第36卷 第1期
2019年 1月

中国医学物理学杂志
Chinese Journal of Medical Physics

Vol. 36 No.1
January 2019

DOI:10.3969/j.issn.1005-202X.2019.01.011

医学影像物理

核磁共振超短回波时间序列技术研究进展

李莎[1,2]，张艺宝[2]，吴昊[2]，高嵩[1]
1.北京大学医学人文学院医学物理系，北京 100191；2.北京大学肿瘤医院暨北京市肿瘤防治研究所放疗科/恶性肿瘤发病机制及转化研究教育部重点实验室，北京 100142

【摘 要】核磁共振成像（MRI）技术拥有良好的软组织分辨率且无电离辐射，在临床和科研方面均得到了广泛应用。超短回波时间序列（UTE）在一定程度上弥补了MRI在短T2组织成像的弱点，使MRI的应用更加广泛。由UTE得到的派生序列有脂肪抑制UTE、单绝热反转恢复UTE、双回波差UTE等。本文介绍核磁共振超短时间回波序列（MR-UTE）技术的发展、原理及其应用，并对MR-UTE技术的发展方向进行展望。

【关键词】超短回波时间序列；磁共振成像；短T2组织
【中图分类号】R9318；R445.2 **【文献标志码】**A **【文章编号】**1005-202X（2019）01-0055-05

Research progress on magnetic resonance with ultrashort echo time sequence

LI Sha[1, 2], ZHANG Yibao[2], WU Hao[2], GAO Song[1]
1. Department of Medical Physics, School of Health Humanities, Peking University, Beijing 100191, China; 2. Key Laboratory of Carcinogenesis and Translational Research (Ministry of Education/Beijing)/Department of Radiation Oncology, Peking University Cancer Hospital & Institute, Beijing 100142, China

Abstract: Magnetic resonance (MR) imaging technology has been widely used in clinical and scientific researches because of its good soft tissue resolution and no ionizing radiation. Ultrashort echo time sequence (UTE) compensates for the weakness of MR imaging in short T2 components to a certain extent, making the application of MR imaging more widely. Sequences derived from UTE include fat-suppressed UTE, single adiabatic inversion recovery UTE, dual-echo UTE and so on. The development, principle and application of MR-UTE are introduced in this review, and its development trends are prospected.

Keywords: ultrashort echo time sequence; magnetic resonance imaging; short T2 component

前 言

核磁共振成像（Magnetic Resonance Imaging，MRI）是利用射频电磁波对置于磁场中的含有自旋不为零的原子核物质进行激发，产生核磁共振，用感应线圈采集磁共振信号，按一定数学方法进行处理而建立的成像方法。作为医学影像学的一种诊断技术，MRI拥有良好的软组织分辨率，无骨性伪影，无电离辐射，能敏感地检查出组织中水含量的变化，显示功能和新陈代谢过程等生理变化，它使机体组织从单纯的解剖显像发展为解剖学与组织学特性变化相结合的图像，为一些早期病变提供了诊断依据，这使核磁共振技术在临床和科研工作方面均得到了广泛的应用。然而，在早期临床使用MRI过程中发现人体内存在骨皮质等部分短T2组织[1]。如果应用常规MR序列对相应短T2组织进行扫描，未开始采集信号其T2信号已经接近零或衰减为零，图像上表现为低或无信号，因此短T2组织的结构和生理信息丢失[2-3]。因此传统MRI不能检测到部分短T2组织信号，如皮质骨、钙化软骨、半月板等。为区分人体内长T2和短T2组织成分，开发了超短回波时间序列（Ultrashort Echo Time, UTE），即二维UTE（2D UTE）序列。随即开发出三维UTE（3D UTE）序列。在常规UTE技术的基础上，人们根据临床需求，开发了更多

【收稿日期】2018-10-25
【基金项目】北京市自然科学基金（7172048, 1174016, 7162112, 1184014）；国家自然科学基金（11505012, 61671026）；首都卫生发展科研专项（首发2018-4-1027）；四川省科技厅项目（2018HH0099）；北京市属医院科研培育计划项目（PX2019042）；北京市医院管理局"青苗"计划专项经费（QML20171104）

【作者简介】李莎，硕士研究生，研究方向：医学物理，E-mail: lisha@bjmu.edu.cn
【通信作者】高嵩，博士，教授，博士生导师，研究方向：医学物理，E-mail: gaoss@bjmu.edu.cn

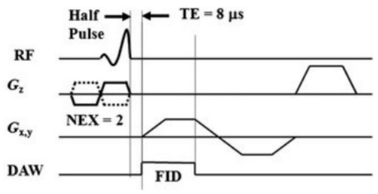
UTE序列，如反转恢复UTE（Inversion Recovery UTE, IR-UTE）、脂肪抑制UTE（fat-suppressed UTE, f-UTE）、双回波UTE（dual-echo UTE, d-UTE）、长T2饱和UTE（long-T2 saturation UTE, s-UTE）、绝热反转恢复UTE（adiabatic inversion recovery UTE）和UTE光谱成像（UTE Spectroscopic Imaging, UTE-SI）等序列，并证明了这些方法的可行性，在一定程度上拓宽了UTE技术的应用范围。

1 UTE序列原理

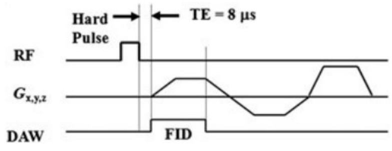
UTE序列并不属于经典的自旋回波序列或梯度回波序列，而是采用硬脉冲激发后直接检测自由感应衰减，但其图像具有梯度回波序列的特征，其回波时间受到射频线圈发射与接收开关时间（0~70 μs）的限制，如果配合专用硬件设备更可以降至8 μs，因此可以使短T2成分成像[4]。

1.1 常规UTE序列

2D UTE和3D UTE原理见图1[5]。如图1a所示，由两个带有相反层面选择梯度的半sinc函数射频脉冲激发后，立刻采集自由衰减信号，两个半脉冲的回波信号叠加在一起填充成一条K空间线；为避免在信号衰减至0之前未填充至K空间中心，数据直接由K空间中心开始采集，并呈放射状填充K空间。同理使用短硬脉冲激发及三维放射状采集可实现3D UTE成像（图1b）。



a: Two-dimensional (2D) UTE with a slice-selective half-pulse excitation, followed by 2D radial ramp sampling



b: Three-dimensional (3D) UTE with a short rectangular hard pulse excitation, followed by 3D radial ramp sampling

图1　UTE脉冲序列图

Fig.1 UTE pulse sequence diagrams

UTE: Ultrashort echo time sequence; DAW: Data acquisition window; FID: Free induction decay; NEX: Number of excitations; RF: Radiofrequency

1.2 非常规UTE序列

为了更好、更直观地观察骨皮质及其周围组织，出现了多种UTE改进方案，主要通过抑制长T2信号，来提高短T2信号的对比度。有3种常用长T2抑制技术[6]：（1）双回波采集和减法[7-8]，如图2a和图2b所示。第一个自由衰减信号中，长T2和短T2信号均较强，短T2信号衰减比长T2信号衰减快，经过一段时间后，短T2信号较弱甚至没有信号，在第二次采集回波信号时，长T2组织信号远大于短T2组织信号，两次回波信号相减可抑制长T2组织信号，从而提高短T2组织对比度。此方法受磁场均匀性影响较小。（2）采用长90°的脉冲，然后施加破坏梯度以选择性地饱和长T2组织[9]，如图2c和图2d所示。这种方法对B_1和B_0的不均匀性很敏感。（3）绝热反转脉冲[6,9]，如图2e、图2f、图2g和图2h所示。绝热即不受外界影响，顺磁场方向施加射频脉冲，使弛豫时间延长，从而绝热反转恢复UTE比常规UTE时间要长。若施加两次反转射频脉冲，可实现脂肪抑制，称为双绝热反转恢复UTE。这种方法对B_1不均匀性不敏感，但对多切片成像困难。

其中，最简单有效的方法是双回波采集和减法。如图2b所示，采集两次回波信号，然后相减，可以得到高对比度的短T2组织信号。为了进一步快速高效的提高短T2组织的对比度，提出了重新缩放的双回波UTE成像（dual echo UTE imaging with Rescaled Digital Subtraction, dUTE-RS）[11-13]，即加权减法，按照一定比例系数缩放信号大小后再相减。具体做法为：不同的回波时间各采集一次回波信号，并命名为S_1和S_2；加权减法公式为：

$$S=S_1-\alpha\times S_2 \tag{1}$$

式中，α为加权因子，当α=1时即为简单的两回波信号相减。

2 应 用

图像常规MR序列采集不清甚至采集不到短T2组织的图像，如骨皮质、肌腱、半月板等。而核磁共振超短回波时间序列（MR-UTE）可以区分长T2和短T2成分，这是医学影像领域的一个重大突破，其应用具有深刻的临床意义和广阔的前景。

2.1 MR-UTE在医学影像学中的应用

2.1.1 骨皮质　随着社会老龄化速度加快，骨的发病率也逐年上升。在美国，骨质疏松症引发的骨折数每年超过150万个，费用约为150亿美元。骨的磁共振信号衰减极快，常规的MRI技术不能清楚检测到骨信号。相对于临床常规T_1加权序列，使用UTE序列检测骨皮质信号，回波时间由4~10 ms减少到0.07~0.20 ms[14-17]。骨皮质内除了矿物质外，还有有机基质和水两种主要成分，关于核磁共振骨皮质成像技术已经有所研究[18]，通过双回波差UTE、绝热反

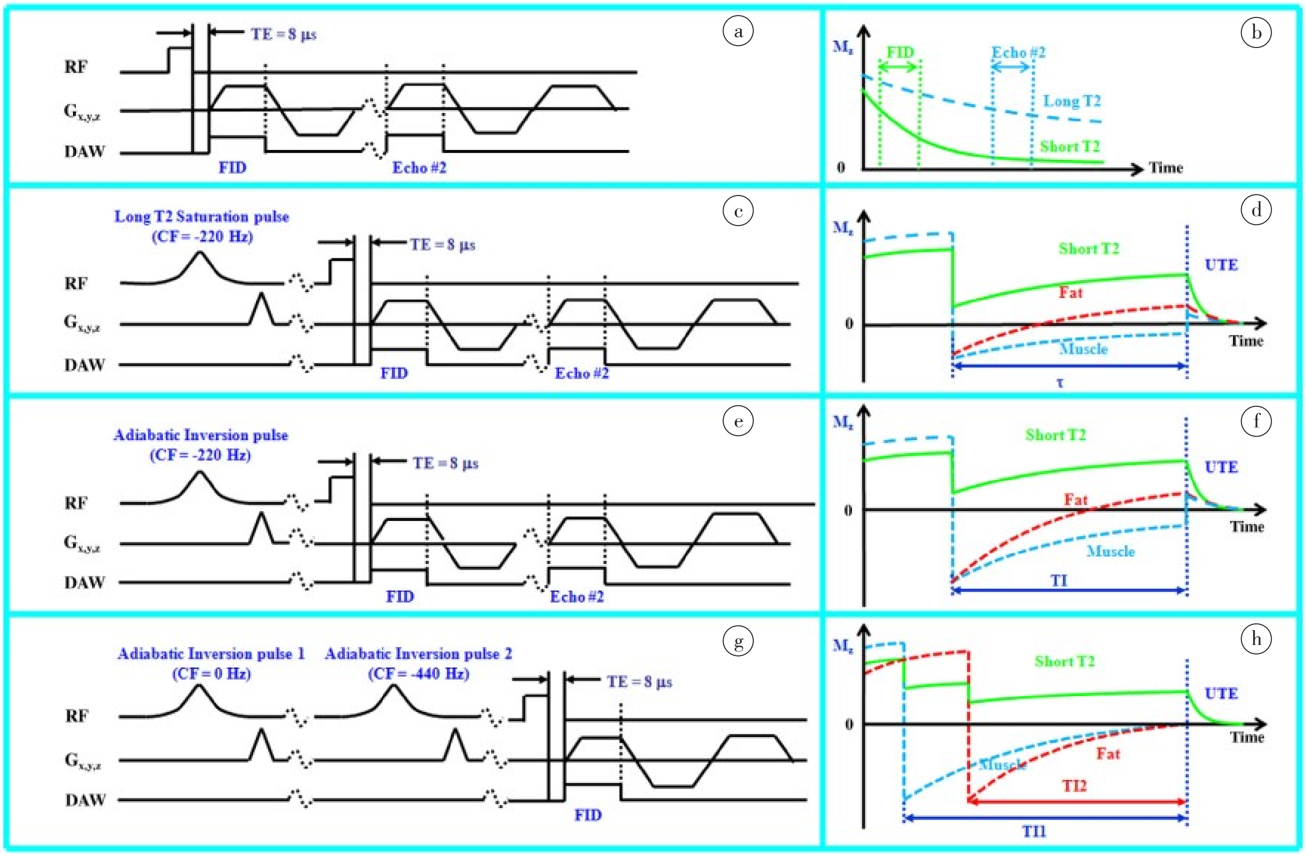


图2 不同UTE序列及其短T2对比机制

Fig.2 Different UTE and the corresponding short T2 contrast mechanisms

Image contrast for short T2 species was generated by acquisitions using dual-echo 3D UTE (a), long T2 saturation dual-echo 3D UTE (c), single adiabatic inversion recovery dual-echo 3D UTE (e) and dual adiabatic inversion recovery 3D UTE (g), respectively. The diagrams on the right (b, d, f and h) show the corresponding short T2 contrast mechanisms for each approach.

转恢复UTE、偏共振饱和UTE和UTE-SI进行定性成像，UTE定量测量T1、T2*、水含量、骨皮质孔隙度、质子密度和自由水和束缚水含量。除此之外，不同大小场强的UTE成像对骨皮质的影响[19]、UTE脉冲序列检测正常和非正常的骨皮质信号[20]、用绝热反转恢复UTE序列扫描时，反转时间对骨皮质成像的影响[21]等多个方面均已有所研究。

2.1.2 膝盖 膝关节是人体最大、构造最复杂、损伤机会较大的关节。膝关节中的半月板的回波时间只有几毫秒，常规的MR-UTE不能获取其影像学信息。Young等[12]采用UTE加权减法的方法来观察膝关节中短T2组织的影像信息。在加权减法中使用最佳加权因子，有效抑制长T2组织信号，提高短T2组织对比度。最佳加权因子(optimal weighting factors)通过调节双回波差UTE图像的信噪比(Signal to Noise Ratio, SNR)和噪声比(Contrast to Noise Ratio, CNR)来确定。综合SNR和CNR，建议最佳加权因子为：肌腱0.3，骨皮质0.4，半月板1.0，表明3D UTE MRI提供了不能通过常规MRI可视化的短T2组织成像。

2.1.3 脑白质 脑白质主要由长T2成分组成，也含有少量的短T2成分。常规回波时间的临床磁共振扫描序列无法检测到回波信号。Du等[22]使用临床3T磁共振中UTE研究脑白质中的短T2成分，定量分析其T2*s和相对质子密度，并证实其可行性。脑白质中超短T2成分的高对比度形态学成像以及相对质子密度和弛豫时间的定量测量，可显著促进相关脑白质疾病的研究。

人体内不仅骨皮质、肌腱、半月板、脑白质等组织存在短T2组织，韧带、关节软骨、椎间盘等也存在大量的短T2组织，能在MR影像上观察到其图像信息，将极大地促进医学影像学和医学诊断学的发展。

2.2 MR-UTE在放射治疗中的应用

MRI用于放射治疗的主要限制在于：(1)MR强度与质子密度和磁弛豫相关[23]，和电子密度之间没有直接对应关系；(2)传统的MR序列不能很好地区分骨和空气信号。

现有多种方法得到分配电子密度的MR图像，如通过密度分配法[24-31]、基于图集的方法[32]或者人工智

能等方法[33]。UTE的开发和应用，对于体内具有短弛豫时间的组织，如关节软骨、半月板、肌腱、韧带、皮质骨和软组织钙化等，常规MR序列显示低信号甚至无信号，UTE序列可以检测其信号[3,15,34-36]。此时的MR图像与CT图像相比，MR图像不仅提供了良好的软组织对比度，还拥有良好的勾画和位置精度[37-42]，在放射治疗过程中具有不可替代的优势。

3 结 论

UTE技术的学习和研究工作已经展开多时，人们在许多领域已经取得一定的进展，例如，可以使短T2组织的对比度增强，用于鉴定健康和疾病[43]。在不影响图像质量的前提下，实时的MR图像采集时间缩短到20 ms[44]。还对技术注意事项进行了研究，如基本物理知识、梯度场、RF系统、安全性等方面[45]。对于UTE的临床研究，除了骨皮质、脑白质、膝盖和骨骼肌肉组织外，还有颞下颌关节动态UTE和心血管等[46-47]。不仅研究了抑制长T2的方法，还比较了多种方法的性能[48]。

UTE作为一种新型的技术，可以区分长T2和短T2的组织成分，在发扬核磁共振优点的同时，弥补了自身缺陷，不仅能够获得较高软组织分辨率的图像，还能对人体内骨皮质等短T2组织成像。MR-UTE技术发展迅速，且实用性强，但广泛投入临床使用还需要做更多的临床测试。让MR-UTE技术更广泛更有效的应用是医学物理工作者及医学工作者共同的责任和目标。

【参考文献】

[1] GATEHOUSE P D, BYDDER G M. Magnetic resonance imaging of short T2 components in tissue[J]. Clin Radiol, 2003, 58(1): 1-19.

[2] KENKELMAN R M, STANISZ G J, GRAHAM S J. Magnetization transfer in MRI: a review[J]. NMR Biomed, 2001, 14(2): 57-64.

[3] ROBSON M D, GATEHOUSE P D, BYDDER M, et al. Magnetic resonance: an introduction to ultrashort echo-time imaging[J]. J Comput Assist Tomogr, 2003, 27(6): 825-846.

[4] 陈宁, 袁慧书. 超短回波时间磁共振成像应用进展[J]. 中国介入影像与治疗学杂志, 2016, 13(6): 378-381.
CHEN N, YUAN H S. Application progresses of ultrashort echo time MRI[J]. Chinese Journal of Interventional Imaging and Therapy, 2016, 13(6): 378-381.

[5] DU J, BYDDER G M. Qualitative and quantitative ultrashort-TE MRI of cortical bone[J]. NMR Biomed, 2013, 26(5): 489-506.

[6] DU J, BYDDER M, TAKAHASHI A M, et al. Short T2 contrast with three-dimensional ultrashort echo time imaging[J]. Magn Reson Imaging, 2011, 29(4): 470-482.

[7] ROBSON M D, TYLER D J, NEUBAUER S. Ultrashort TE chemical shift imaging (UTE-CSI)[J]. Magn Reson Med, 2005, 53(2): 267-274.

[8] RAHMER J, BORNERT P, GROEN J, et al. Three-dimensional radial ultrashort echo-time imaging with T2 adapted sampling[J]. Magn Reson Med, 2006, 55(5): 1075-1082.

[9] LARSON P E, GURNEY P T, NAYAK K, et al. Designing long-T2 suppression pulses for ultrashort echo time imaging[J]. Magn Reson Med, 2006, 56(1): 94-103.

[10] LARSON P E, CONOLLY S M, PAULY J M, et al. Using adiabatic inversion pulses for long-T2 suppression in ultrashort echo time (UTE) imaging[J]. Magn Reson Med, 2010, 58(5): 952-961.

[11] DU J, CHUNG C B, BYDDER G M. Ultrashort TE imaging with rescaled digital subtraction (UTE RDS)[C]. In Proceedings 17th Scientific Meeting, International Society for Magnetic Resonance in Medicine, 2009: 3992.

[12] YOUNG H L, KIM S J, SONG H T, et al. Weighted subtraction in 3D ultrashort echo time (UTE) imaging for visualization of short T2 tissues of the knee[J]. Acta Radiol, 2014, 55(4): 454-461.

[13] ZHU Y C, DU J, QUN H, et al. Dual echo UTE imaging with rescaled subtraction (dUTE-RS): scaling factor optimization study[C]. In Proceedings 23th Scientific Meeting, International Society for Magnetic Resonance in Medicine, 2015.

[14] BERGIN C J, PAULY J M, MACOVSKI A. Lung parenchyma: projection reconstruction MR imaging[J]. Radiology, 1991, 179(3): 777-781.

[15] GOLD G E, PAULY J M, MACOVSKI A, et al. MR spectroscopic imaging of collagen tendons and knee menisci[J]. Magn Reson Med, 1995, 34(5): 647-654.

[16] ROBSON M D, GATEHOUSE P D, BYDDER M, et al. Magnetic resonance: an introduction to ultrashort echo-time imaging[J]. J Comput Assist Tomogr, 2003, 27(6): 825-846.

[17] GATEHOUSE P D, THOMAS R W, ROBSON M D, et al. Magnetic resonance imaging of the knee with ultrashort TE pulse sequences[J]. Magn Reson Imaging, 2004, 22(8): 1061-1067.

[18] 包尚联, 杜江, 高嵩. 核磁共振骨皮质成像关键技术研究进展[J]. 物理学报, 2013, 62(8): 088701.
BAO S L, DU J, GAO S. Review of the ultrashort echo time magnetic resonance imaging of cortical bone[J]. Acta Physica Sinica, 2013, 62(8): 088701.

[19] LI S, CHANG E Y, BAE W C, et al. Ultrashort echo time bi-component analysis of cortical bone-a field dependence study[J]. Magn Reson Med, 2014, 71(3): 1075-1081.

[20] REICHERT I L, ROBSON M D, GATEHOUSE P D, et al. Magnetic resonance imaging of cortical bone with ultrashort TE pluse sequences[J]. Magn Reson Imaging, 2005, 23(5): 611-618.

[21] GAO S, ZHU Y C, ZHANG H L, et al. Adiabatic inversion recovery prepared ultrashort echo time (IR-UTE) imaging of cortical bone: effects of inversion time and undersampling[C]. International Society for Magnetic Resonance in Medicine, 2014: 5520.

[22] DU J, MA G, LI S, et al. Ultrashort echo time (UTE) magnetic resonance imaging of the short T2 components in white matter of the brain using a clinical 3T scanner[J]. Neuroimage, 2014, 87: 32-41.

[23] HOFMANN M, PICHLER B, SCHOLKOPF B, et al. Towards quantitative PET/MRI: a review of MR-based attenuation correction techniques[J]. Eur J Nucl Med Mol Imaging, 2009, 36(Suppl 1): S93-S104.

[24] LEE Y K, BOLLET M, CHARLES-EDWARDS G, et al. Radiotherapy treatment planning of prostate cancer using magnetic resonance imaging alone[J]. Radiother Oncol, 2003, 66(2): 203-216.

[25] CHEN L, NGUYEN T B, JONES É, et al. Magnetic resonance-based treatment planning for prostate intensity-modulated radio-therapy: creation of digitally reconstructed radiographs[J]. Int J Radiat Oncol Biol Phys, 2007, 68(3): 903-911.

[26] LAMBERT J, GREER P B, MENK F, et al. MRI-guided prostate

radiation therapy planning: investigation of dosimetric accuracy of MRI-based dose planning[J]. Radiother Oncol, 2011, 98(3): 330-334.

[27] HOOGCARSPEL S J, VAN DER VELDEN J M, LAGENDIJK J J, et al. The feasibility of utilizing pseudo CT-data for online MRI based treatment planadaptation for a stereotactic radiotherapy treatment of spinal bone metastases[J]. Phys Med Biol, 2014, 59(23): 7383-7391.

[28] KORSHOLM M E, WARING L W, EDMUND J M. A criterion for the reliable use of MRI-only radiotherapy[J]. Radiat Oncol, 2014, 9(1): 1-7.

[29] JOHANSSON A, KARLSSON M, NYHOLM T. CT substitute derived from MRI sequences with ultrashort echo time[J]. Med Phys, 2011, 38(5): 2708-2714.

[30] HSU S, CAO Y, HUANG K, et al. Investigation of a method for generating synthetic CT models from MRI scans of the head and neck for radiation therapy[J]. Phys Med Biol, 2013, 58(23): 8419-8435.

[31] JOHANSSON A, GARPEBRING A, KARLSSON M, et al. Improved quality of computed tomography substitute derived from magnetic resonance (MR)data by incorporation of spatial information potential application for MRI only radiotherapy and attenuation correction in positron emission tomography[J]. Acta Oncol, 2013, 52(7): 1369-1373.

[32] DOWLING J A, LAMBERT J, PARKER J, et al. An atlas-based electron density mapping method for magnetic resonance imaging (MRI)-alone treatment planning and adaptive MRI-based prostate radiation therapy[J]. Int J Radiat Oncol Biol Phys, 2012, 83(1): E5-E11.

[33] HAN X. MR-based synthetic CT generation using a deep convolutional neural network method[J]. Med Phys, 2017, 44(4): 1408-1419.

[34] BAE W C, DWEK J R, ZNAMIROWSKI R, et al. Ultrashort echo time MR imaging of osteochondral junction of the knee at 3T: identification of anatomic structures contributing to signal intensity [J]. Radiology, 2010, 254(3): 837-845.

[35] DU J, CARL M, BYDDER M, et al. Qualitative and quantitative ultrashort echo time (UTE) imaging of cortical bone[J]. J Magn Reson, 2010, 207(2): 304-311.

[36] KRUG R, LARSON P E, WANG C, et al. Ultrashort echo time MRI of cortical bone at 7 tesla field strength: a feasibility study[J]. J Magn Reson Imaging, 2011, 34(3): 691-695.

[37] RASCH C, STEENBAKKERS R, HERK M V. Target definition in prostate, head, and neck[J]. Semin Radiat Oncol, 2005, 15(3): 136-145.

[38] PRABHAKAR R. Comparison of computed tomography and magnetic resonance based target volume in brain tumors[J]. J Cancer Res Ther, 2007, 3(2): 121-123.

[39] FIORENTINO A, CAIVANO R, PEDICINI P, et al. Clinical target volume definition for glioblastoma radiotherapy planning: magnetic resonance imaging and computed tomography[J]. Clin Transl Oncol, 2013, 15(9): 754-758.

[40] BARILLOT I, REYNAUD-BOUGNOUX A. The use of MRI in planning radiotherapy for gynaecological tumours [J]. Cancer Imaging, 2006, 6: 100-106.

[41] THIAGARAJAN A, CARIA N, SCHODER H, et al. Target volume delineation in oropharyngeal cancer: impact of PET, MRI and physical examination[J]. Int J Radiat Oncol Biol Phys, 2012, 38(1): 220-227.

[42] AOYAMA H, SHIRATO H, NISHIOKA T, et al. Magnetic resonance imaging system for three-dimensional conformal radiotherapy and its impact on gross tumor volume delineation of central nervous system tumors[J]. Int J Radiat Oncol Biol Phys, 2001, 50(3): 821-827.

[43] ROBSON M D, GATEHOUSE P D, SO P W, et al. Contrast enhancement of short T2 tissues using ultrashort TE (UTE) pulse sequences[J]. Clin Radiol, 2004, 59(8): 720-726.

[44] UECKER M, ZHANG S, VOIT D, et al. Real-time MRI at a resolution of 20ms[J]. NMR Biomed, 2010, 23(8): 986-994.

[45] TYLER D J, ROBSON M D, HENKELMAN R M, et al. Magnetic resonance imaging with ultrashort TE (UTE) pulse sequences: technical considerations[J]. J Magn Reson Imaging, 2007, 25(2): 279-289 .

[46] ZHU Y C, DU J, GAO S, et al. Dynamic ultrashort TE (UTE) imaging of the temporomandibular joint (TMJ)[C]. International Society for Magnetic Resonance in Medicine, 2014: 4609.

[47] HOERR V, NAGELMANN N, ARNO N, et al. Cardiac-respiratory self-gated cine ultra-short echo time (UTE) cardiovascular magnetic resonance for assessment of functional cardiac parameters at high magnetic fields[J]. J Cardiovasc Magn Reson, 2013, 15(1): 59.

[48] LI C, MAGLAND J F, RAD H S, et al. Comparison of optimized soft-tissue suppression schemes for ultra-short echo time MRI [J]. Magn Reson Med, 2012, 68(3): 680-689.

（编辑：薛泽玲）