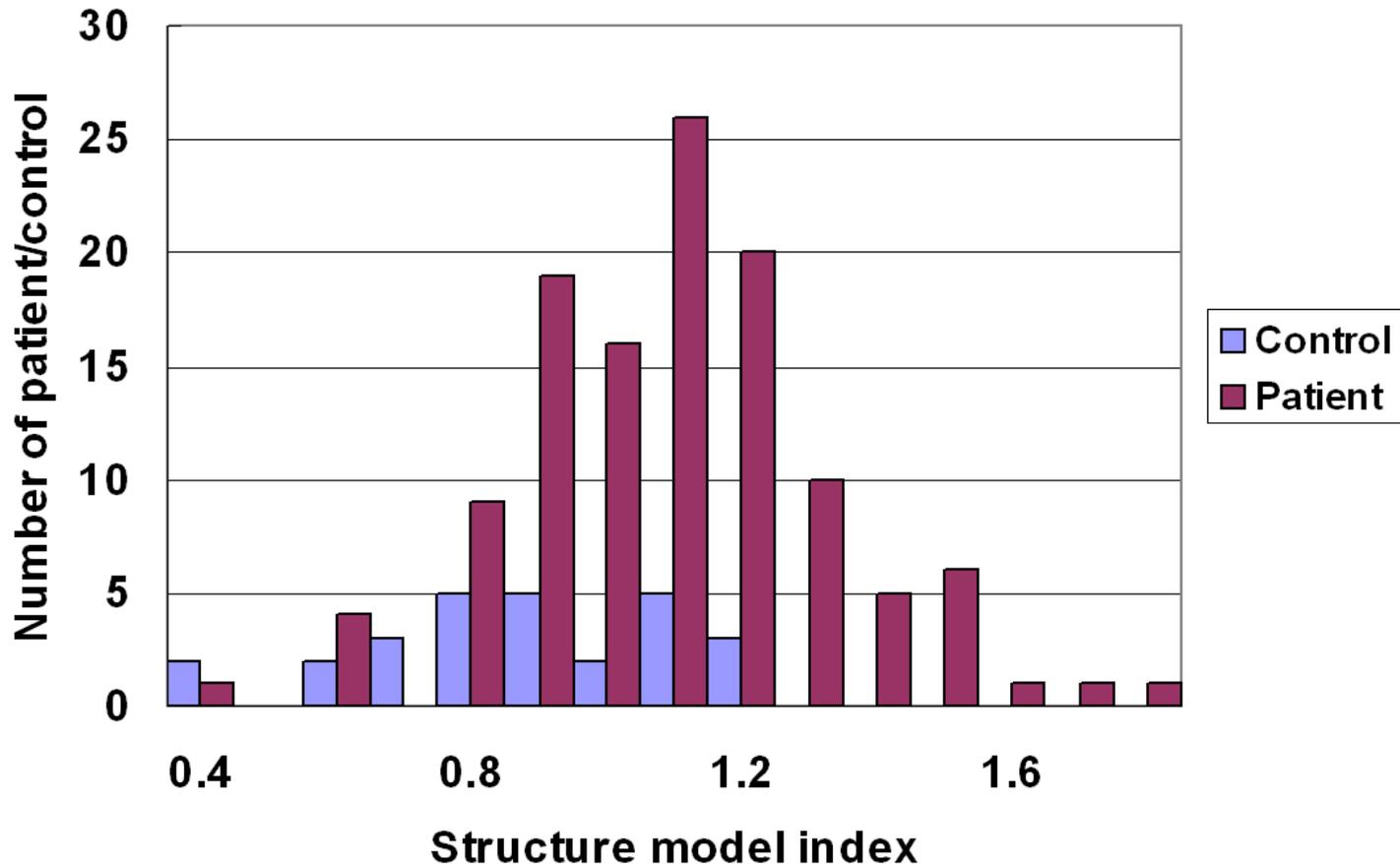
SMI=0.8

指骨骨微細構造計測用MRI(5)



長崎大学の伊東昌子先生のグループで、臨床データ(119人)を収集していただいた。

指骨骨微細構造計測用MRI(6)



Structure model indexという骨微細構造パラメタで, control(27人)とpatient(119人)を区別できる可能性が示唆された.

関節リウマチ診断用MRI (1)

Development of a local electromagnetic shielding for an extremity magnetic resonance imaging system

Shinya Handa,^{1,a)} Tomoyuki Haishi,² and Katsumi Kose¹

¹*Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan*

²*MRTechnology Inc., Tsukuba, Ibaraki 305-8573, Japan*

RSI vol.79
113706 (2008)

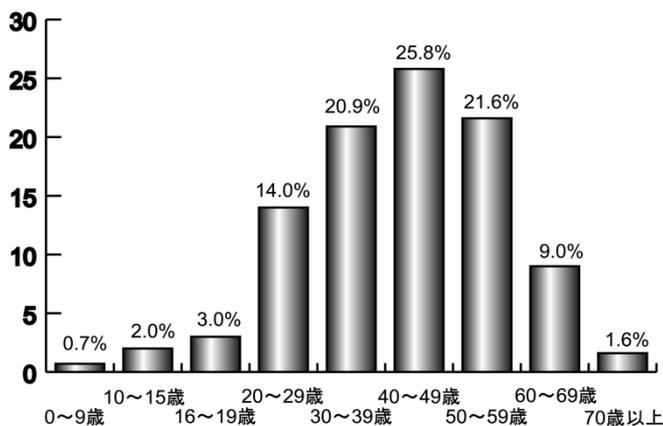


0.3T, 12cmギャップの磁石を使用

関節リウマチ (RA) とは？

関節リウマチ(Rheumatoid Arthritis : RA)

- 自己免疫疾患の一種，原因不明の全身性炎症性疾患で慢性進行性の関節破壊が特徴
- 患者数は国内に約70万人，1万5千人が新たに発症するとされている
- 病状が進行するにつれて関節破壊進み，患者のQOLを著しく低下させる



関節リウマチと診断された年齢



末期RA症例の手

関節リウマチ診断用MRIの必要性

RAは、かつては、治療が難しく、進行を抑えることが難しい病気とされていたが、最近では、**早期に発見して適切な治療**を行えば、かなり回復することが分かってきた。

早期発見には、抗体検査だけでなく、**手のMRI検査の併用**が診断精度を向上させると言われており、また、手のMRIは**薬剤の治療効果判定**にも有用であるとされている。

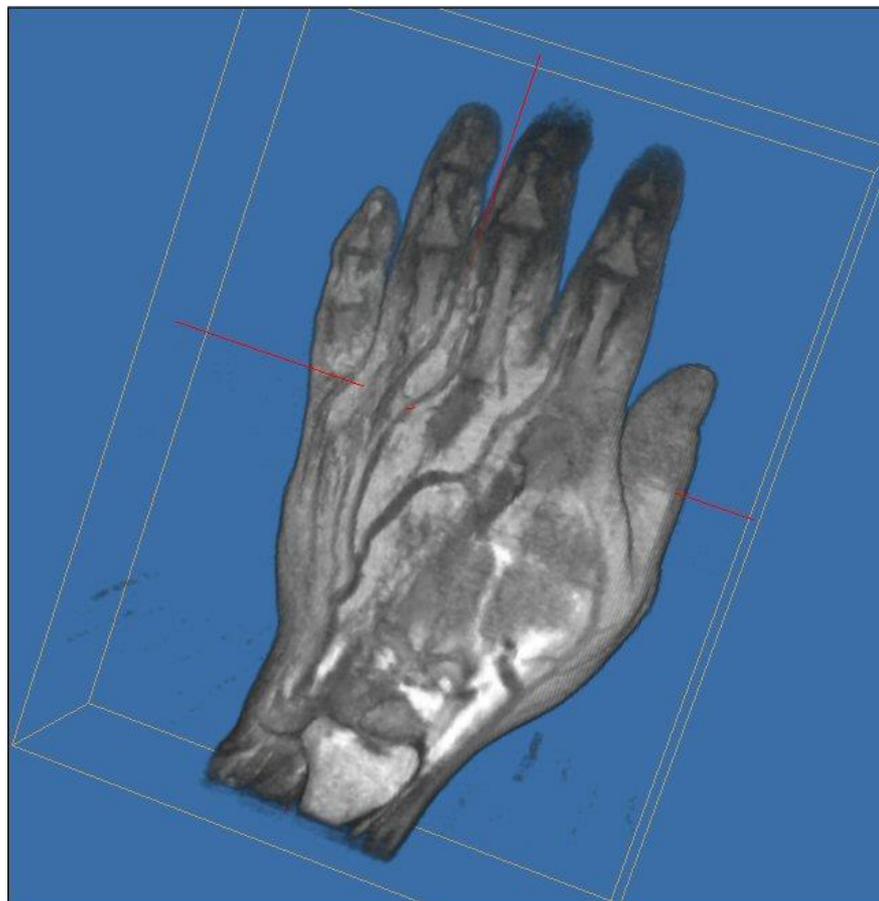
ところが、WB-MRIを使用した手の検査は、頭部や腹部を主な検査対象とする**大規模病院では優先度が低く**、また検査は他の部位に比べ煩雑であるため、小規模病院でも使用できる、**手専用のMRI開発**が渴望されてきた。

関節リウマチ診断用MRI (2)

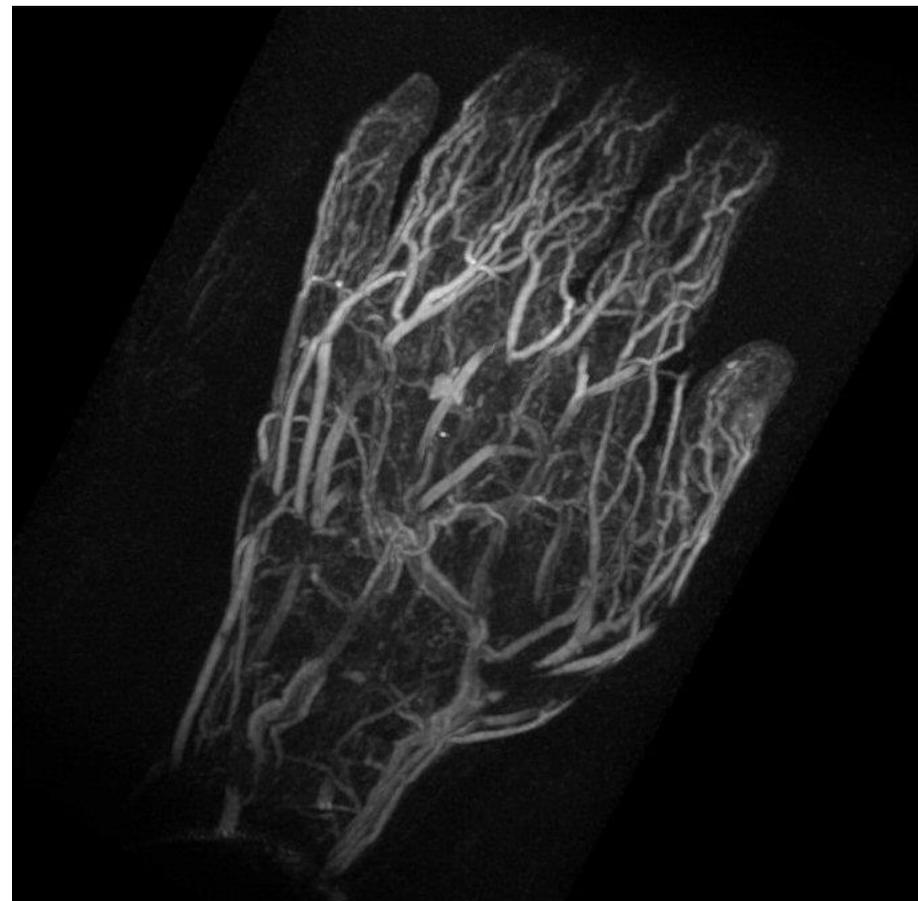


関節リウマチ診断用MRI(0.3 T): 2008年11月医用機器認可

RA用MRIによる撮像例



T_1 強調画像



脂肪抑制 T_2 強調画像

0.3T:手専用MRIによる撮像

関節リウマチ診断用MRI：臨床例



RA症例 35歳女性の左手の症例：筑波大学附属病院提供

小児骨年齢計測用MRI

Improved Reliability in Skeletal Age Assessment Using a Pediatric Hand MR Scanner with a 0.3T Permanent Magnet

Yasuhiko TERADA^{1*}, Saki KONO¹, Tomomi UCHIUMI¹, Katsumi KOSE¹,
Ryo MIYAGI², Eiko YAMABE², Yasunari FUJINAGA², and Hiroshi YOSHIOKA²

MRMS online
2014



0.3T, 12cmギャップの磁石を使用

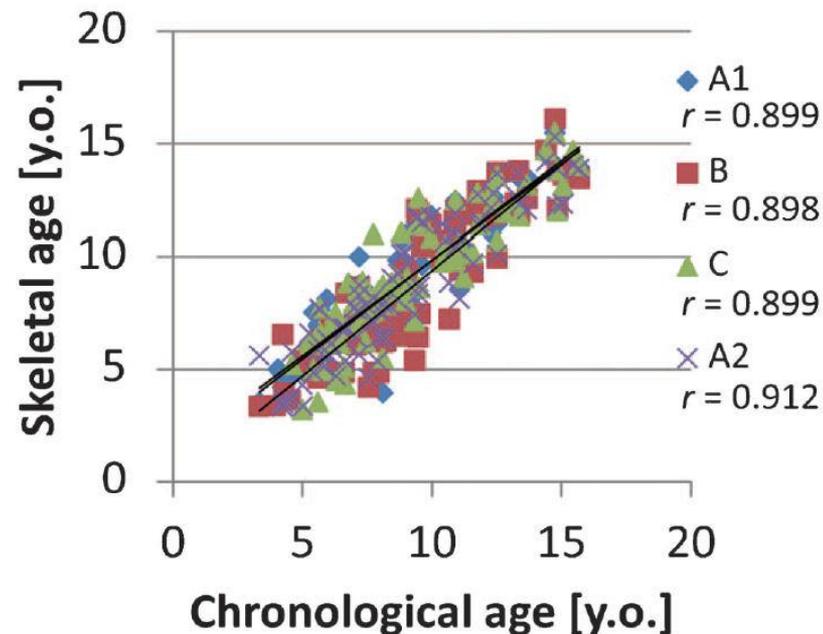


Fig. 3. Correlation between skeletal age rated from magnetic resonance (MR) images and chronological age.

講演の内容

1. はじめに

2. Compact/Mobile MRIの誕生と概要

3. 人体局所用MRI

踵骨骨密度測定用MRI, 指骨骨微細構造計測用MRI

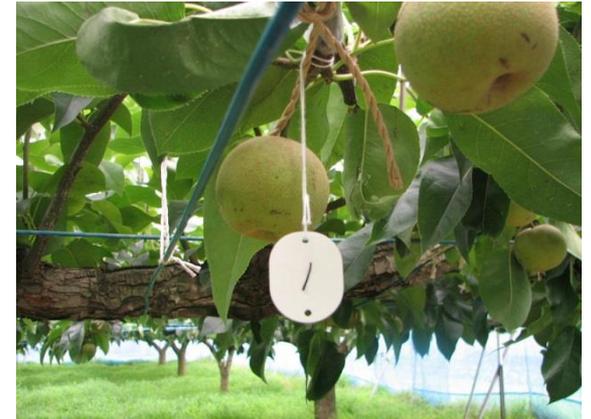
関節リウマチ診断用MRI, 小児骨年齢計測用MRI

4. 植物計測用MRI

梨果実計測用MRI, 梨枝計測用MRI, 樹木計測用MRI

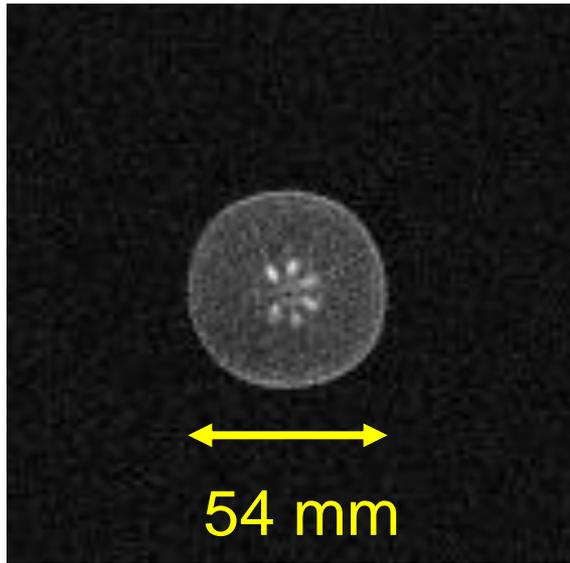
5. むすび

梨果実計測用MRI at 0.12T (1)

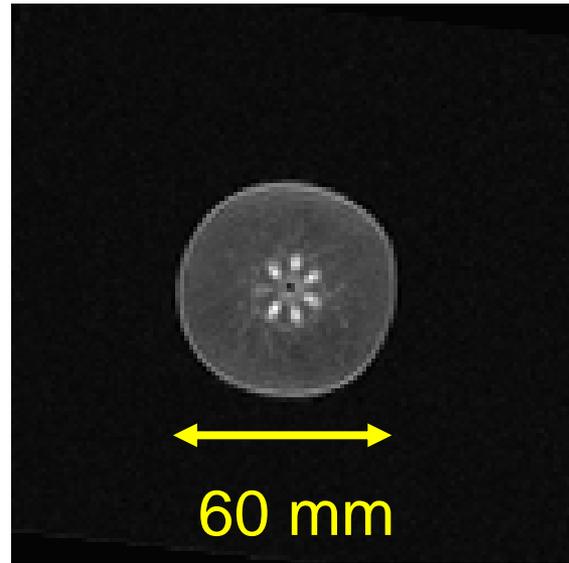


3D images (128 x 128 x 128 matrix) of five pears were acquired *in situ* from July 10th to August 12th, 2009.

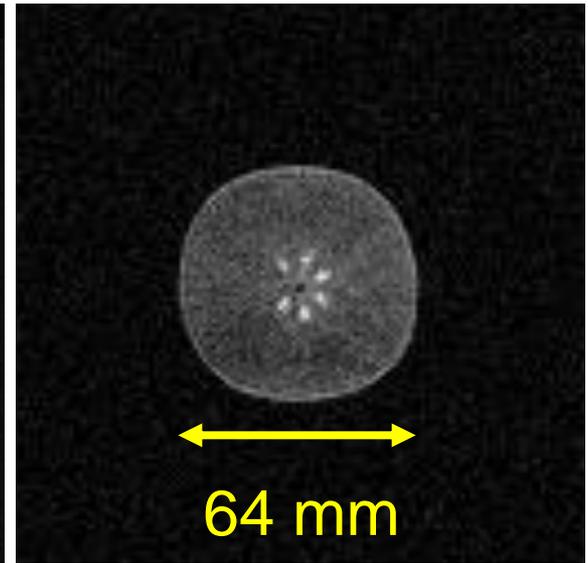
梨果実計測用MRI at 0.12T(2)



July, 10th



July, 16th

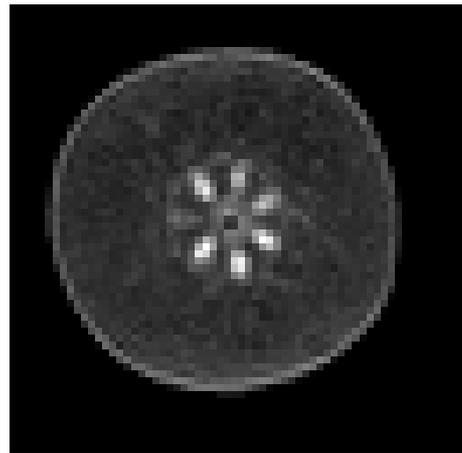


July, 22nd



同一サンプルの同一断層面を表示

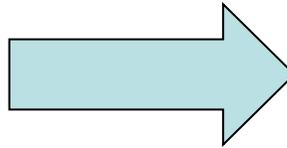
梨果実計測用MRI at 0.12T(3)



76.8 mm

July, 16th

4 weeks



128 mm

August, 12th

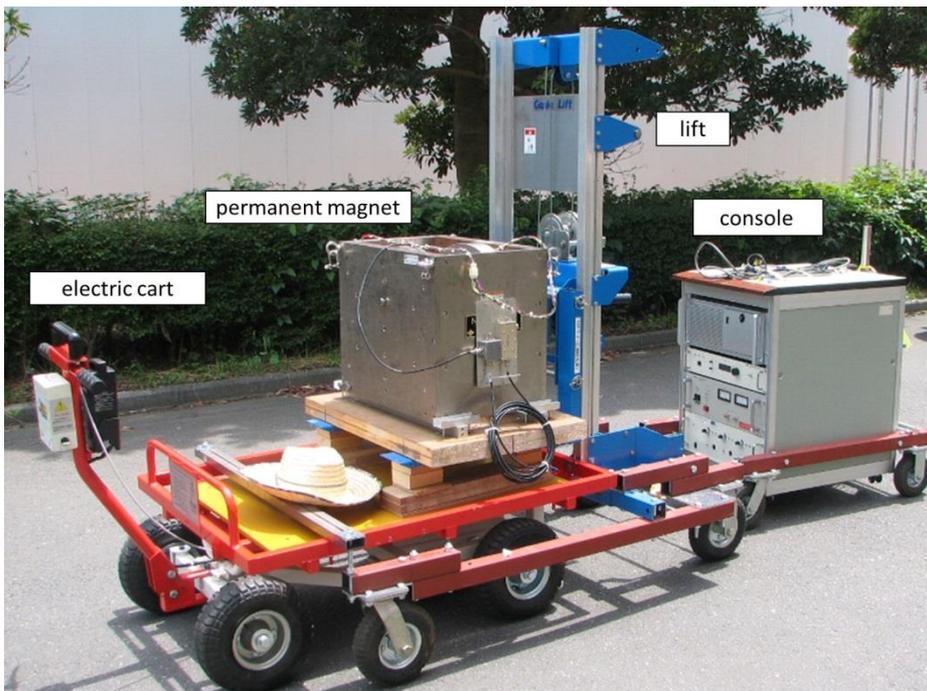
成長のプロセスにおいて、緩和時間が大きく変化する

梨果実計測用MRI at 0.2T (1)

Longitudinal NMR parameter measurements of Japanese pear fruit during the growing process using a mobile magnetic resonance imaging system

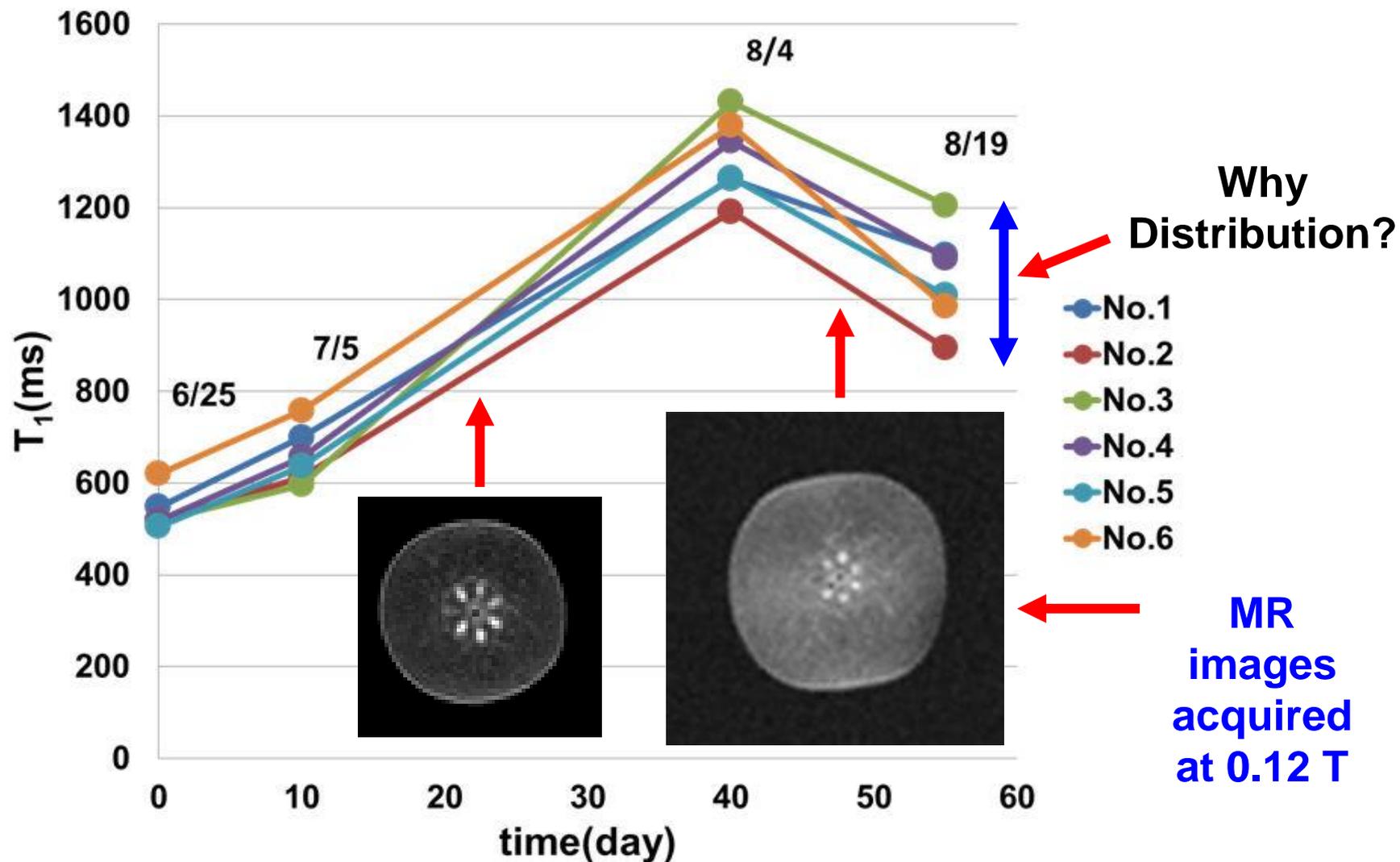
JMR vol.226
45-51 (2013)

Yuto Geya^a, Takeshi Kimura^a, Hirotaka Fujisaki^a, Yasuhiko Terada^a, Katsumi Kose^{a,*}, Tomoyuki Haishi^b, Hiroshi Gemma^c, Yoshihiko Sekozawa^c



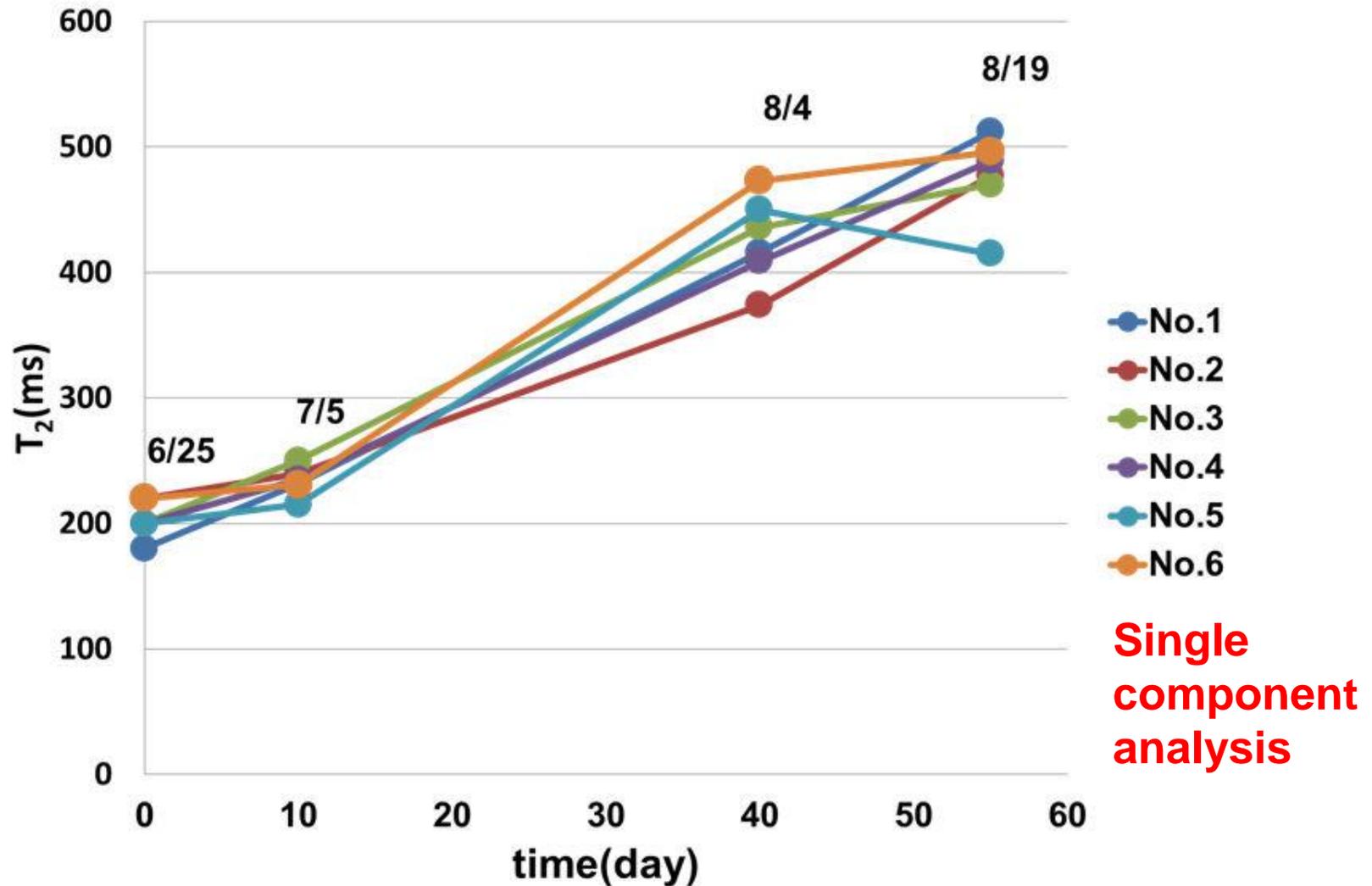
0.2T, 16cm gap, 200kgの磁石とMobile MRIを使用, 2010~2011

In situ T_1 measurements for six pears



T_1 monotonously increased with time but **finally decreased**.

In situ T_2 measurements for six pears



T_2 monotonously increases with time.

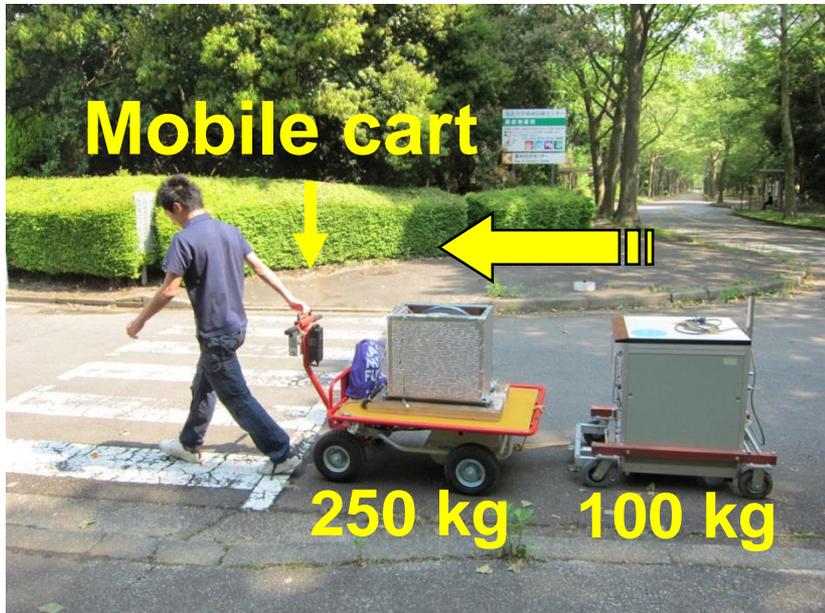
In situ NMR using a 0.2T MRI system

Problems:

1. 梨果実は木から取れ易いため、磁石中央の静磁場・高周波磁場の均一性の高い領域に置くことが難しい。
2. 緩和時間の個体差の原因が不明
→ 多数の梨サンプルを用いた正確な緩和時間計測. 摘果直後に計測.



Ex vivo NMR using a 0.2T MRI system (2011)



Lightest
on the day

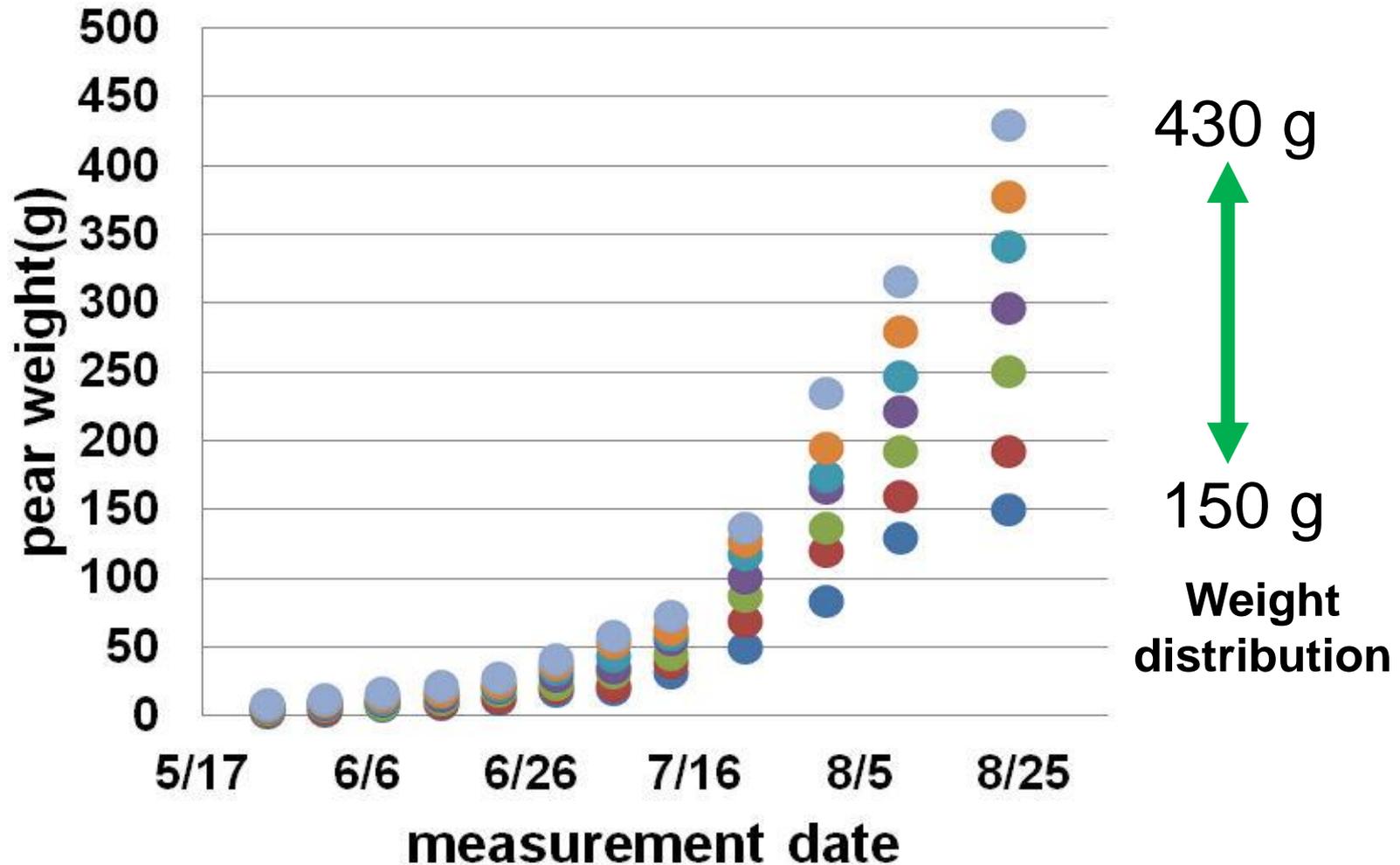


Heaviest
on the day

The weight is evenly distributed.

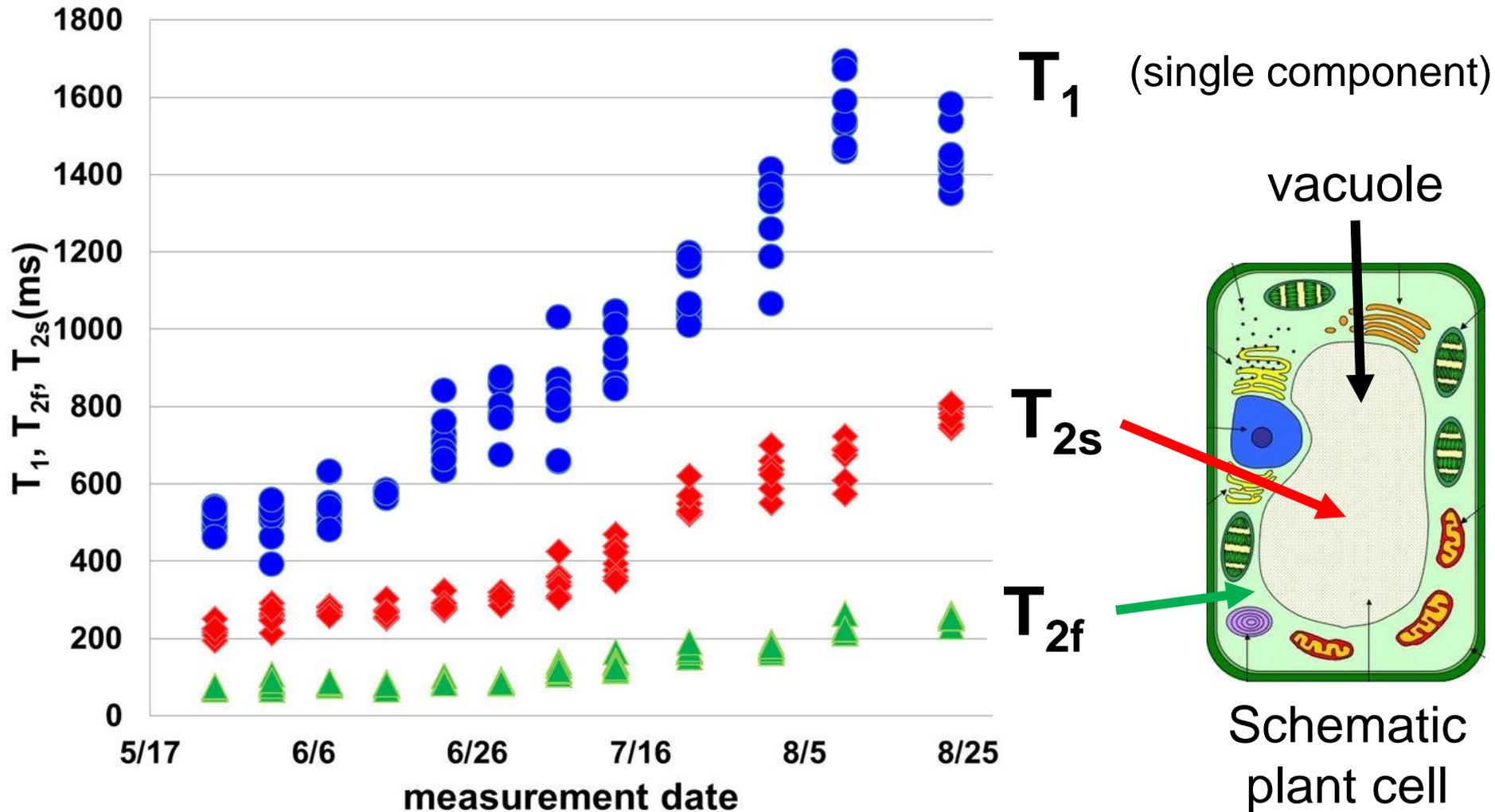
5月25日から8月23日まで、ほぼ毎週、7個の梨の緩和時間計測を行った。

Weight distribution of the harvested pears



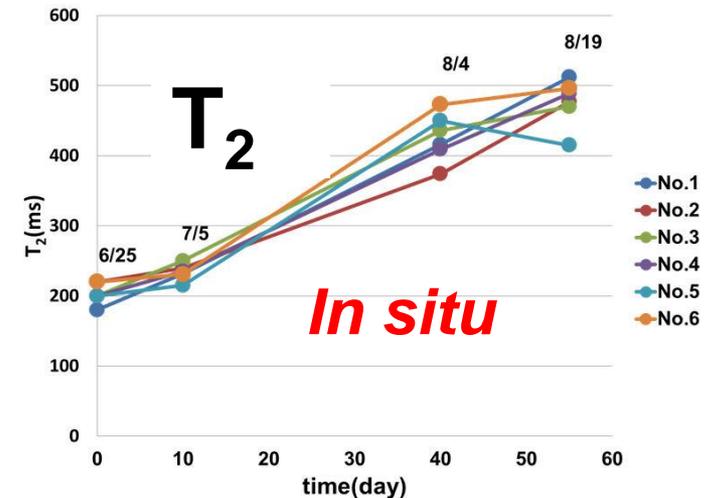
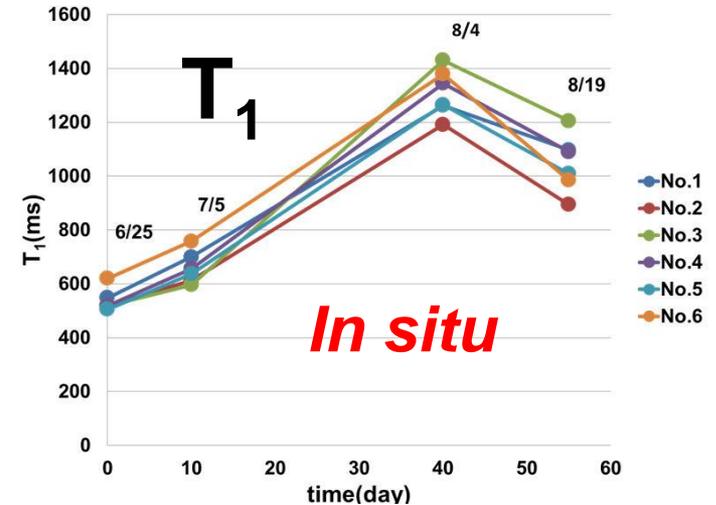
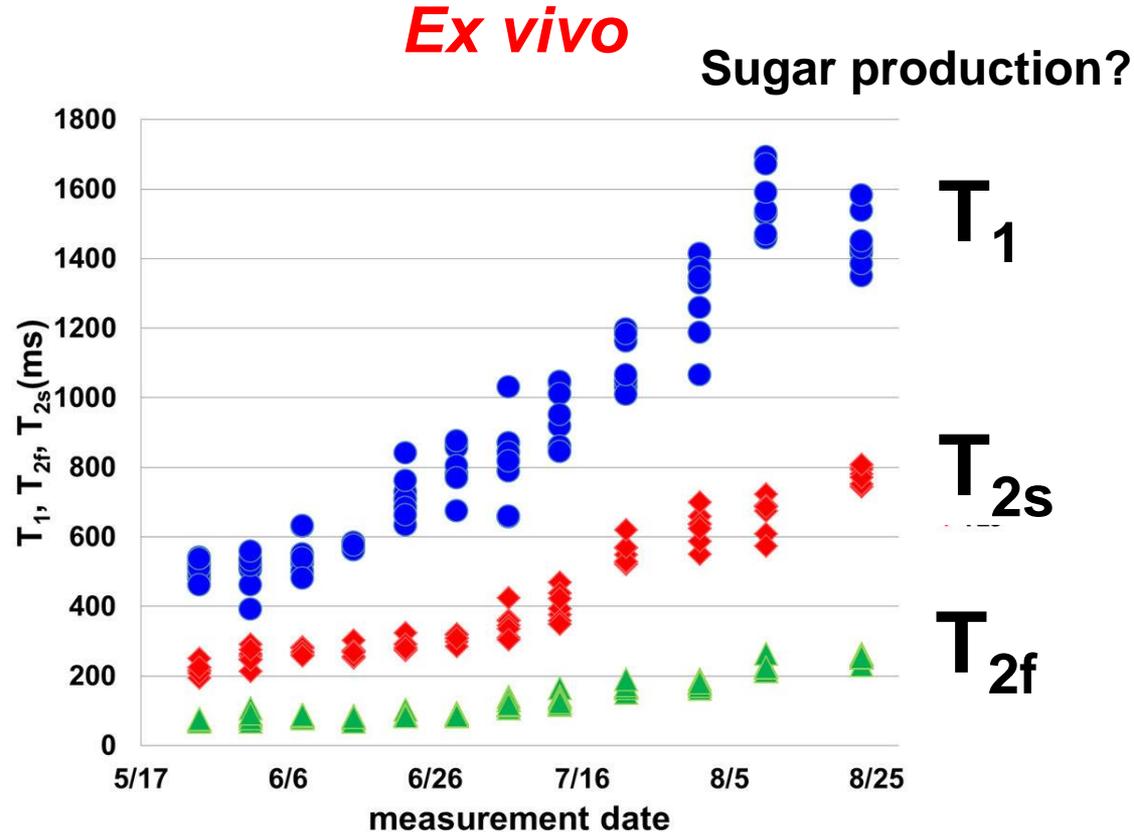
84 pears were harvested from a **single Japanese pear tree**, which bears more than **several hundreds pears** every year.

T_1 , T_2 vs. measured date



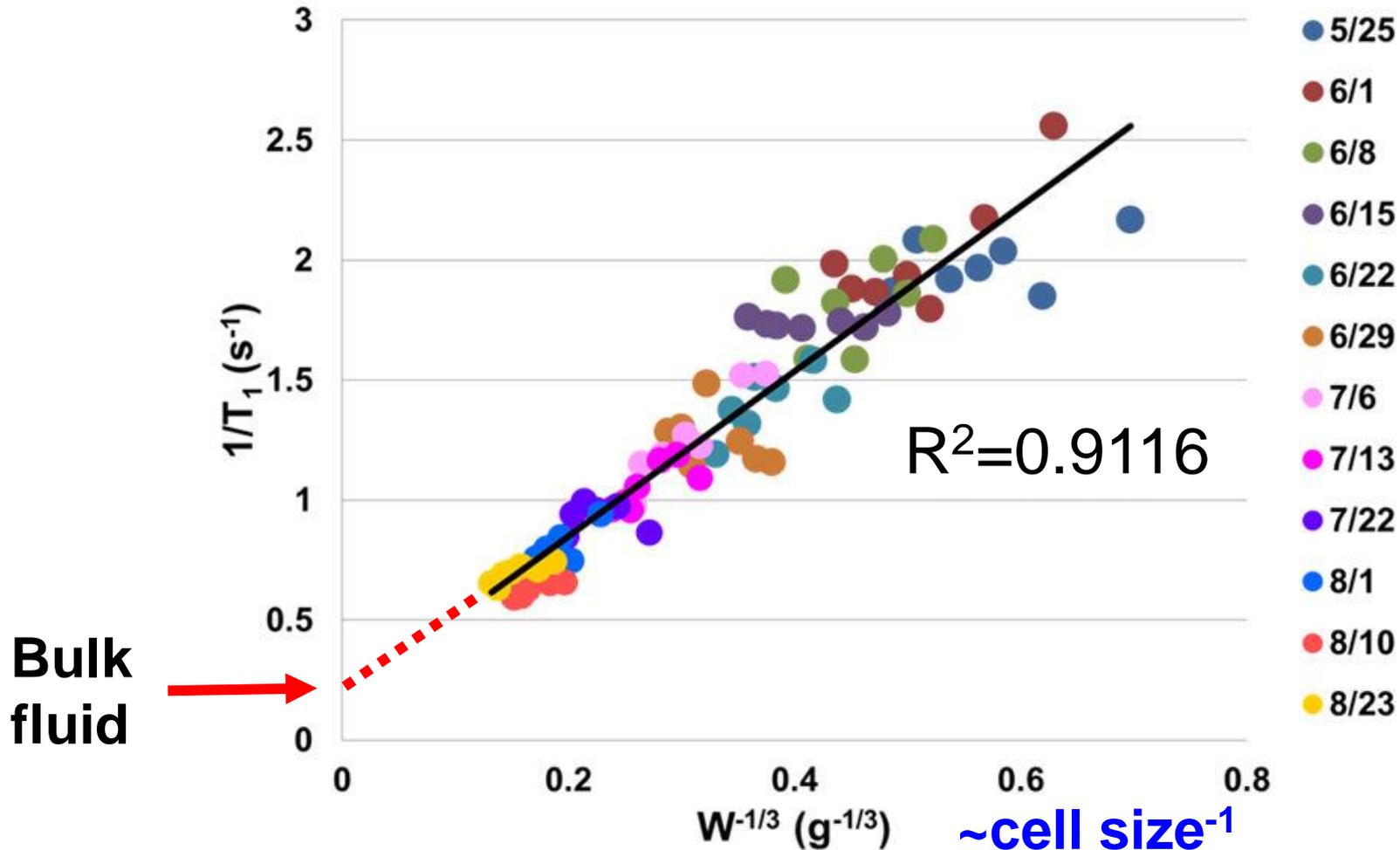
Relaxation times increase with time but T_1 finally decreases.

Comparison between *ex vivo* and *in situ* results



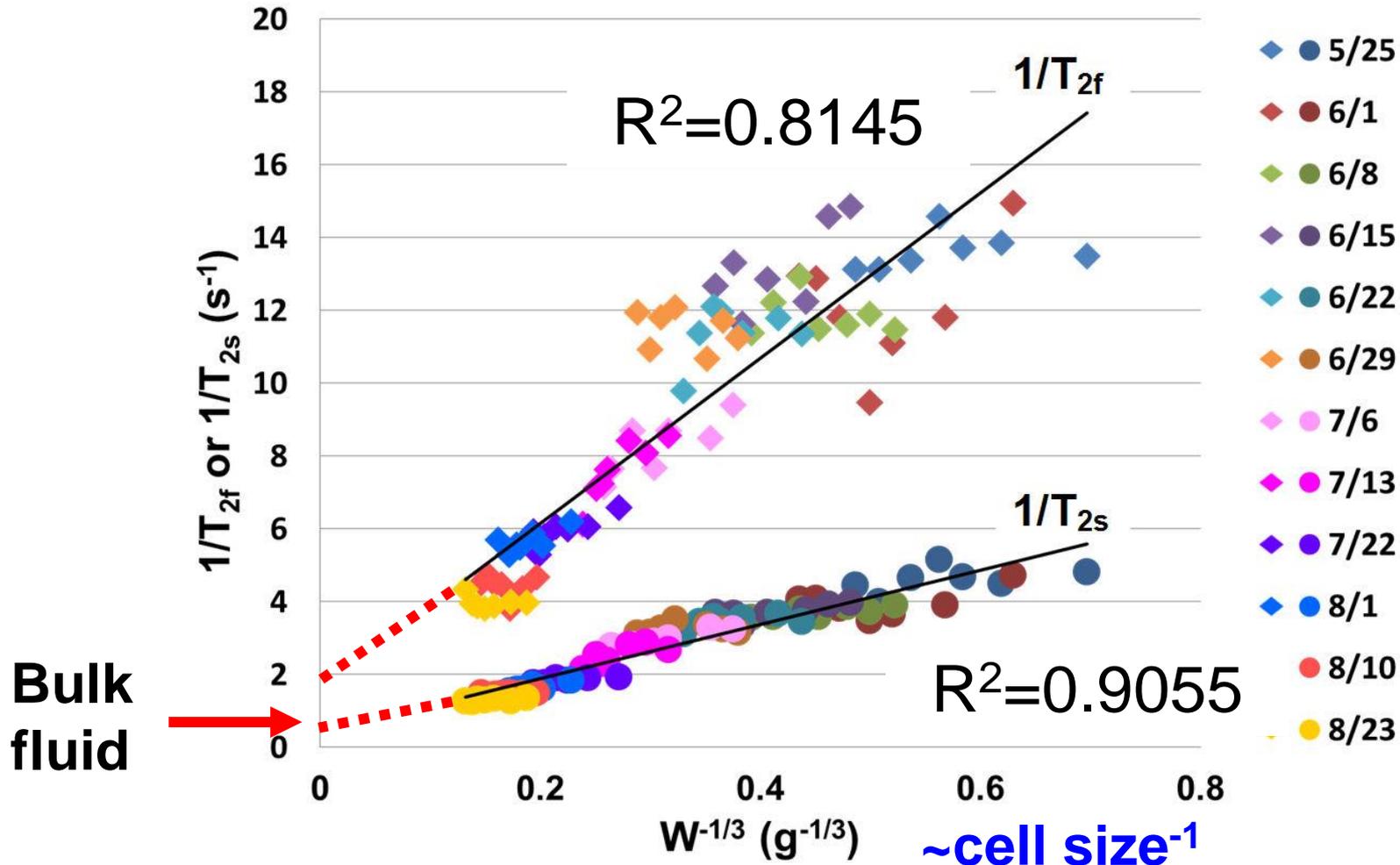
Ex vivo and **in situ** results show **good agreements**. T_2 was not decomposed for **in situ** measurements.

Relaxation rate ($1/T_1$) vs (weight) $^{-1/3}$



The T_1 relaxation rates plotted against the inverse of **the cubic root of the weight (~cell size)** shows good linear relations.

Relaxation rate ($1/T_2$) vs (weight) $^{-1/3}$



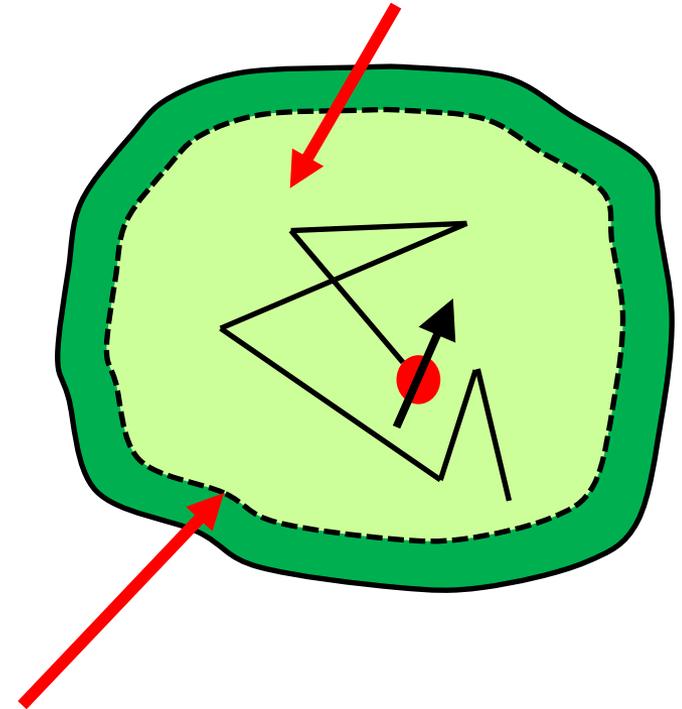
The T_2 relaxation rates plotted against the inverse of **the cubic root of the weight (\sim cell size)** shows good linear relations.

Relaxation mechanism for the pear fruit cell

$$\frac{1}{T_1} = \frac{1}{T_{1bulk}} + \frac{1}{T_{1surface}}$$

$$\frac{1}{T_2} = \frac{1}{T_{2bulk}} + \frac{1}{T_{2surface}} + \frac{1}{T_{2diffusion}}$$

Bulk fluids: longer T_2



Boundary of the fluid: faster relaxation

Relaxation times in plant cells are dominated by the **surface relaxation** mechanism.

Relaxation mechanism for the pear fruit cell

$$\frac{1}{T_{1surface}} = \rho_1 \left(\frac{S}{V} \right)_{pore}$$

ρ_1 : T_1 surface relaxivity

ρ_2 : T_2 surface relaxivity

$$\frac{1}{T_{2surface}} = \rho_2 \left(\frac{S}{V} \right)_{pore}$$

$\left(\frac{S}{V} \right)_{pore}$: ratio of surface area to fluid volume

$$\left(\frac{S}{V} \right) \propto \frac{1}{L} \propto W^{-1/3}$$

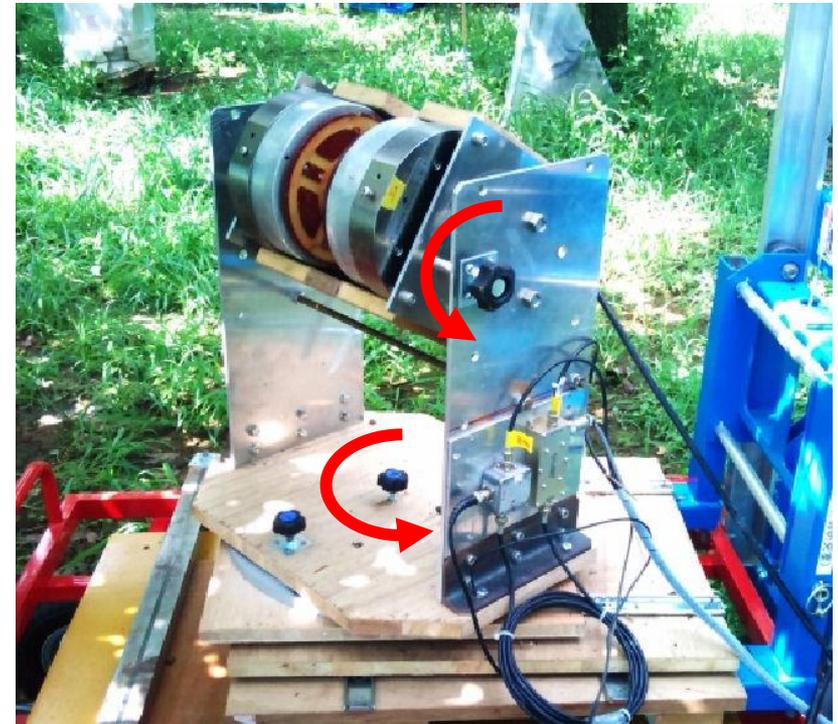
Because the **surface relaxation rate** are proportional to the ratio of the surface to the volume of the pore, or the **inverse of the linear dimension of the cell**. This is the reason why the relaxation rate linearly changes with the inverse of the cubic root of the fruit weight.

梨枝計測用電動モバイルMRI

Development of a mobile magnetic resonance imaging system for outdoor tree measurements

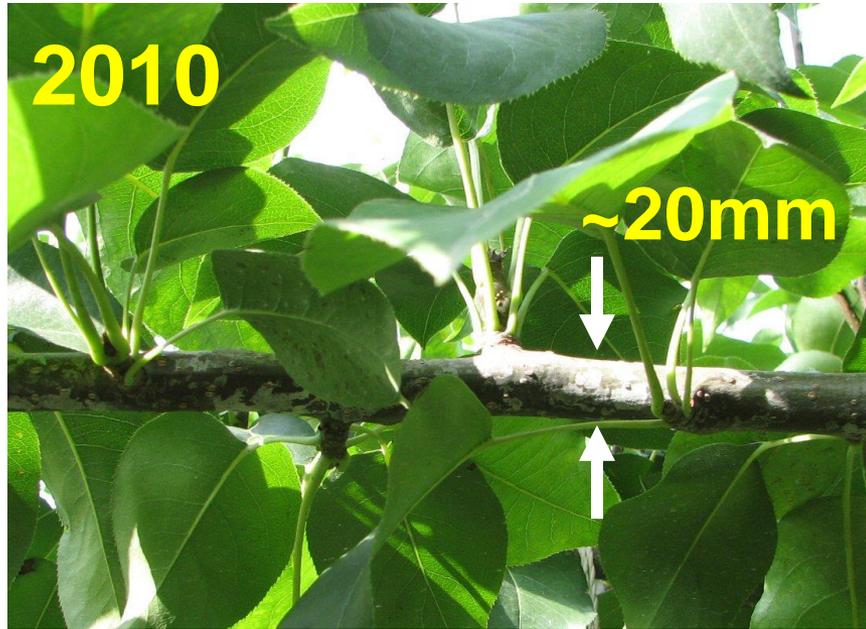
Takeshi Kimura,¹ Yuto Geya,¹ Yasuhiko Terada,¹ Katsumi Kose,^{1,a)} Tomoyuki Haishi,² Hiroshi Gemma,³ and Yoshihiko Sekozawa³

RSI vol.82
053704 (2011)



0.3T, 80mm gap磁石を使用. 1998年に購入. 2軸回転機構.

MRI of normal/diseased branches of a pear tree



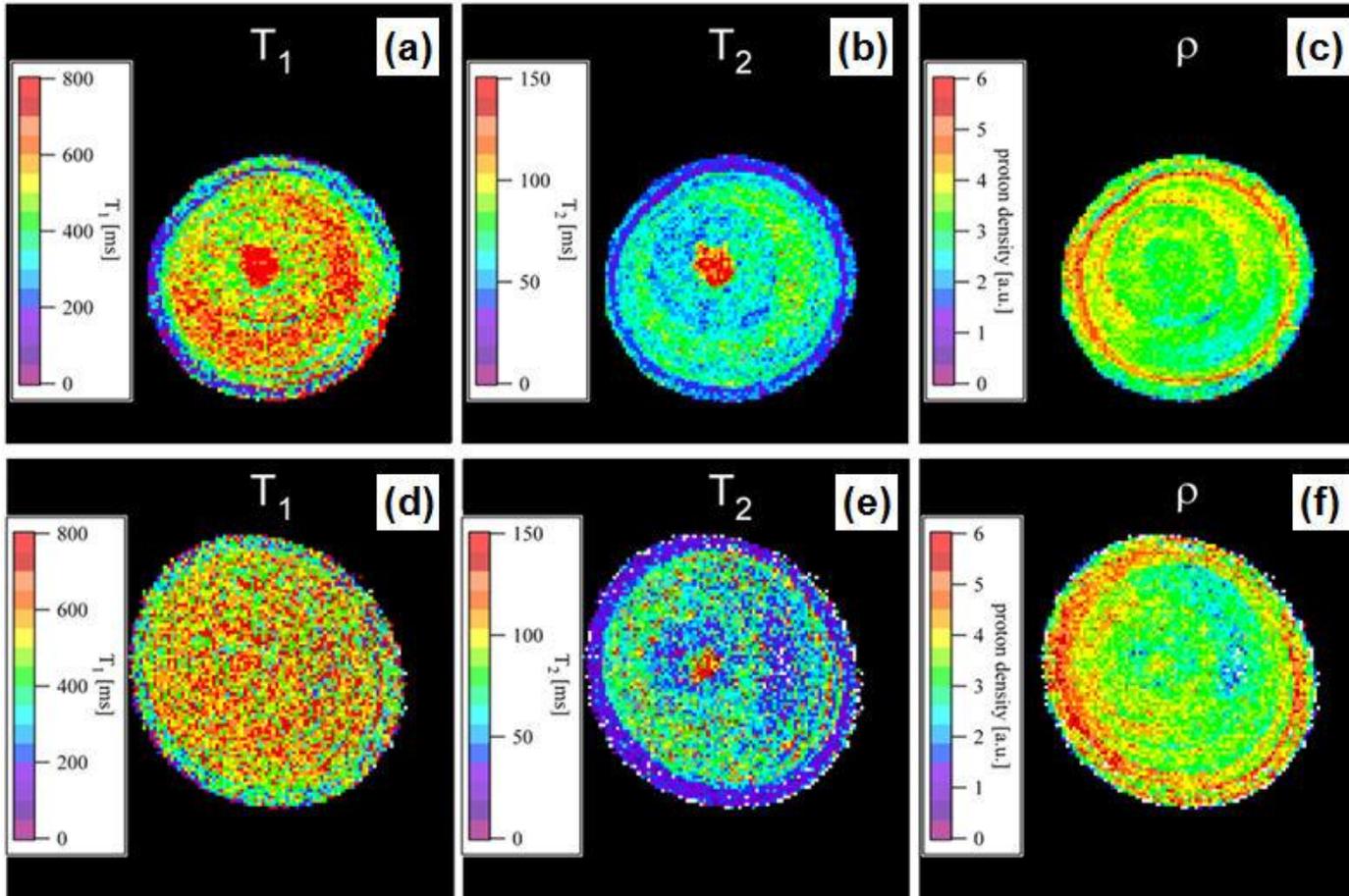
normal branch



diseased branch

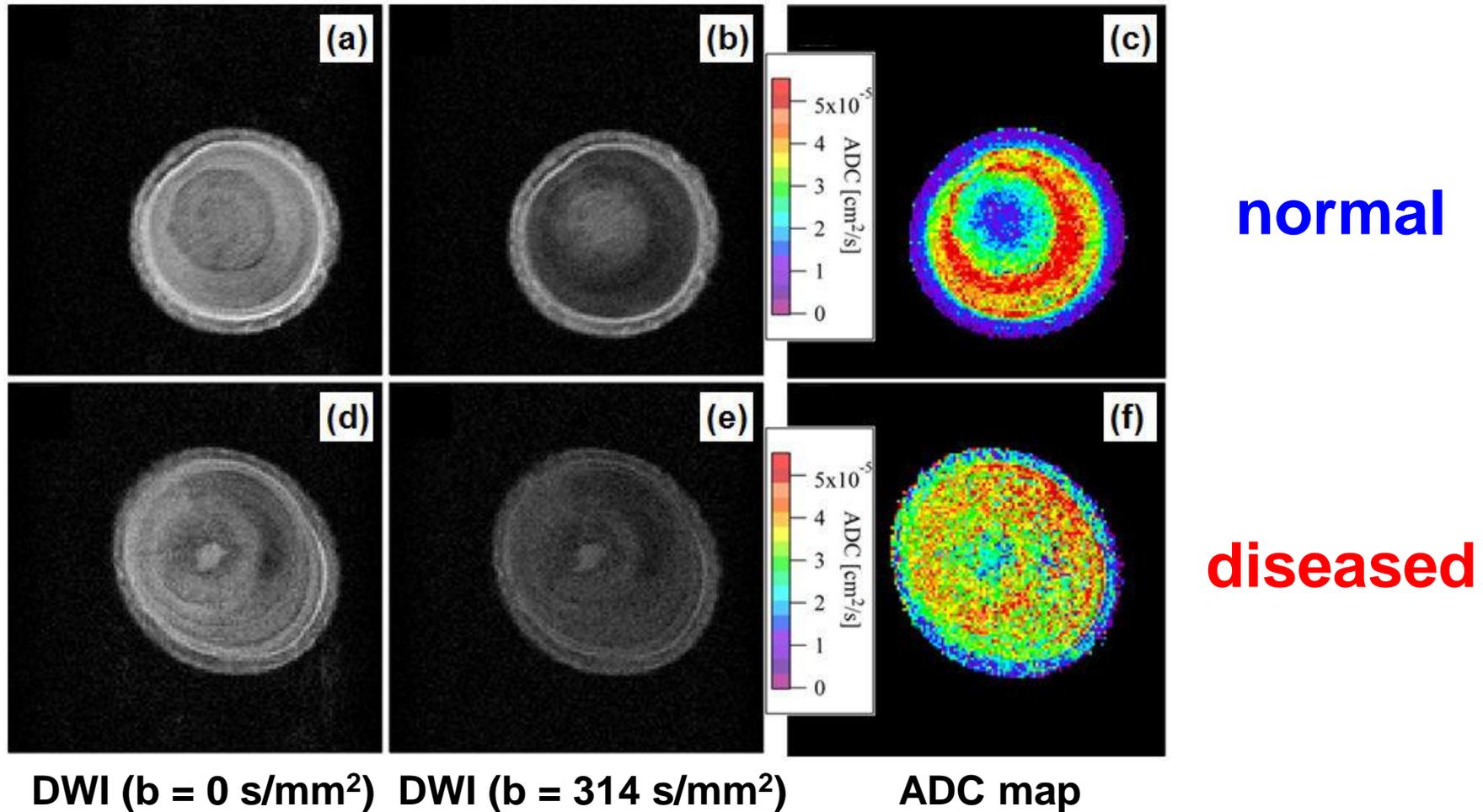
The **dwarf disease** is a serious disease in Japanese pear farms, because this disease damages the **branches** and **drastically reduces yields** of pear fruit. To observe the **function** of the pear branches, we measured MR images of the cross-sections.

NMR parameter mapping



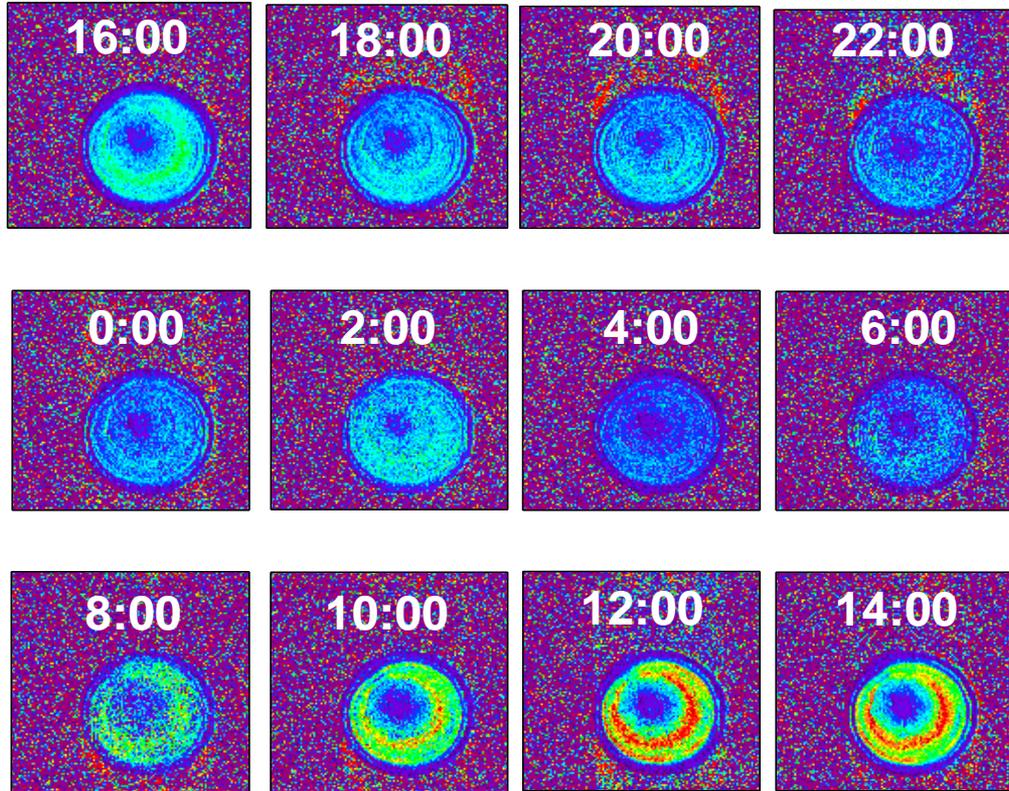
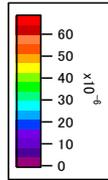
T_1 , T_2 , and proton density of the normal and diseased branches in the cross sections. Clear difference was not observed.

DWI and ADC mapping

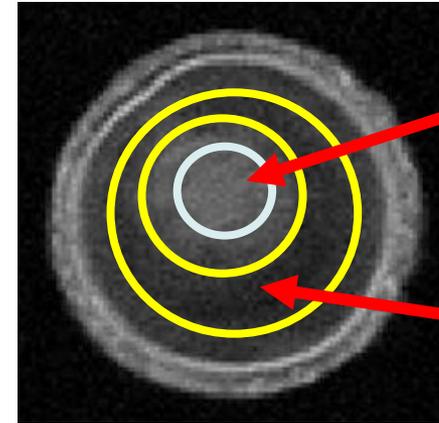


In the ADC map, we can see **very clear structure** in the normal branch but we cannot see such structure in the disease branch.

24-hour measurements (every 2 hours)

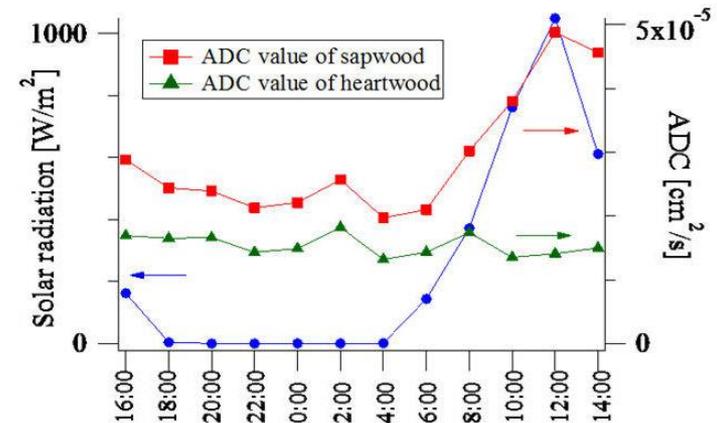


**Maximum
ADC**



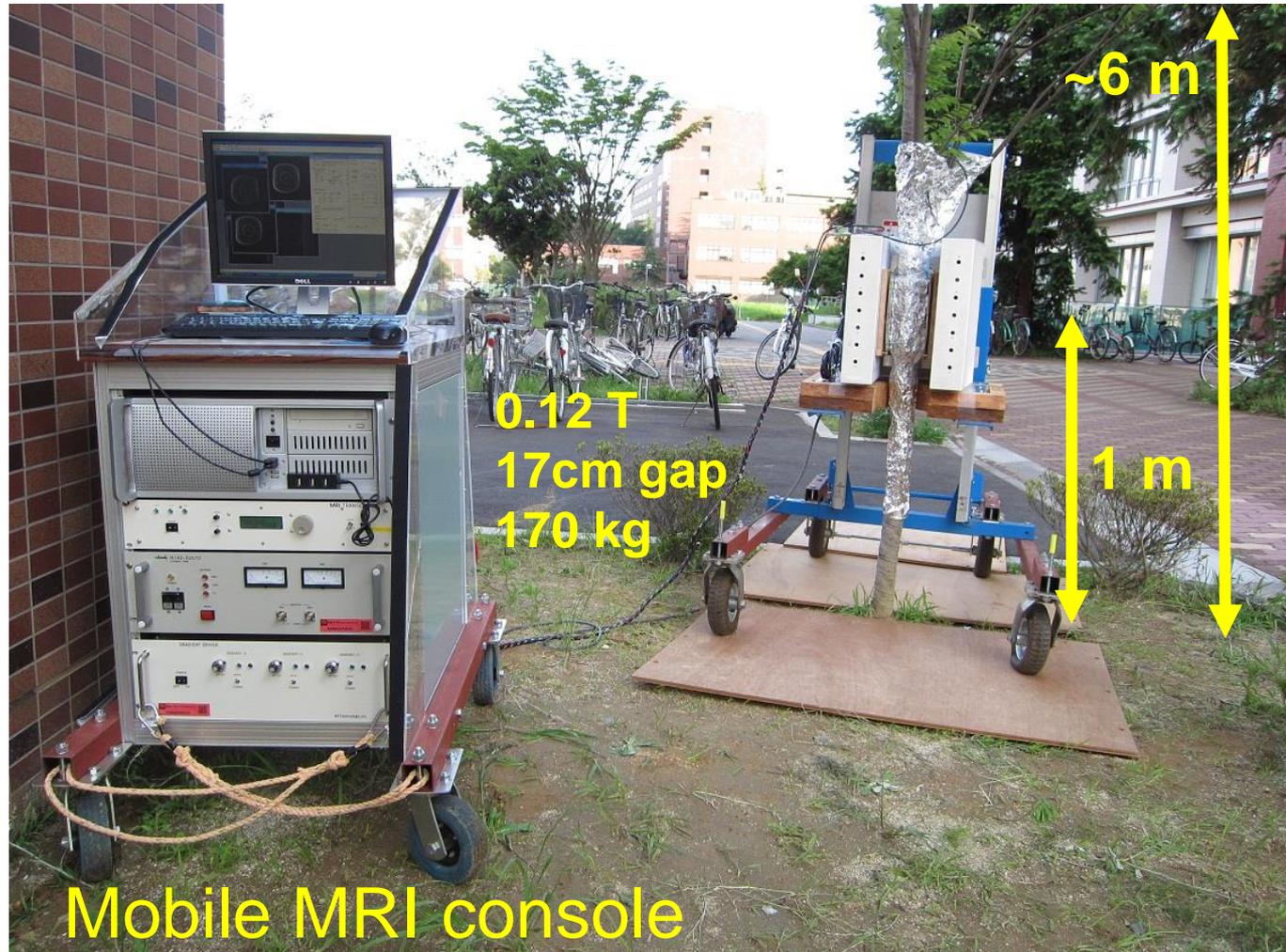
**heart
wood**

**sap
wood**



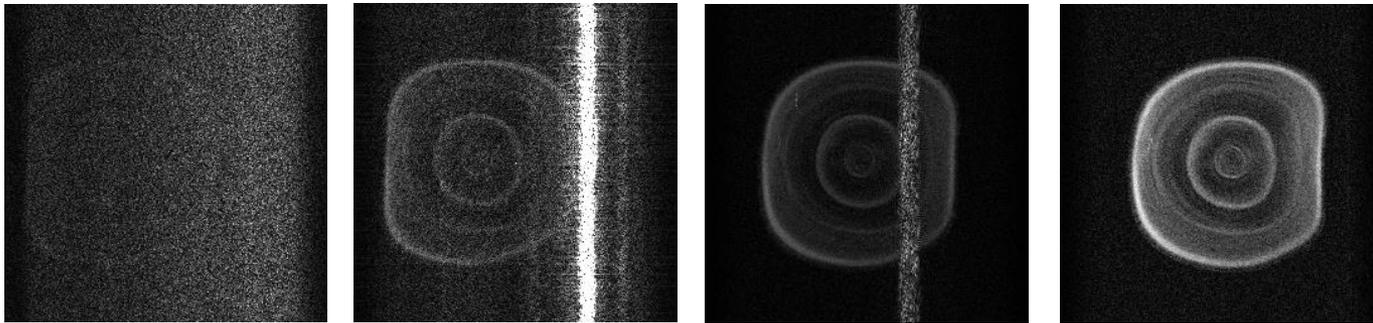
This slide shows ADC map measured **every two hours for 24 hours**. This graph clearly shows that ADC and solar radiation are closely correlated.

樹木計測用MRI at 0.12T(1)



MRI of a tree with a **60 mm diameter** at **0.12 T**.

樹木計測用MRI at 0.12T (2)

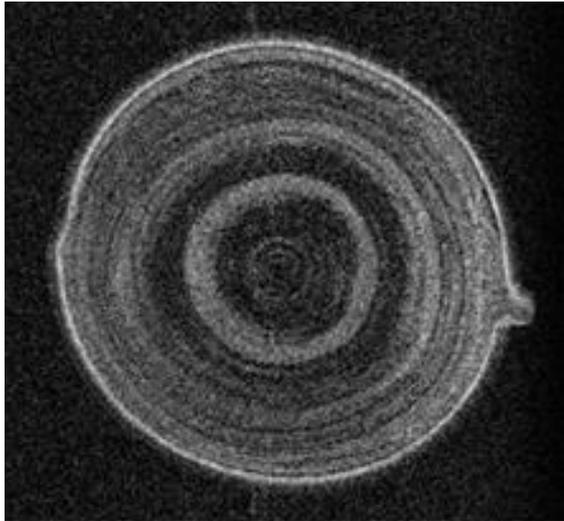


External noise was **absent** (switched off)

Thickness of Al foil

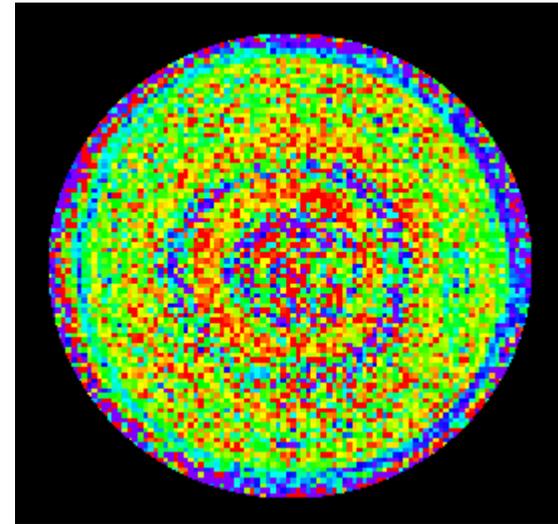
The RF coil was wound around the tree and shielded with aluminum foils. This is **effective for most external noise** but **ineffective for powerful one**.

樹木計測用MRI at 0.12T (3)



PDW image

TR/TE = 800ms/20ms
NEX = 1, 256x256x16
FOV (80 mm)³, Slice 5mm

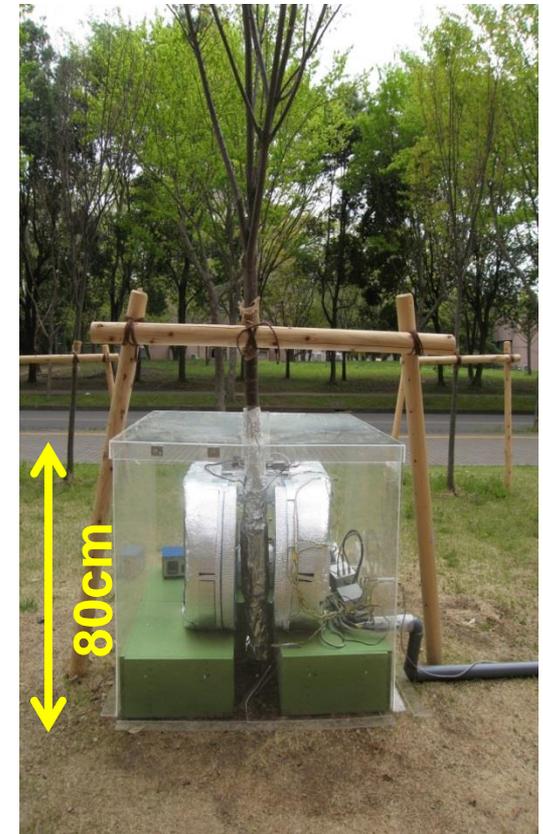


ADC map (parallel to the tree)

TR/TE = 800ms/46ms
NEX = 4, 128x128
FOV (80 mm)², Slice 30mm

Because the ADC map is measured **in January 2013**, water function was very low. **Much higher SNR is desired!**

樹木計測用MRI at 0.2T (1)



Field strength: **0.21T**, Gap = **16 cm**

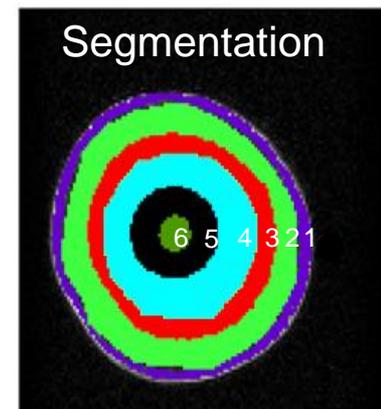
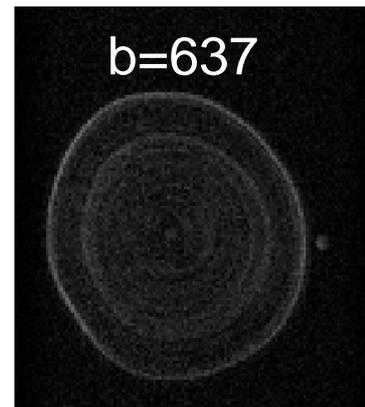
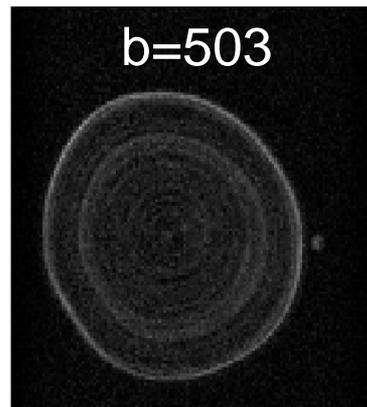
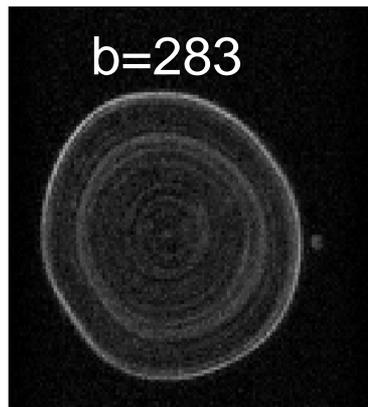
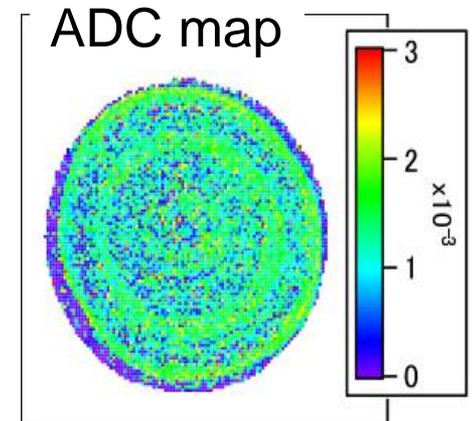
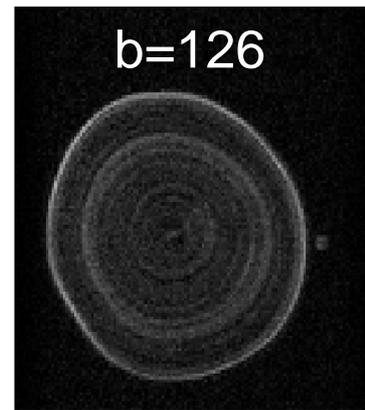
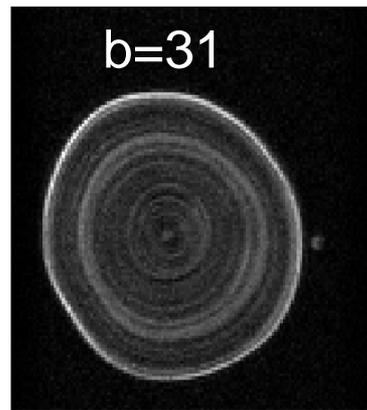
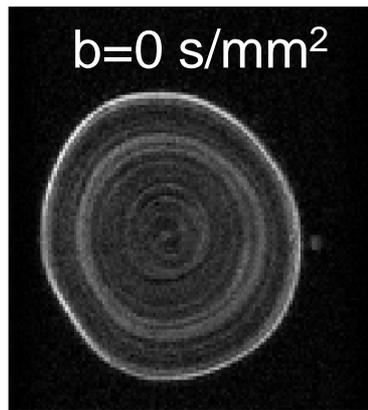
Homogeneity: 34.6 ppm for $(20\text{cm})^2 \times 12\text{cm}$ dev

Weight: **520 kg**

Japanese Zelkova

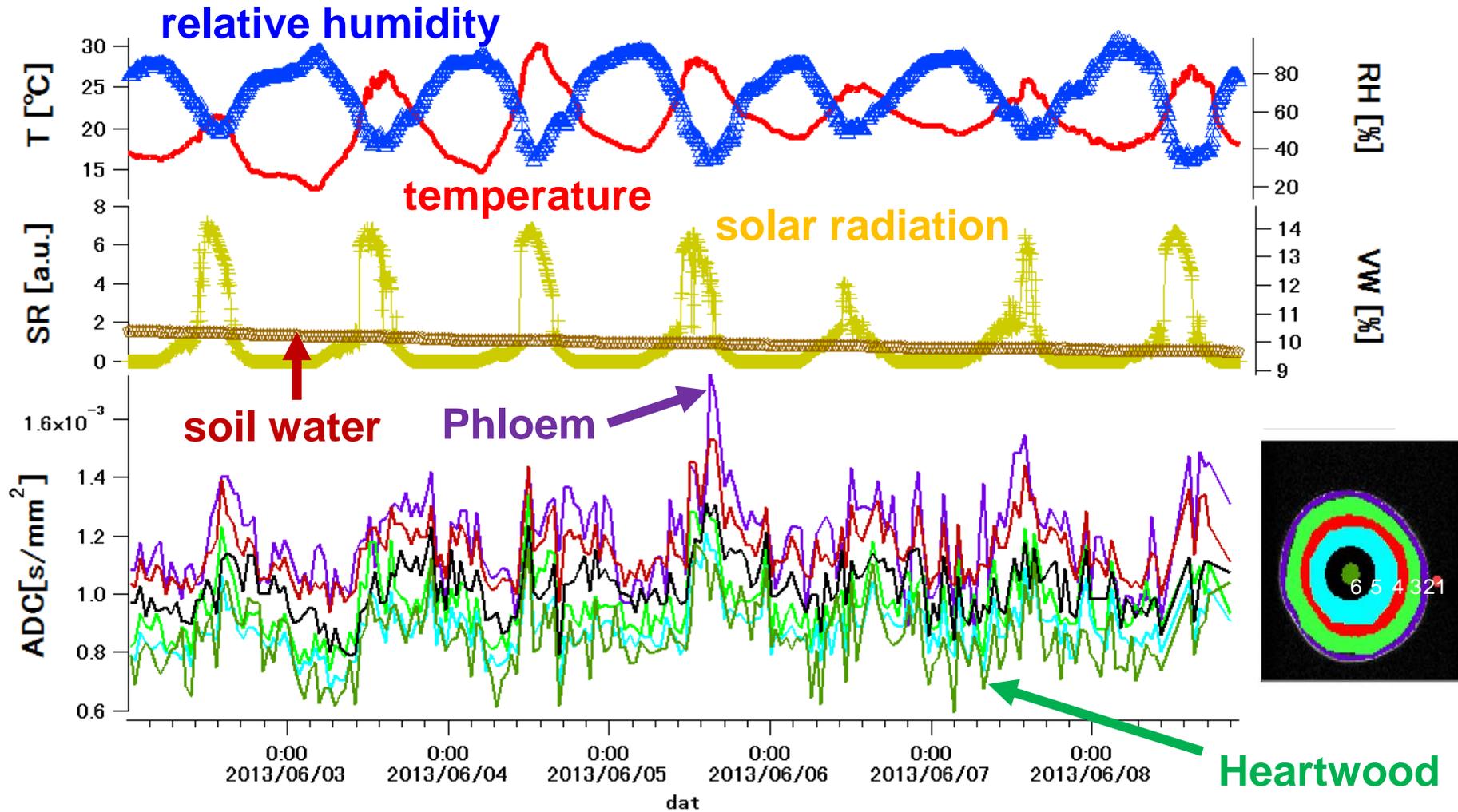
明日の口頭発表

樹木計測用MRI at 0.2T (2)



TR = 1200 ms, TE = 50 ms, $\delta = 18$ ms, $\Delta = 25$ ms, matrix = 128 × 128, FOV = 10 cm × 10 cm, slice thickness = 2 cm, NEX = 2, pixel bandwidth = 195 Hz

樹木計測用MRI at 0.2T (3)



ADC map is measured automatically **every 30 minutes** with the climate data. Water function is not active, but distribution of ADC is correctly measured.

むすび

現状では、永久磁石の超伝導磁石に対する**価格優位性**は崩れつつある。

このため、**Mobile MRI**では、永久磁石以外の選択はありえないが、それ以外のCompact MRIでは、永久磁石の選択は自明ではなくなってきている。

ただし、**教育用途**、**特殊環境**への設置、**開放性**が必要な用途には、**永久磁石の優位性**は依然として揺るがない。

よって、どのようにして、このような磁石を確保するかが、今後は、大きな課題になってくると思われる。