ANTICANCER RESEARCH *41*: 4423-4429 (2021)
doi:10.21873/anticanres.15249

T2-weighted Imaging of the Breast at 1.5T Using Simultaneous Multi-slice Acceleration

JULIA RIFFEL[1], STEPHAN KANNENGIESSER[2], STEFAN O. SCHOENBERG[1], ANNA K. KAISER[1], DANIEL OVERHOFF[2], PHILIPP RIFFEL[1] and CLEMENS G. KAISER[1]

[1]*Clinic of Radiology and Nuclear Medicine, University Medical Centre Mannheim, Medical Faculty Mannheim, University of Heidelberg, Mannheim, Germany;*
[2]*MR Application Predevelopment, Siemens Healthcare GmbH, Erlangen, Germany*

Abstract. *Aim: To evaluate the image quality and time saving using simultaneous multi-slice (SMS)-accelerated T2-weighted turbo spin echo (TSE) sequences compared to standard T2 TSE sequences in breast magnetic resonance imaging (MRI). Patients and Methods: Thirty patients were examined with an SMS-accelerated T2 TSE sequence and a standard T2 TSE sequence as part of a breast MRI protocol at 1.5T. Image quality, signal homogeneity and tissue delineation were evaluated. For quantitative assessment, the signal-to-noise ratio (SNR) was measured from representative SNR maps. Results: There were no significant differences regarding tissue delineation and signal homogeneity. Image quality was rated equal at the chest wall and the breasts but decreased in the axilla on SMS-T2 TSE (p=0.01) with a simultaneous decrease of SNR (p=0.03). This did not significantly impact the overall image quality (p=0.2). The acquisition time for SMS-T2 TSE was 48% shorter compared to standard T2 TSE. Conclusion: SMS-acceleration for T2-weighted imaging of the breast at 1.5T substantially reduces acquisition time while maintaining comparable quantitative and qualitative image quality. This may pave the way for protocol abbreviation especially in a high-throughput clinical workspace.*

Overcoming the limitations of conventional imaging with breast ultrasound and x-ray mammography, breast magnetic resonance imaging (MRI) is increasingly used for diagnosis and further workup of breast lesions (1, 2). Although excellent diagnostic accuracy of breast MRI was demonstrated in multiple prospective and multicenter trials (3-6), economic aspects, such as a long standard acquisition time is still a matter of scientific dispute and one of the major issues preventing breast MRI from being a feasible screening tool.

The basic full-scale protocol of breast MRI includes T2-weighted (T2w) images, preferably using a Turbo Spin Echo (TSE) sequence (7) along a full dynamic runoff. Diffusion-weighted imaging (DWI) with apparent diffusion coefficient (ADC) mapping has emerged as a reliable adjunct to dynamic breast MRI and may increase the diagnostic accuracy for breast masses (8-10). T2w images are considered to be especially helpful for anatomical and morphological correlation of detected breast lesions (7, 11). In order to reduce expensive examination time, the use of abbreviated protocols has been increasingly investigated (12-15). Several working groups achieved a comparable diagnostic accuracy reducing the number of T1-weighted sequences after administration of contrast media (14, 16). A further approach to reduce the examination time is to shorten the acquisition time of each sequence. Using the simultaneous multi-slice (SMS) technique, fewer slice excitations are required to achieve the same slice coverage. The SMS technique uses the spatial sensitivity of multichannel array coils to separate the simultaneously acquired slices. Acceleration by SMS can provide substantially higher signal-to-noise ratio (SNR) per time, which may be used for shortening the examination time while keeping TR stable (17-19). However, the SMS reconstruction may also reduce the SNR of individual images and introduce artifacts.

The aim of the present study was to evaluate the feasibility of a SMS-accelerated T2 TSE sequence of the breast and compare it to a standard T2 TSE sequence in terms of image quality and scan time.

Correspondence to: Julia Riffel, Clinic of Radiology and Nuclear Medicine, University Medical Center Mannheim, Theodor-Kutzer-Ufer 1-3, 68167 Mannheim, Germany. Tel: +49 06213832067, Fax: +49 06213831910, e-mail: julia.riffel@medma.uni-heidelberg.de

Key Words: Breast cancer, breast imaging, simultaneous multi-slice acceleration, breast MRI, T2-weighted imaging.

Patients and Methods

Study population. Approval for this retrospective study was granted by the ethics committee of the institution. Thirty women who underwent breast MRI were selected (median age 55, range 35-72 years) between May and June 2020. All examinations were performed during clinical routine at our breast care center. Twenty women (67%) underwent breast MRI for high-risk screening and 10 (33%) for further workup of findings on conventional imaging. Patients with breast inlays or mastectomy were not included in the study.

Data acquisition. MR examinations were performed on a 1.5T system (MAGNETOM Sola, Siemens Healthcare, Erlangen, Germany). A T2 TSE as well as a SMS-T2 TSE sequence were performed in all patients. The sequence parameters are displayed in Table I. For SNR quantification, raw data and noise adjustment information from ten representative breasts were exported from the scanner.

Image quality analysis. The original DICOM data files were anonymized before the analysis. Three independent radiologists with 15, 14 and 11 years of experience in breast MR reading performed qualitative assessments of the images using the OsiriX 5.0 DICOM viewer (OsiriX Foundation, Geneva, Switzerland). Two reading sessions at least 2 weeks apart were performed in order to avoid possible bias in the results due to a direct comparison between images of the same patient. The two sequences of each patient were alternatively and randomly split between the two reading sessions. Sequence parameters were hidden. Images of both sequences were rated for each patient according to the following parameters: image quality, delineation of breast tissue and signal homogeneity. The image quality was subdivided into overall image quality and image quality according to the anatomical localization: breast, chest wall and axilla. A 5-point Likert scale was applied with the highest value of 5 representing the best image quality, best delineation of breast tissue and best signal homogeneity, whereas a score of 1 implied the opposite.

SNR analysis. To quantitatively compare the SNR of the two sequences, SNR maps were created using the pseudo-replica method (20). For each of the exported raw data sets, 16 pseudo-replicas were generated by repeating the scanner image reconstruction with 10% synthetic noise of the same statistics as the natural noise added to the raw data. The noise statistics were derived from a noise-only prescan included in the scanner adjustments. Subsequently, SNR maps were calculated *via* a prototype inline implementation by pixel-wise division of mean and standard deviation along the pseudo-replica series. The standard deviation was calculated in a 5x5 neighborhood of the current pixel (21) and scaled by 10 to reflect the amount of synthetic noise added; SNR maps were again scaled by 10 prior to integer conversion for the DICOM output to reduce digitization noise.

Finally, SNR was evaluated by segmenting the breast tissue on SNR maps. Circular regions of interest (ROIs) of 1 cm^2 were manually drawn at similar slice positions for T2 TSE and SMS-T2 TSE and at the same respective anatomical locations. A ROI was drawn in each quadrant of both breasts and one additional ROI in the central segment on the level of the nipple. The mean of these 10 measurements was then compared between the sequences. The previously introduced scale factor of 10 was divided out in the process. Structures such as blood vessels, cysts or dilated ducts were avoided for ROI placement.

Statistical evaluation. All statistical tests were performed with SPSS (SPSS Inc, USA, Version 22) and Microsoft Excel 2013 (Microsoft, Redmond, WA, USA). If not otherwise noted, continuous variables are represented by mean±standard deviation. To test for normality of the data, a Shapiro-Wilk W test was performed. If data was not normally distributed, the Wilcoxon rank sum test was utilized for statistical comparisons. If the data was normally distributed, a paired Student's *t*-test was used. The qualitative parameters to assess subjective image quality are provided as median and interquartile ranges from first to third quartile. To compare these discontinuous parameters, a two-sided paired Wilcoxon rank sum test was applied. A two-tailed *p*-value of <0.05 was chosen as a cut-off for statistical significance. To quantify the inter-reader agreeability, Fleiss' kappa was calculated for each parameter and both sequences. Agreeability was defined in the following categories: <0.4=poor agreement, 0.41-0.75=good agreement, >0.75=excellent agreement.

Table I. *Sequence parameters of T2 TSE and SMS-T2 TSE.*

Sequence parameters	T2 TSE	SMS-T2 TSE
Echo time (ms)	130	130
Repetition time (ms)	6,100	6,300
FoV read (mm)	512	512
FoV Phase	100%	100%
In plane resolution (mm^2)	0.66±0.66	0.66±0.66
Slice thickness (mm)	3	3
No. slices	50	52
Bandwidth per pixel (Hz)	181	181
In-plane acceleration factor (GRAPPA)	2	2
SMS acceleration factor	-	2
Concatenations	2	1
Acquisition time Mean±SD (s)	232±10	113±8

FoV: Field of view; SD: standard deviation; GRAPPA: generalized autocalibrating partial parallel acquisition.

Results

Qualitative analysis. Delineation of breast tissue [T2 TSE 5 (5-5) *vs*. SMS-T2 TSE 5 (5-5), $p>0.05$] and signal homogeneity [T2 TSE 5 (5-5) *vs*. SMS-T2 TSE 5 (4-5), $p>0.05$] were rated equal for both sequences. SMS-T2 TSE received significantly lower scores for image quality at the axilla [T2 TSE 5 (5-5) *vs*. SMS-T2 TSE 5 (4-5), $p=0.01$], but not at the chest wall [T2 TSE 5 (5-5) *vs*. SMS-T2 TSE 5 (5-5), $p>0.05$] and in the breast itself [T2 TSE 5 (5-5) *vs*. SMS-T2 TSE 5 (5-5), $p>0.05$]. This did not significantly impact the overall image quality [T2 TSE 5 (5-5) *vs*. SMS-T2 TSE 5 (5-5), $p>0.05$]. Inter-reader agreement was good or excellent (kappa range 0.56-1.0) with a median kappa of 0.86 reflecting excellent agreement between the three readers. The detailed parameters of the qualitative analysis are displayed in Table II. Representative images showing the image quality are provided in Figure 1. The mean acquisition time for SMS-T2 TSE was significantly lower than the acquisition time of T2 TSE (113±8 s *vs*. 234±10 s, $p<0.01$).

Quantitative analysis. SNR maps were successfully created, and ROI placements were performed in both breasts and

Table II. *Qualitative parameters of T2 TSE and SMS-T2 TSE on a 5-point-Likert scale. Kappa and p statistical values only refer to the median.*

	T2 TSE			SMS-T2 TSE			
Imaging parameter	Median (IQR)	Mean±SD	kappa	Median (IQR)	Mean±SD	kappa	*p*-Value
Delineation breast tissue	5 (5-5)	5±0	1.0	5 (5-5)	4.95±0.22	0.88	1
Signal homogeneity	5 (5-5)	5±0	1.0	5 (5-5)	5±0	1.0	1
Overall image quality	5 (5-5)	5±0	1.0	5 (5-5)	4.85±0.37	0.85	0.2
Image quality breast	5 (5-5)	5±0	1.0	5 (5-5)	5±0	1.0	1
Image quality chest wall	5 (5-5)	5±0	1.0	5 (5-5)	4.95±0.22	0.88	1
Image quality axilla	5 (5-5)	5±0	1.0	5 (4-5)	4.65±0.49	0.56	0.01

IQR: Interquartile range; SD: standard deviation; n/a: not applicable.

axillary region for quantitative SNR measurements. SNR mean values and standard deviation of the breast were comparable between both sequences with a tendency towards a higher SNR for T2 TSE (mean SNR 4.8±1.2) compared to SMS-T2 TSE (mean SNR 4.7±1.2); no statistical significance was reached ($p>0.05$, Table III). The relative within-sequence heterogeneity represented by the coefficient of variation (CV) of the SNR did not significantly differ in the breast itself (T2 TSE 25% *vs*. SMS-T2 TSE 25%, $p>0.05$). At the axillary level, a significant loss of SNR was registered for both sequences with a mean SNR of T2 TSE of 2.0±0.2 ($p<0.001$) and a mean SNR of SMS-T2 TSE of 1.4±0.3 ($p<0.001$). In the axillary region, SNR values of SMS-T2 TSE were significantly lower compared to T2 TSE ($p=0.03$) with comparable CV (T2 TSE 17% *vs*. SMS-T2 TSE 19%, $p>0.05$). Figure 2 illustrates SNR maps of a representative patient.

Discussion

Compared to conventional mammography and breast ultrasound, MRI of the breast has the highest sensitivity for breast cancer detection among current clinical imaging modalities and is an indispensable imaging method for breast imaging. In the last decades, breast MRI has emerged from a primarily contrast-enhanced to a multiparametric technique, in which T2w and DWI sequences are routinely performed within the full-scale protocol (7, 9, 11, 22, 23). T2w imaging allows for a better characterization of lesion morphology and increases the specificity for benign and malignant breast lesions (24, 25). It also allows the depiction of perifocal or prepectoral edema within the breast, which improves lesion classification and is correlated with a poorer prognosis in patients with known breast cancer (26, 27).

Recently, varying indications for breast MRI have been examined. Multiple studies have confirmed its benefit in intermediate risk and high-risk patients for the detection of recurrent breast cancer or the preoperative staging (28). Recent studies strongly indicate that women at average risk (lifetime risk up to 15%) may also benefit from breast MRI screening (29). Despite those encouraging results, breast MRI screening is not yet implemented for women at average risk. The main factors that preclude the widespread use of this are the limited availability of MRI units compared to conventional imaging methods and its high costs. The costs are caused by the initial purchase price of the MRI equipment and the relatively long acquisition, limiting high-volume patient throughput. Abbreviated MRI protocols have the potential to shorten image acquisition and interpretation time, which reduces costs and may increase availability.

Kuhl *et al*. (14) were the first to report on abbreviated protocols for breast cancer screening using reduced numbers of T1w sequences. They found an equivalent diagnostic accuracy for an abbreviated protocol in 606 MRM studies. A recent review of 21 studies on abbreviated breast MRI in more than 4500 women confirmed a similar diagnostic accuracy compared to full scan protocols (30). Nearly all studies in this review achieved scan time reduction by reducing the number of acquired sequences.

A different approach to achieve scan time reduction is to shorten the acquisition time of single sequences. The SMS technique was first introduced in neuroimaging (31). It substantially reduces imaging time by acquiring several images during each repetition time by using multiband composite radiofrequency pulses causing a simultaneous excitation of multiple image planes (32, 33). The technique was also tested for DWI sequences of the abdomen (20, 34-36) and breast (37-40) achieving similar results of decreased imaging acquisition time while maintaining image quality. Focusing on the breast, it has to be mentioned that Filli *et al*. (38) only included 8 healthy women for their feasibility study, whereas Ohlmeyer *et al*. (37), Sanderik *et al*. (39) and Hu *et al*. (40) also reported on the diagnostic accuracy for the evaluation of breast lesions including overall 166 malignant breast lesions. All studies were performed at 3T and found comparable diagnostic accuracy with no significant loss of image quality using SMS technique for DWI.

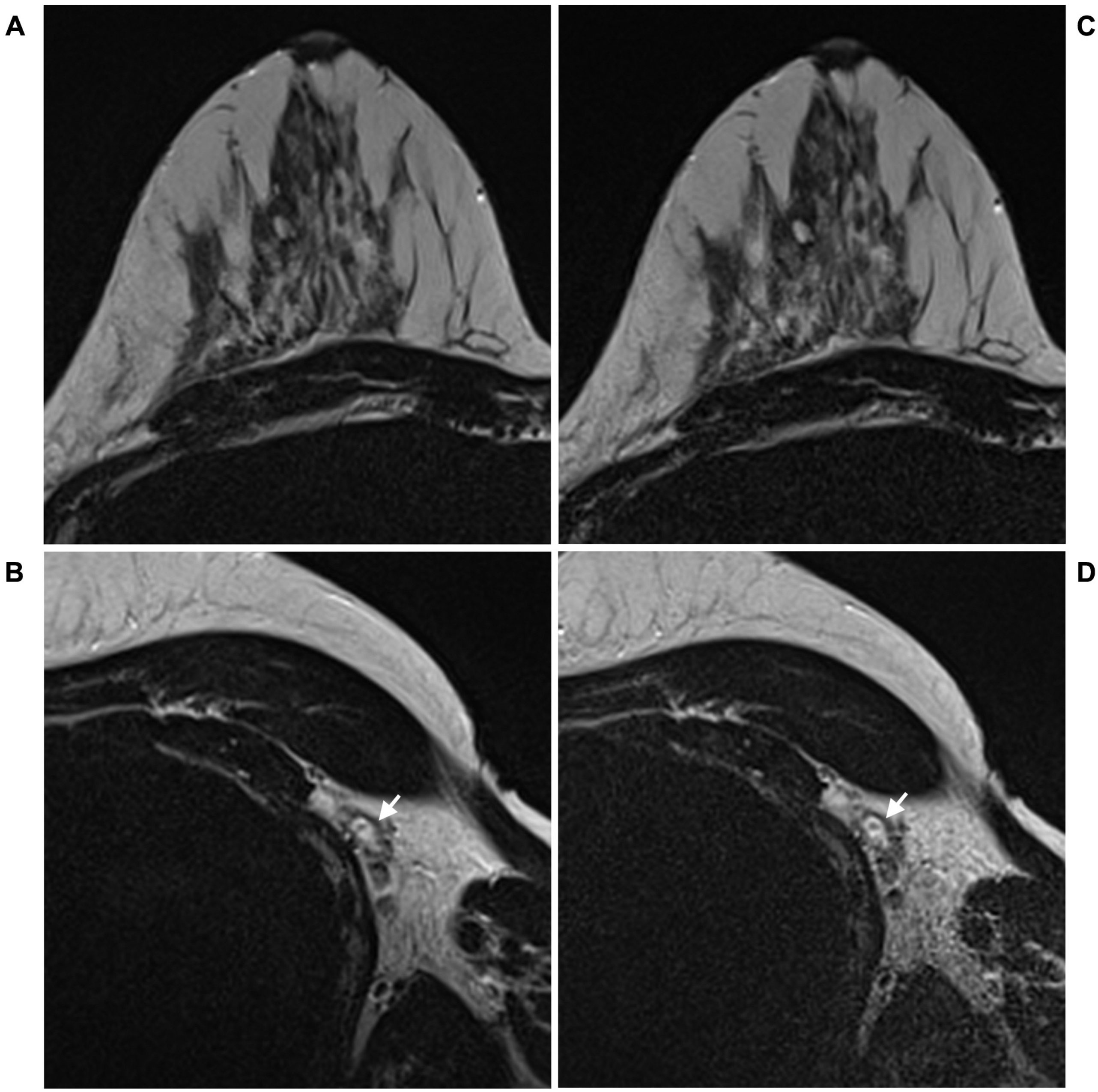

Figure 1. *Slices of T2 TSE (A, B) and SMS-T2 TSE (C, D) in a high-risk woman. Overall image quality, delineation of breast tissue and signal homogeneity were rated as equal (A, B). Image quality at the axillary region was decreased using SMS-T2 TSE, but anatomical structures like lymph nodes were still detectable (B, D, arrow).*

In our study the SMS technique was applied and compared to T2-weighted images of the breast for the first time. We have especially chosen an MRI scanner with 1.5T field strength, as this represented the vast majority of available MRI scanners outside a university setting. The most important finding was a substantial reduction of acquisition time, i.e., 48% time saving using SMS technique while preserving comparable overall image quality. Further, a comparable delineation of the breast tissue with no loss of signal homogeneity was found in all patients. The only differences in the image quality according to the anatomical region were registered as following: there was slightly increased image noise with a loss of image sharpness in the axillary region (p=0.01), whereas no significant differences

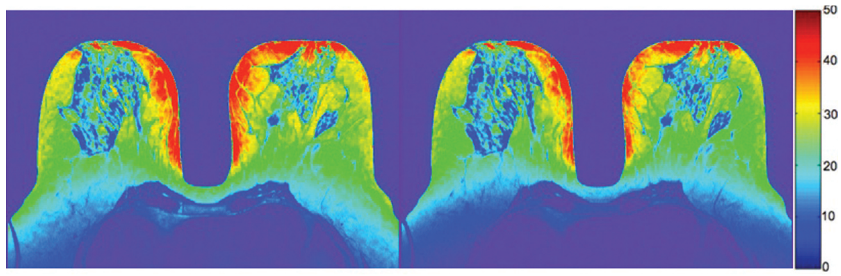

Figure 2. *SNR MAP of T2 TSE (left) and SMS-T2 TSE (right) in a high-risk patient. Comparable SNR of the breast with a moderate loss of SNR in the axillary region, which was even higher using the SMS technique, were measured.*

Table III. *SNR evaluation of T2 TSE vs. SMS-T2 TSE from SNR maps (n=5).*

		T2 TSE	SMS-T2 TSE	*p*-Value
Breast	Mean	47.9	46.7	0.62
	SD	11.9	12.0	0.70
	CV (%)	24.9	25.8	0.81
Axilla	Mean	20.2	14.3	0.03
	SD	1.9	2.7	0.12
	CV (%)	16.9	19.2	0.08

SD: Standard deviation; CV: coefficient of variation; SNR: signal-to-noise ratio.

were recorded in the breast and at the chest wall ($p>0.05$). This was also evident by quantitative measures of SNR maps showing a moderate loss of SNR in the axilla ($p=0.03$). However, anatomical axillary structures, especially lymph nodes, were still well detectable in size, configuration and morphology (Figure 1B, D). Thus, we do not expect a clinically relevant loss of diagnostic information in the axilla. If necessary, care may be taken in patients with breast tissue extending to the axillary region or patients after total mastectomy, since the diagnostic field of interest may extend into regions with slightly pronounced image noise. Since this information is usually available from conventional imaging with ultrasound or mammography prior to MRI, these patients may rather benefit from a full MRI protocol without acceleration.

There are limitations in this study. First, the study population was rather small; however, considering the very good agreement of inter- and intrasubject measurements, we regard the population size as sufficient for this feasibility study. Further, no specific cohort with breast lesions was examined. This also means that no conclusion can be drawn as to whether SMS-T2 TSE facilitates an improved diagnostic assessment and also improves detection of small breast lesions. However, since we were able to show that SMS technique is a feasible acceleration tool for T2w breast imaging, especially keeping comparable tissue delineation and image quality, we do not expect any loss of diagnostic confidence when used for breast lesions. This will be the subject of further studies.

In conclusion, the current study demonstrates comparable image quality and reduced acquisition times for breast imaging with SMS-T2 TSE compared to standard T2 TSE. Since screening indications are growing, this may be beneficial to establish abbreviated breast MRI protocols and help manage the associated costs for breast cancer screening.

Conflicts of Interest

All Authors declare that they have no conflicts of interest.

Authors' Contributions

JR, PR, SK, SOS and CGK made substantial contributions to the conception and design of the study and acquisition of data. JR, PR, CGK, SK, AKK and DO analysed and interpreted the data. JR, AKK, CGK and PR drafted the article. JR, PR, SK, AKK, DO, SOS and CGK reviewed it critically for important intellectual content and gave final approval of the version to be published. JR, PR, SK, AKK, DO, SOS and CGK are accountable for all aspects of the work related to its accuracy or integrity.

References

1 Sardanelli F, Boetes C, Borisch B, Decker T, Federico M, Gilbert FJ, Helbich T, Heywang-Köbrunner SH, Kaiser WA, Kerin MJ, Mansel RE, Marotti L, Martincich L, Mauriac L, Meijers-Heijboer H, Orecchia R, Panizza P, Ponti A, Purushotham AD, Regitnig P, Del Turco MR, Thibault F and Wilson R: Magnetic resonance imaging of the breast: recommendations from the EUSOMA working group. Eur J Cancer *46(8)*: 1296-1316, 2010. PMID: 20304629. DOI: 10.1016/j.ejca.2010.02.015

2 Sardanelli F, Aase HS, Álvarez M, Azavedo E, Baarslag HJ, Balleyguier C, Baltzer PA, Beslagic V, Bick U, Bogdanovic-Stojanovic D, Briediene R, Brkljacic B, Camps Herrero J, Colin C, Cornford E, Danes J, de Geer G, Esen G, Evans A, Fuchsjaeger MH, Gilbert FJ, Graf O, Hargaden G, Helbich TH, Heywang-Köbrunner SH, Ivanov V, Jónsson Á, Kuhl CK,

Lisencu EC, Luczynska E, Mann RM, Marques JC, Martincich L, Mortier M, Müller-Schimpfle M, Ormandi K, Panizza P, Pediconi F, Pijnappel RM, Pinker K, Rissanen T, Rotaru N, Saguatti G, Sella T, Slobodníková J, Talk M, Taourel P, Trimboli RM, Vejborg I, Vourtsis A and Forrai G: Position paper on screening for breast cancer by the European Society of Breast Imaging (EUSOBI) and 30 national breast radiology bodies from Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Israel, Lithuania, Moldova, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland and Turkey. Eur Radiol *27(7)*: 2737-2743, 2017. PMID: 27807699. DOI: 10.1007/s00330-016-4612-z

3 Kuhl CK, Schrading S, Bieling HB, Wardelmann E, Leutner CC, Koenig R, Kuhn W and Schild HH: MRI for diagnosis of pure ductal carcinoma *in situ*: a prospective observational study. Lancet *370(9586)*: 485-492, 2007. PMID: 17693177. DOI: 10.1016/S0140-6736(07)61232-X

4 Sardanelli F, Podo F, Santoro F, Manoukian S, Bergonzi S, Trecate G, Vergnaghi D, Federico M, Cortesi L, Corcione S, Morassut S, Di Maggio C, Cilotti A, Martincich L, Calabrese M, Zuiani C, Preda L, Bonanni B, Carbonaro LA, Contegiacomo A, Panizza P, Di Cesare E, Savarese A, Crecco M, Turchetti D, Tonutti M, Belli P, Maschio AD and High Breast Cancer Risk Italian 1 (HIBCRIT-1) Study: Multicenter surveillance of women at high genetic breast cancer risk using mammography, ultrasonography, and contrast-enhanced magnetic resonance imaging (the high breast cancer risk italian 1 study): final results. Invest Radiol *46(2)*: 94-105, 2011. PMID: 21139507. DOI: 10.1097/RLI.0b013e3181f3fcdf

5 Kuhl C, Weigel S, Schrading S, Arand B, Bieling H, König R, Tombach B, Leutner C, Rieber-Brambs A, Nordhoff D, Heindel W, Reiser M and Schild HH: Prospective multicenter cohort study to refine management recommendations for women at elevated familial risk of breast cancer: the EVA trial. J Clin Oncol *28(9)*: 1450-1457, 2010. PMID: 20177029. DOI: 10.1200/JCO.2009.23.0839

6 Kaiser CG, Reich C, Dietzel M, Baltzer PA, Krammer J, Wasser K, Schoenberg SO and Kaiser WA: DCE-MRI of the breast in a stand-alone setting outside a complementary strategy - results of the TK-study. Eur Radiol *25(6)*: 1793-1800, 2015. PMID: 25577524. DOI: 10.1007/s00330-014-3580-4

7 Kuhl CK, Klaschik S, Mielcarek P, Gieseke J, Wardelmann E and Schild HH: Do T2-weighted pulse sequences help with the differential diagnosis of enhancing lesions in dynamic breast MRI? J Magn Reson Imaging *9(2)*: 187-196, 1999. PMID: 10077012. DOI: 10.1002/(sici)1522-2586(199902)9:2<187::aid-jmri6>3.0.co;2-2

8 Marini C, Iacconi C, Giannelli M, Cilotti A, Moretti M and Bartolozzi C: Quantitative diffusion-weighted MR imaging in the differential diagnosis of breast lesion. Eur Radiol *17(10)*: 2646-2655, 2007. PMID: 17356840. DOI: 10.1007/s00330-007-0621-2

9 Guo Y, Cai YQ, Cai ZL, Gao YG, An NY, Ma L, Mahankali S and Gao JH: Differentiation of clinically benign and malignant breast lesions using diffusion-weighted imaging. J Magn Reson Imaging *16(2)*: 172-178, 2002. PMID: 12203765. DOI: 10.1002/jmri.10140

10 Rahbar H, Zhang Z, Chenevert TL, Romanoff J, Kitsch AE, Hanna LG, Harvey SM, Moy L, DeMartini WB, Dogan B, Yang WT, Wang LC, Joe BN, Oh KY, Neal CH, McDonald ES, Schnall MD, Lehman CD, Comstock CE and Partridge SC: Utility of diffusion-weighted imaging to decrease unnecessary biopsies prompted by breast MRI: A trial of the ECOG-ACRIN Cancer Research Group (A6702). Clin Cancer Res *25(6)*: 1756-1765, 2019. PMID: 30647080. DOI: 10.1158/1078-0432.CCR-18-2967

11 Westra C, Dialani V, Mehta TS and Eisenberg RL: Using T2-weighted sequences to more accurately characterize breast masses seen on MRI. AJR Am J Roentgenol *202(3)*: W183-W190, 2014. PMID: 24555613. DOI: 10.2214/AJR.13.11266

12 Comstock CE, Gatsonis C, Newstead GM, Snyder BS, Gareen IF, Bergin JT, Rahbar H, Sung JS, Jacobs C, Harvey JA, Nicholson MH, Ward RC, Holt J, Prather A, Miller KD, Schnall MD and Kuhl CK: Comparison of abbreviated breast MRI *vs* digital breast tomosynthesis for breast cancer detection among women with dense breasts undergoing screening. JAMA *323(8)*: 746-756, 2020. PMID: 32096852. DOI: 10.1001/jama.2020.0572

13 Ko ES and Morris EA: Abbreviated magnetic resonance imaging for breast cancer screening: Concept, early results, and considerations. Korean J Radiol *20(4)*: 533-541, 2019. PMID: 30887736. DOI: 10.3348/kjr.2018.0722

14 Kuhl CK, Schrading S, Strobel K, Schild HH, Hilgers RD and Bieling HB: Abbreviated breast magnetic resonance imaging (MRI): first postcontrast subtracted images and maximum-intensity projection-a novel approach to breast cancer screening with MRI. J Clin Oncol *32(22)*: 2304-2310, 2014. PMID: 24958821. DOI: 10.1200/JCO.2013.52.5386

15 Grimm LJ, Soo MS, Yoon S, Kim C, Ghate SV and Johnson KS: Abbreviated screening protocol for breast MRI: a feasibility study. Acad Radiol *22(9)*: 1157-1162, 2015. PMID: 26152500. DOI: 10.1016/j.acra.2015.06.004

16 Mango VL, Morris EA, David Dershaw D, Abramson A, Fry C, Moskowitz CS, Hughes M, Kaplan J and Jochelson MS: Abbreviated protocol for breast MRI: are multiple sequences needed for cancer detection? Eur J Radiol *84(1)*: 65-70, 2015. PMID: 25454099. DOI: 10.1016/j.ejrad.2014.10.004

17 Barth M, Breuer F, Koopmans PJ, Norris DG and Poser BA: Simultaneous multislice (SMS) imaging techniques. Magn Reson Med *75(1)*: 63-81, 2016. PMID: 26308571. DOI: 10.1002/mrm.25897

18 Moeller S, Yacoub E, Olman CA, Auerbach E, Strupp J, Harel N and Uğurbil K: Multiband multislice GE-EPI at 7 tesla, with 16-fold acceleration using partial parallel imaging with application to high spatial and temporal whole-brain fMRI. Magn Reson Med *63(5)*: 1144-1153, 2010. PMID: 20432285. DOI: 10.1002/mrm.22361

19 Feinberg DA, Moeller S, Smith SM, Auerbach E, Ramanna S, Gunther M, Glasser MF, Miller KL, Ugurbil K and Yacoub E: Multiplexed echo planar imaging for sub-second whole brain FMRI and fast diffusion imaging. PLoS One *5(12)*: e15710, 2010. PMID: 21187930. DOI: 10.1371/journal.pone.0015710

20 Tavakoli A, Attenberger UI, Budjan J, Stemmer A, Nickel D, Kannengiesser S, Morelli JN, Schoenberg SO and Riffel P: Improved liver diffusion-weighted imaging at 3 T using respiratory triggering in combination with simultaneous multislice acceleration. Invest Radiol *54(12)*: 744-751, 2019. PMID: 31335634. DOI: 10.1097/RLI.0000000000000594

21 Wiens CN, Kisch SJ, Willig-Onwuachi JD and McKenzie CA: Computationally rapid method of estimating signal-to-noise ratio

for phased array image reconstructions. Magn Reson Med *66(4)*: 1192-1197, 2011. PMID: 21465545. DOI: 10.1002/mrm.22893

22 Partridge SC, Zhang Z, Newitt DC, Gibbs JE, Chenevert TL, Rosen MA, Bolan PJ, Marques HS, Romanoff J, Cimino L, Joe BN, Umphrey HR, Ojeda-Fournier H, Dogan B, Oh K, Abe H, Drukteinis JS, Esserman LJ, Hylton NM, ACRIN 6698 Trial Team and I-SPY 2 Trial Investigators: Diffusion-weighted MRI findings predict pathologic response in neoadjuvant treatment of breast cancer: The ACRIN 6698 multicenter trial. Radiology *289(3)*: 618-627, 2018. PMID: 30179110. DOI: 10.1148/radiol.2018180273

23 Le Bihan D: Apparent diffusion coefficient and beyond: what diffusion MR imaging can tell us about tissue structure. Radiology *268(2)*: 318-322, 2013. PMID: 23882093. DOI: 10.1148/radiol.13130420

24 Ballesio L, Savelli S, Angeletti M, Porfiri LM, D'Ambrosio I, Maggi C, Castro ED, Bennati P, Fanelli GP, Vestri AR and Manganaro L: Breast MRI: Are T2 IR sequences useful in the evaluation of breast lesions? Eur J Radiol *71(1)*: 96-101, 2009. PMID: 18479866. DOI: 10.1016/j.ejrad.2008.03.025

25 Arponen O, Masarwah A, Sutela A, Taina M, Könönen M, Sironen R, Hakumäki J, Vanninen R and Sudah M: Incidentally detected enhancing lesions found in breast MRI: analysis of apparent diffusion coefficient and T2 signal intensity significantly improves specificity. Eur Radiol *26(12)*: 4361-4370, 2016. PMID: 27114285. DOI: 10.1007/s00330-016-4326-2

26 Cheon H, Kim HJ, Kim TH, Ryeom HK, Lee J, Kim GC, Yuk JS and Kim WH: Invasive breast cancer: Prognostic value of peritumoral edema identified at preoperative MR imaging. Radiology *287(1)*: 68-75, 2018. PMID: 29315062. DOI: 10.1148/radiol.2017171157

27 Uematsu T, Kasami M and Watanabe J: Can T2-weighted 3-T breast MRI predict clinically occult inflammatory breast cancer before pathological examination? A single-center experience. Breast Cancer *21(1)*: 115-121, 2014. PMID: 23104394. DOI: 10.1007/s12282-012-0425-3

28 Saslow D, Boetes C, Burke W, Harms S, Leach MO, Lehman CD, Morris E, Pisano E, Schnall M, Sener S, Smith RA, Warner E, Yaffe M, Andrews KS, Russell CA and American Cancer Society Breast Cancer Advisory Group: American Cancer Society guidelines for breast screening with MRI as an adjunct to mammography. CA Cancer J Clin *57(2)*: 75-89, 2007. PMID: 17392385. DOI: 10.3322/canjclin.57.2.75

29 Kuhl CK, Strobel K, Bieling H, Leutner C, Schild HH and Schrading S: Supplemental breast MR imaging screening of women with average risk of breast cancer. Radiology *283(2)*: 361-370, 2017. PMID: 28221097. DOI: 10.1148/radiol.2016161444

30 Leithner D, Moy L, Morris EA, Marino MA, Helbich TH and Pinker K: Abbreviated MRI of the breast: Does it provide value? J Magn Reson Imaging *49(7)*: e85-e100, 2019. PMID: 30194749. DOI: 10.1002/jmri.26291

31 Frost R, Jezzard P, Douaud G, Clare S, Porter DA and Miller KL: Scan time reduction for readout-segmented EPI using simultaneous multislice acceleration: Diffusion-weighted imaging at 3 and 7 Tesla. Magn Reson Med *74(1)*: 136-149, 2015. PMID: 25078777. DOI: 10.1002/mrm.25391

32 Larkman DJ, Hajnal JV, Herlihy AH, Coutts GA, Young IR and Ehnholm G: Use of multicoil arrays for separation of signal from multiple slices simultaneously excited. J Magn Reson Imaging *13(2)*: 313-317, 2001. PMID: 11169840. DOI: 10.1002/1522-2586(200102)13:2<313::aid-jmri1045>3.0.co;2-w

33 Feinberg DA and Setsompop K: Ultra-fast MRI of the human brain with simultaneous multi-slice imaging. J Magn Reson *229*: 90-100, 2013. PMID: 23473893. DOI: 10.1016/j.jmr.2013.02.002

34 Tavakoli A, Krammer J, Attenberger UI, Budjan J, Stemmer A, Nickel D, Kannengiesser S, Morelli JN, Schoenberg SO and Riffel P: Simultaneous multislice diffusion-weighted imaging of the kidneys at 3 T. Invest Radiol *55(4)*: 233-238, 2020. PMID: 31917764. DOI: 10.1097/RLI.0000000000000637

35 Obele CC, Glielmi C, Ream J, Doshi A, Campbell N, Zhang HC, Babb J, Bhat H and Chandarana H: Simultaneous multislice accelerated free-breathing diffusion-weighted imaging of the liver at 3T. Abdom Imaging *40(7)*: 2323-2330, 2015. PMID: 25985968. DOI: 10.1007/s00261-015-0447-3

36 Kenkel D, Wurnig MC, Filli L, Ulbrich EJ, Runge VM, Beck T and Boss A: Whole-body diffusion imaging applying simultaneous multi-slice excitation. Rofo *188(4)*: 381-388, 2016. PMID: 26815283. DOI: 10.1055/s-0035-1567032

37 Ohlmeyer S, Laun FB, Palm T, Janka R, Weiland E, Uder M and Wenkel E: Simultaneous multislice echo planar imaging for accelerated diffusion-weighted imaging of malignant and benign breast lesions. Invest Radiol *54(8)*: 524-530, 2019. PMID: 30946181. DOI: 10.1097/RLI.0000000000000560

38 Filli L, Ghafoor S, Kenkel D, Liu W, Weiland E, Andreisek G, Frauenfelder T, Runge VM and Boss A: Simultaneous multi-slice readout-segmented echo planar imaging for accelerated diffusion-weighted imaging of the breast. Eur J Radiol *85(1)*: 274-278, 2016. PMID: 26547123. DOI: 10.1016/j.ejrad.2015.10.009

39 Sanderink WBG, Teuwen J, Appelman L, Moy L, Heacock L, Weiland E, Karssemeijer N, Baltzer PAT, Sechopoulos I and Mann RM: Comparison of simultaneous multi-slice single-shot DWI to readout-segmented DWI for evaluation of breast lesions at 3T MRI. Eur J Radiol *138*: 109626, 2021. PMID: 33711569. DOI: 10.1016/j.ejrad.2021.109626

40 Hu Y, Zhan C, Yang Z, Zhang X, Zhang H, Liu W, Xia L and Ai T: Accelerating acquisition of readout-segmented echo planar imaging with a simultaneous multi-slice (SMS) technique for diagnosing breast lesions. Eur Radiol *31(5)*: 2667-2676, 2021. PMID: 33146797. DOI: 10.1007/s00330-020-07393-5

Received May 28, 2021
Revised July 14, 2021
Accepted July 20, 2021