Biomedical Letters
2017| Volume 3 |Issue 2|Pages 116-121

REVIEW ARTICLE OPEN ACCESS

Multi-Modality Clinical Breast Imaging: A Concise Review and Future Advances

Atiya Allarakha, Pei−Jun Wang*

Department of Radiology, Tongji Hospital affiliated to Tongji University School of Medicine, Shanghai 200065, P.R. China.

Abstract
Breast Imaging has, and still is, evolving with continuous research and with the advent of new promising imaging modalities. With breast carcinoma being one of the most prevalent malignancies worldwide among women, much emphasis is being paid on more accurately diagnosing breast lesions, particularly at an earlier stage. Compared to earlier times, where conventional mammography was the sole imaging technique used, nowadays, the radiologist has a paraphernalia of imaging modalities to choose from, namely, conventional Digital Mammography (DM), Digital Breast Tomosynthesis (DBT), Contrast-Enhanced Digital Mammography (CEDM), Ultrasound (US), and multiparametric Magnetic Resonance Imaging (mp-MRI). Breast Imaging modalities were previously used for screening, for diagnosing malignancies and for follow up, but currently, are also being used to do guided biopsies and to evaluate the patient post operatively for recurrence and both pre and post chemotherapy. Novel techniques like sodium MRI, Blood Oxygen Level-Dependent (BOLD) MRI to name but a few, have also come to light and hint at a promising future for breast lesion diagnosis via medical imaging. This article is a concise review of what imaging modalities are currently being used for the breast and in what context. A brief overview of the latest emerging imaging modalities is also discussed.

Keywords: Breast Imaging, Digital Mammography, Ultrasound, Multiparametric MRI, DCE-MRI.

Received July 02, 2017; **Revised** August 06, 2017; **Accepted** August 15, 2017
***Correspondence:** Pei-Jun Wang **Email**: tongjipjwang@vip.sina.com, **Contact**: +86139 0169 0566

To cite this manuscript: Allarakha A, Wang PJ. Multi-Modality Clinical Breast Imaging: A Concise Review and Future Advances. Biomed Lett 2017; 3(2):116-121.

Introduction

Breast Carcinoma is the most common cancer diagnosed among females globally, being among one of the leading causes of deaths from malignancy[1, 2]. In the clinical setting, physicians daily come across patients with breast-related complaints and, if need be, invariably refer to the radiologist for a clearer picture to help them for diagnosis. The imaging evaluation of a breast lesion is usually done in a chronological order, starting with a basic mammography and in ascending order, an ultrasound and a Dynamic Contrast Enhanced (DCE)-MRI, depending on each patient's requirement. The American College of Radiology has issued guidelines and indications for the use of mammography, ultrasound and Breast MRI and has even published separate Breast Imaging Reporting and Data System (BIRADS) lexicons for each of them to standardize imaging reporting for the radiologist and universalize interpretation of the images by giving a lexicon of descriptors and a BIRADS category in each report [3, 4]. Over the years, imaging has played a crucial role in the diagnosis and management of breast lesions, and the ever-increasing demand for breast imaging has led to several studies and research being conducted worldwide to improve its sensitivity, specificity and positive predictive value (PPV)[5]. They all aim to diagnose breast lesions precisely, non-invasively, and ultimately, give the treating physician a more accurate picture of what's going on. This review summarizes the different breast imaging modalities currently available and their application and uses, and also gives an outline of the new advances in breast imaging on the horizon.

Conventional Digital Mammography (DM)

Mammography has been widely established as the most cost-effective screening method to diagnose breast malignancy worldwide and it has been proven by randomized clinical trials to reduce breast cancer mortality [6, 7]. In fact, a mammogram is now an essential part of any public health screening program in most countries[8, 9]. This relatively simple, rapid, cheap and two-dimensional (2D) imaging investigation is usually the first step in the evaluation of any breast lesion in adjunct with ultrasound. A mammogram consists of 2 views namely, the Cranio-

Caudal (CC) view and the Medio-Lateral Oblique (MLO) view. Abnormalities seen on a mammography present as hyperdense masses, calcifications (whether irregular or microcalcifications), enlarged lymph nodes and skin changes (such as skin thickening, distortion, and retraction of the nipple). The BIRADS lexicon for mammography is used universally, and no report is complete without assigning it with a BIRADS category. Although the specificity of mammography is high, its sensitivity is lower. The major limitation of mammography is difficulty in diagnosing lesions in dense breast tissues due to overlapping and blurring of lesion margins by dense breast tissues[8, 10]. This is worrisome especially since high breast density is a recognized risk factor for malignancy [11, 12]and inability to spot lesions due to this leads to false negative reports and directly impacts and lowers the sensitivity, therefore needing the development of other imaging techniques with better sensitivity.

Digital Breast Tomosynthesis (DBT)

DBT is a three-dimensional (3D) imaging technique where multiple projection images are obtained at limited angles[13]. It was initially developed to improve detection and characterization of breast lesions, especially in women with dense breasts[14]. Reconstruction of the DBT images with resulting thin slices, as thin as 0.5mm, have dramatically improved the sensitivity of mammography as lesions are seen more clearly, without being overlapped by breast tissue in adjacent planes, and margins which were obscured by conventional mammography are also better seen [15-17]. DBT is particularly useful in cases of non-calcified lesions, as these are sometimes difficult to identify on conventional mammography. Several studies over the last decade have proven the superiority of DBT over DM, with an increase in detection rates of malignancy by 10-53%, and with reduced recall rates [18-20]. This increased diagnostic accuracy with little increase in radiation has resulted in the call for DBT to replace DM as a screening modality for malignancy[13, 21]. DBT has been FDA approved as a modality for breast cancer screening in 2011 and is now routinely used in several centers worldwide[22].

Contrast-Enhanced Digital Mammography (CEDM)

CEDM is the combination of conventional mammography along with the injection of iodinated intravenous contrast. There are two main types of CEDM namely, serial CEDM and dual energy CEDM[23]. In serial CEDM, a pre-contrast image is first obtained, and serial post contrast images are then obtained, while in dual energy CEDM, all images are obtained in rapid succession, and image subtraction is done simultaneously. The aim of CEDM is to assess vascularity of tumors, but this competes directly with a Dynamic Contrast Enhanced (DCE)-MRI, which has already exploited this aspect since a long time back[24, 25]. Although CEDM could be more affordable and quick, it cannot assess kinetic curves and is not superior to MRI in showing invasion of chest wall structures and lymph nodes. However, a recent study by Lee-Felker SA et al. in 2017 has shown CEDM to be potentially as accurate as MRI to demonstrate the extent of disease and with a higher PPV [26]. More studies need to be done with regard to this aspect, but till date in routine clinical practice, a DCE-MRI is usually preferred over CEDM for contrast enhanced visualization of breast tissues and lesions[10, 27].

Ultrasound (US)

Breast ultrasound is the most commonly used breast imaging technique worldwide, due to its affordability, widespread availability and no radiation exposure. It is well tolerated and widely accepted by the patient since it is rapid and usually painless (does not require breast compression as in mammography). Furthermore, as there is no exposure to radiation, it can be done safely during pregnancy and breastfeeding and in young patients as well. It is routinely requested to evaluate clinically palpable breast lumps and is excellent in differentiating if they are of a cystic or a solid nature via their echogenicity. It is also the primary imaging technique recommended for interventional procedures, and US-guided biopsies are routinely performed daily worldwide[12].

Ultrasound has also been proposed as an adjunct screening technique in patients with dense breast and negative mammograms, but it is generally not used as a screening tool for breast cancer detection because it does not always detect some early signs of cancer such as micro-calcifications. The issue of whether the US can differentiate benign from malignant breast lesions has long been debated and researched upon, leading to several studies which have shown some descriptors that may potentially guide us to predict malignancy via ultrasound[11, 28]. These descriptors now form the basis of BIRADS US lexicons [29]. Doppler US showing the vascularity and blood flow in breast lesions were initially promising, but studies showed significant overlap between benign and malignant breast lesions[30-32]. Therefore, although Doppler evaluation of a lesion is recommended by BIRADS-US lexicon, it is not mandatory [33].

Advances in US imaging include harmonic imaging, compound imaging, power Doppler, higher resolution transducers, and, more recently, elastography and three-dimensional (3D) US[34, 35]. This year in 2017, new studies have just started to show the potential of contrast enhanced US to detect sentinel lymph node status and neoadjuvant chemotherapy response [36], but it is still too early to pronounce how cost effective, accurate and practical this promising area of breast US will be. Technological advances in the portable US in recent years have also given us more efficient equipment with improved image quality that can even be performed in consultation rooms. As a result, increasing numbers of breast surgeons worldwide have their portable ultrasound equipment and perform office US directly, which is in turn, more convenient for the patient [37].

Multiparametric Magnetic Resonance Imaging (mp- MRI)

In clinical practice, MRI is usually not the first imaging modality to be used because of its higher cost and longer time is taken for the investigation, as well as non-availability of an MRI scanner in smaller centers. Some patients are also unable to undergo MRI because of contraindications or allergy to contrast agents[38]. The ACR, in its practice guidelines, has issued indications for doing a Breast MRI, for example, in cases of ambiguity after DM and US, for assessing the extent of disease pre-operatively, for staging, for screening in high risk patients, and also to evaluate the lesion post-surgery, or during neoadjuvant/post chemotherapy [39, 40]. Especially in the western world, MRI is also done to assess breast implants. MRI has proven its worth by showing its superiority in categorizing lesions, in assessing their morphological and architectural characteristics, as well as in assessing their kinetic parameters and also by showing us deep occult foci which could be otherwise missed on other imaging modalities. MRI also shows us invasion of chest wall structures and lymph nodes status. A mp-MRI comprises of a DCE-MRI, DWI/ADC and Magnetic Resonance Spectroscopy (MRS).

DCE-MRI

A DCE-MRI is now the basis and foundation of any MRI protocol, and has excellent sensitivity, with a negative predictive value (NPV) of >98% [41] and good specificity for breast cancer diagnosis. Studies have also shown the higher sensitivity of MR imaging compared with mammography or other conventional imaging techniques [42, 43]. DCE-MRI gives us not only morphological characteristics of lesions, like shape and size, but also gives us kinetic parameters and vascularity of lesions, which are different in benign and malignant tissues, like degree of enhancement, types of kinetic curves, time taken for contrast to peak and whether there is any washout of contrast from the lesions.BIRADS lexicons have even been revised and now have a separate category about kinetic parameters with dynamic contrast [4, 44]. DCE-MRI also is superior in showing us chest wall structures invasion, lymph node involvement status and showing us occult or deep foci not visible on DM, US or not palpable clinically.

Role of DWI and ADC

MRI protocols also contain Diffusion Weighted Images (DWI), through which we can assess the cellularity of lesions and also via Apparent Diffusion Coefficients (ADC) values, give the clinician an indication of whether a lesion is malignant or not [45]. Malignant tumors have low ADC values and are of high signal intensity on DWI [46]. ADC value has now been established as a tumor marker, with lower values suggestive of malignancy. ADC values also give an indication about theresponse to chemotherapy, with an increase in the ADC value being suggestive of regression of tumor [47, 48]. In clinical practice, the combination of DWI and DCE-MRI images not only improve the diagnostic accuracy pre-operatively, but also helps us to assess tumor recurrence post-operatively, distinguishes recurrence from scar tissue, and assesses the response of lesions to neo-adjuvant or post-operative chemotherapy[49-51].

Magnetic Resonance Spectroscopy (MRS)

MRS is a non-invasive means of assessing the chemical composition of tissues, by showing the concentrations of different metabolites in specific regions of interest. In the breast, MRS can distinguish between normal, benign and malignant tissues, with malignant breast lesions having higher choline concentrations [52]. Therefore expectedly, the primary use of MRS is to distinguish benign from malignant breast lesions. Recently, several researchers have also found other promising uses of MRS, like to screen for early cancer in BRCA gene carriers, or to evaluate the response to chemotherapy by monitoring the metabolites levels [53].Long before any changes are seen on DM, US or DCE-MRI, metabolism in malignant cells could be assessed via the monitoring of choline, lipid and lactate levels. A study by Jagannathan NR et al. showed that the choline concentrations decreased within less than 24 hours after a first dose of chemotherapy in cases of regression of the tumor, long before any morphologic changes could be seen via other MRI parameters [54]. Unfortunately, MRS is not performed in all tertiary care centers, and it might take some time and more studies for MRS to be implemented to a greater extent and to find its way in MRI protocols.

PET-MRI

PET-MRI is a relatively new hybrid imaging technique which blends the functions of PET with a DCE- MRI. MRI shows us excellent anatomic and soft tissue detail while PET gives us in-vivo molecular functional information. The merging of these two powerful modalities brings the best of both worlds together [55]. One of the uses of PET-MRI is to detect local or distant metastasis, hence more accurately staging breast malignancies and in so doing, helping the oncologist to create better tailor-made individual chemotherapy plans [56, 57]. Another use is to assess neoadjuvant chemotherapy and post chemotherapy response. The latest research by Jane Wang et al. have shown the efficacy of PET-MRI by proving that combined hybrid parameters are more accurate than individual PET or individual MRI parameters [58]. PET-MRI scanners though, are not widely available and are quite expensive, not to forget that few technicians and medical personnel are trained to interpret them. Therefore, it might still take a few years for this very promising modality to expand its coverage globally.

Latest breast imaging modalities on the horizon- What to expect in the future?

Despite all the above imaging techniques available, research is still going on to achieve the ideal scenario and push the limits further. Sodium MRI is among the new techniques being looked into, with studies having demonstrated that it shows a rise in intracellular levels of sodium in malignancies [59]. Conversely, the decline in intracellular sodium can act as a biomarker of response to chemotherapy as well [60, 61]. Phosphorus Spectroscopy, Blood Oxygen Level Dependent (BOLD) MRI, Chemical Exchange Saturation Transfer (CEST) Imaging and Hyperpolarized MRI are also new techniques that are undergoing clinical trials and research worldwide, with all of them investigating deeper into physiological and molecular aspects of breast cancer cellular metabolism and showing the potential to differentiate benign from malignant lesions, to stage breast cancer and to monitor chemotherapy and post-operative response [62-65]. Due to limitations of costs, scanner availability, need for 7T scanners in some cases and special breast coils, only time will tell how far each one of these novel techniques will proceed to become part of the diagnostic imaging workup of breast lesions.

Conclusion

Multimodality breast imaging has evolved far past our imagination could ever have fathomed in the last decade. In clinical practice till date, ACR guidelines and BIRADS lexicons remain the cornerstones for clinicians for ordering investigations related to breast disorders and for radiologists for image reporting. DM still remains the method of choice for screening for malignancy worldwide, unless for high-risk patients who would undergo MRI directly. DBT has revolutionized DM and is coming back to tell us that old is indeed gold. DBT as a 3D technique giving us far better resolution than conventional DM and is widely used in several centers.US is used as an adjunct to mammography for clinically palpable lesions and is the investigation of choice in pregnancy and breastfeeding for obvious reasons, and in younger patients to limit radiation exposure. US is also the primary imaging modality for interventions like aspiration of cysts or for obtaining biopsies from suspicious breast lesions. Mp-MRI with all its mind-boggling parameters is constantly reminding us of how powerful it is and how many territories remain to be explored with it. DCE-MRI with DWI has already been established in clinical practice and is currently widely performed universally. MRS and PET-MRI have made their tentative baby steps after being FDA approved and are slowly proving their use, but due to limited availability and higher costs, have yet to expand their coverage to a larger level. Newer techniques like Sodium MRI, Phosphorus Spectroscopy, Blood Oxygen Level Dependent (BOLD) MRI, Chemical Exchange Saturation Transfer (CEST) Imaging and Hyperpolarized MRI are still in the clinical trial phases, and they all show promise in not only increasing diagnostic accuracy but also assessing post-operative and chemotherapy response in breast malignancy. The future of breast imaging with all its modalities and parameters is indeed very bright, and only time will tell how clinical practice for breast pathology will change with relation to medical imaging.

Conflict of interest

The authors have no conflicts of interest to declare.

References

[1] Pace LE, Keating NL. A systematic assessment of benefits and risks to guide breast cancer screening decisions. JAMA 2014; 311(13): 1327-35.

[2] DeSantis C, Ma J, Bryan L, Jemal A. Breast cancer statistics 2013. CA Cancer J. Clin 2014; 64(1): 52-62.

[3]Sedgwick EL, Ebuoma L, Hamame A, Phalak K, Ruiz-Flores L, Ortiz-Perez T et al. BI-RADS update for breast cancer caregivers. Breast Cancer Res Treat 2015;150(2): 243-54.

[4] Spak DA, Plaxco JS, Santiago L, Dryden MJ, Dogan BE. BI-RADS® fifth edition: A summary of changes. Diagnostic and Interventional Imaging 2017;98(3):179-90.

[5] Menezes GL, Winter-Warnars GA, Koekenbier EL, Groen EJ, Veerkoijen HM, Pijnappel RM. Simplifying Breast Imaging Reporting and Data System classification of mammograms with pure suspicious calcifications. Journal of Medical Screening 2017: 0969141317715281.

[6] Marmot MG, Altman DG, Cameron DA, Dewar JA, Thompson SG,Wilcox M. The benefits and harms of breast cancer screening: an independent review: A report jointly commissioned by Cancer Research UK and the Department of Health (England) October 2012. Br J Cancer 2013; 108(11): 2205-40.

[7] Myers ER, Moorman P, Gierisch JM, Havrilesky LJ, Grimm LJ, Ghate S et al. Benefits and harms of breast cancer screening: a systematic review. JAMA 2015; 314(15): 1615-34.

[8] Brown AL, Phillips J, Slanetz PJ, Fein-Zachary V, Venkataraman S, Dialani V, et al. Clinical Value of Mammography in the Evaluation of Palpable Breast Lumps in Women 30 Years Old and Older. AJR Am J Roentgenol 2017: 1-8.

[9] Sandoval JL, Theler JM, Cullati S, Bouchardy C, Manor O, Gaspoz JM et al. Introduction of an organised programme and social inequalities in mammography screening: A 22-year population-based study in Geneva, Switzerland. Prev Med 2017;103:49-55.

[10] Pollán M, Ascunce N, Ederra M, Murillo A, Erdozáin N, Alés-Martínez J et al.Mammographic density and risk of breast cancer according to tumor characteristics and mode of detection: a Spanish population-based case-control study. Breast Cancer Res 2013; 15(1): R9.

[11]Ko SY, Kim EK, Kim MJ, Moon HJ. Mammographic density estimation with automated volumetric breast density measurement. Korean J Radiol 2014;15(3): 313-21.

[12]Sprague BL, Gangnon RE, Burt V, Trentham-Dietz A, Hampton JM, Wellman RD et al. Prevalence of mammographically dense breasts in the United States. J Natl Cancer Inst 2014; 106(10).

[13]Takahashi TA, Lee CI, Johnson KM. Breast cancer screening: Does tomosynthesis augment mammography? Cleve Clin J Med 2017;84(7): 522-527.

[14]Skaane P, Bandos AI, Gullien R, Eben EB, Ekseth U, Haakenaasen U et al., Comparison of digital mammography alone and digital mammography plus tomosynthesis in a population-based screening program. Radiology, 2013;267(1): 47-56.

[15]Helvie MA. Digital mammography imaging: breast tomosynthesis and advanced applications. Radiol Clin North Am 2010;48(5): 917-29.

[16]Melnikow J, Fenton JJ, Whitlock EP, Miglioretti DL, Weyrich MS, Thompson JH et al. Supplemental Screening for Breast Cancer in Women with Dense Breasts: A Systematic Review for the US Preventive Services Task ForceSupplemental Breast Cancer Screening in Women with Dense Breasts. Annals of Inter Med2016;164(4): 268-78.

[17]Thomassin-Naggara I, Perrot N, Dechoux S, Ribeiro C, Chopier J, de Bazelaire C. Added value of one-view breast tomosynthesis combined with digital mammography according to reader experience. Eur J Radiol 2015;84(2):235-41.

[18]Andersson I, Ikeda DM, Zackrisson S, Ruschin M, Svahn T, Timberg P et al., Breast tomosynthesis and digital mammography: a comparison of breast cancer visibility and BIRADS classification in a population of cancers with subtle mammographic findings. Eur Radiol 2008;18(12): 2817-25.

[19]Castillo-García M, Chevalier M, Garayoa J, Rodriguez-Ruiz A, García-Pinto D, Valverde J. Automated Breast Density Computation in Digital Mammography and Digital Breast Tomosynthesis: Influence on Mean Glandular Dose and BIRADS Density Categorization. Acad Radiol 2017; 24(7):802-810.

[20]Skaane P, Bandos AI, Gullien R, Eben EB, Ekseth U, Haakenaasen U et al. Prospective trial comparing full-field digital mammography (FFDM) versus combined FFDM and tomosynthesis in a population-based screening programme using independent double reading with arbitration. Eur Radiol 2013;23(8): 2061-71.

[21]Lang K., Andersson I, Zackrisson S. Breast cancer detection in digital breast tomosynthesis and digital mammography—a side-by-side review of discrepant cases. Br J Radiol 2014; 87(1040): 20140080.

[22]Haas BM, Kalra V, Geisel J, Raghu M, Durand M, Philpotts LE. Comparison of tomosynthesis plus digital mammography and digital mammography alone for breast cancer screening. Radiology 2013; 269(3): 694-700.

[23]Ambicka A, Luczynska E, Adamczyk A, Harazin-Lechowska A, Sas-Korczynska B, Niemiec J. The tumour border on contrast-enhanced spectral mammography and its relation to histological characteristics of invasive breast cancer. Pol J Pathol 2016; 67(3): 295-99.

[24]Mandelson MT, Oestreicher N, Porter PL, White D, Finder CA, Taplin SH et al. Breast density as a predictor of mammographic detection: comparison of interval-and screen-detected cancers. J Natl Cancer Inst 2000; 92(13): 1081-87.

[25]Patel BK.,Naylor ME, Kosiorek HE, Lopez-Alvarez YM, Miller AM, Pizzitola VJ et al., Clinical utility of contrast-enhanced spectral mammography as an adjunct for tomosynthesis-detected architectural distortion. Clin Imaging 2017; 46:44-52.

[26]Lee-Felker SA, Tekchandani L, Thomas M, Gupta E, Andrews-Tang D, Roth A et al. Newly Diagnosed Breast Cancer: Comparison of Contrast-enhanced Spectral Mammography and Breast MR Imaging in the Evaluation of Extent of Disease. Radiology 2017: 161592.

[27]Boyd NF, Guo H, Martin LJ, Sun L, Stone J, Fishell E et al. Mammographic density and the risk and detection of breast cancer. N Engl J Med 2007;356(3): 227-36.

[28]Graf O, Helbich TH, Hopf G, Graf C, Sickles EA. Probably benign breast masses at US: is follow-up an acceptable alternative to biopsy? Radiology 2007;244(1): 87-93.

[29] Sedgwick E. The breast ultrasound lexicon; breast imaging reporting and data system (BI-RADS). Semin Roentgenol. 2011; 46(4):245-51.

[30]Hooley RJ, Scoutt LM, Philpotts LE. Breast ultrasonography: state of the art. Radiology 2013; 268(3): 642-59.

[31]Gokalp G, Topal U, Kizilkaya E. Power Doppler sonography: Anything to add to BI-RADS US in solid breast masses? Eur J Radiol 2009;70(1): 77-85.

[32] Moon WK, Lee YW, Huang YS, Lee SH, Bae MS, Yi A et al. Computer-Aided Prediction of Axillary Lymph Node Status in Breast Cancer Using Tumor Surrounding Tissue Features in Ultrasound Images. Comput Methods Programs Biomed 2017;146: 143-150.

[33]Zhang Q, Yuan C, Dai W, Tang L, Shi J, Li Z et al. Evaluating pathologic response of breast cancer to neoadjuvant chemotherapy with computer-extracted features from contrast-enhanced ultrasound videos. Phys Med 2017;39: 156-163.

[34]Seo M, Ahn HS, Park SH, Lee JB, Choi BI, Sohn YM et al., Comparison and Combination of Strain and Shear Wave Elastography of Breast Masses for Differentiation of Benign and Malignant Lesions by Quantitative Assessment: Preliminary Study. J Ultrasound Med 2017.

[35]Wang Y, Nasief HG, Kohn S, Milkowski A, Clary T, Barnes S et al., Three-dimensional ultrasound elasticity imaging on an automated breast volume scanning system. Ultrasonic Imaging 2017: 161734617712238.

[36]Wang Y, Zhou W, Li C, Gong H, Li C, Yang N et al., Variation of sentinel lymphatic channels (SLCs) and sentinel lymph nodes (SLNs) assessed by contrast-enhanced ultrasound (CEUS) in breast cancer patients. World J Surg Oncology 2017; 15(1): 127.

[37]Law MT, Kollias J, Bennett I. Evaluation of office ultrasound usage among Australian and New Zealand breast surgeons. World J Surg 2013; 37(9): 2148-54.

[38]Chudgar A, Conant EF, Weinstein SP, Keller BM, Synnestvedt M, Yamartino P et al. Assessment of disease extent on contrast-enhanced MRI in breast cancer detected at digital breast tomosynthesis versus digital mammography alone. Clin Radiol 2017.;72(7): 573-79.

[39]Dang CM, Zaghiyan K, Karlan SR, Phillips EH. Increased use of MRI for breast cancer surveillance and staging is not associated with increased rate of mastectomy. Am Surg 2009;75(10): 937-40.

40. Strobel K., Schrading S, Hansen NL, Barabasch A,Kuhl CK. Assessment of BI-RADS category 4 lesions detected with screening mammography and screening US: utility of MR imaging. Radiology 2015;274(2): 343-51.

[41]Dorrius MD, Pijnappel RM, Sijens PE, van der Weide MC, Oudkerk M. The negative predictive value of breast Magnetic Resonance Imaging in noncalcified BIRADS 3 lesions. Eur J Radiol 2012; 81(2): 209-13.

[42]Partridge SC, Demartini WB, Kurland BF, Eby PR, White SW, Lehman CD. Differential diagnosis of mammographically and clinically occult breast lesions on diffusion-weighted MRI. J Magn Reson Imaging 2010;31(3):562-70.

[43]Marino MA, Helbich T, Baltzer P, Pinker-Domenig K. Multiparametric MRI of the breast: A review. J Magn Reson Imaging 2017.

[44]Xu HD, Zhang YQ. Evaluation of the efficacy of neoadjuvant chemotherapy for breast cancer using diffusion-weighted imaging and dynamic contrast-enhanced magnetic resonance imaging. Neoplasma 2017; 64(3): 430-436.

[45]An YY, Kim SH, Kang BJ. Differentiation of malignant and benign breast lesions: Added value of the qualitative analysis of breast lesions on diffusion-weighted imaging (DWI) using readout-segmented echo-planar imaging at 3.0 T. PloS One 2017;12(3): e0174681.

[46]Partridge SC, McDonald ES. Diffusion weighted MRI of the Breast: Protocol optimization, guidelines for interpretation, and potential clinical applications. Magn Reson Imaging Clin N Am 2013; 21(3): 601-24.

[47]Galban C, Hoff BA, Chenevert TL, Ross BD.Diffusion MRI in early cancer therapeutic response assessment. NMR Biomed 2017;30(3).

[48]Altay C, Balci P, Altay S, Karasu S, Saydam S, Canda T et al. Diffusion-weighted MR imaging: role in the differential diagnosis of breast lesions. JBR–BTR 2014; 97(4): 211-16.

[49]Ma D, Lu F, Zou X, Zhang H, Li Y, Zhang L et al. Intravoxel incoherent motion diffusion-weighted imaging as an adjunct to dynamic contrast-enhanced MRI to improve accuracy of the differential diagnosis of benign and malignant breast lesions. Magn Reson Imaging 2017; 36: 175-79.

[50]Dijkstra H, Dorrius MD, Wielema M, Pijnappel RM, Oudkerk M, Sijens PE. Quantitative DWI implemented after DCE-MRI yields increased specificity for BI-RADS 3 and 4 breast lesions. J Magn Reson Imaging 2016.;44(6): 1642-49.

[51]Zhang L, Tang M, Min Z, Lu J, Lei X, Zhang X. Accuracy of combined dynamic contrast-enhanced magnetic resonance imaging and diffusion-weighted imaging for breast cancer detection: a meta-analysis. Acta Radiol 2016; 57(6): p. 651-60.

[52] Clauser P, Marcon M, Dietzel M, Baltzer PAT. A new method to reduce false positive results in breast MRI by evaluation of multiple spectral regions in proton MR-spectroscopy. Eur J Radiol 2017.;92: 51-57.

[53] Bolan PJ. Magnetic resonance spectroscopy of the breast: current status. Magn Reson Imaging Clin N Am.2013;21(3):625-39.

[54]Jagannathan N, Kumar M, Seenu V, Coshic O, Dwivedi SN, Julka PK et al. Evaluation of total choline from in-vivo volume localized proton MR spectroscopy and its response to neoadjuvant chemotherapy in locally advanced breast cancer. Br J Cancer 2001; 84(8): 1016-22.

[55]Bolus NE, George R, Washington J, Newcomer BR. PET/MRI: the blended-modality choice of the future? J Nucl Med Technol 2009;37(2): 63-71.

[56]Goorts B, Vöö S, van Nijnatten TJA, Kooreman LFS, de Boer M, Keymeulen KBMI et al. Hybrid 18F–FDG PET/MRI might improve locoregional staging of breast cancer patients prior to neoadjuvant chemotherapy. Eur J Nucl Med Mol Imaging 2017;Jun 10.

[57]Melsaether A, Moy L. Breast PET/MR Imaging. Radiol Clin North Am 2017;55(3): 579-89.

[58]Ehman EC, Johnson GB, Villanueva-Meyer JE, Cha S, Leynes AP, Larson PE. PET/MRI: Where might it replace PET/CT? J Magn ResonImaging 2017.

[59]Ouwerkerk R. Sodium MRI. Methods Mol Biol. 2011;711:175-201.

[60]Zaric O, Pinker K, Zbyn S, Strasser B, Robinson S, Minarikova L et al. Quantitative sodium MR imaging at 7 T: initial results and comparison with diffusion-weighted imaging in patients with breast tumors. Radiology 2016.;280(1): 39-48.

[61]Jacobs MA, Stearns V, Wolff AC, Macura K, Argani P, Khouri N et al. Multiparametric magnetic resonance imaging, spectroscopy and multinuclear (23 Na) imaging monitoring of preoperative chemotherapy for locally advanced breast cancer. Acad Radiol 2010;17(12): 1477-85.

[62]Rakow-Penner R.,Daniel B, Glover GH. Detecting blood oxygen level-dependent (BOLD) contrast in the breast. J Magn Reson Imaging 2010;32(1): 120-29.

[63]Rivlin M, Horev J, Tsarfaty I, Navon G et al. Molecular imaging of tumors and metastases using chemical exchange saturation transfer (CEST) MRI. Sci Rep 2013;3:3045.

[64]Asghar Butt S, Søgaard LV, Ardenkjaer-Larsen JH, Lauritzen MH, Engelholm LH, Paulson OB et al. Monitoring mammary tumor progression and effect of tamoxifen treatment in MMTV-PymT using MRI and magnetic resonance spectroscopy with hyperpolarized [1-13C] pyruvate. Magn Reson Med 2015;73(1): 51-8.

[65]Kemp WJ, Stehouwer BL, Boer VO, Luijten PR, Klomp DW, Wijnen JP et al. Proton and phosphorus magnetic resonance spectroscopy of the healthy human breast at 7 T. NMR Biomed 2017;30(2).