Diagnostic Accuracy Study

Medicine®

OPEN

The diagnostic performance of dynamic contrast-enhanced MRI and its correlation with subtypes of breast cancer

Xun Li, MD[a], Peng Fu, MD[a], Ming Jiang, MD[a], Jiaming Zhang, MD[a], Lun Tan, MD[b], Tao Ai, MD[c], Xingrui Li, MD[d,*]

Abstract

To evaluate diagnostic performance of perfusion-weighted imaging in differentiating benign from malignant breast lesions, and the correlation between the prognostic factors/subtypes of breast cancers and the perfusion parameters.

A total of 76 patients (59 cases with breast cancer) were included in our study. The Wilcoxon rank-sum test or the Kruskal–Wallis test were adopted for comparisons according to the dichotomous histopathologic prognostic factors or immunohistochemical subtypes. Receiver operating characteristic curves were used to determine the area under the curve (AUC) values for perfusion parameters to assess discrimination ability.

Confirming by pathology after operation, the percentage of benign lesions is 22.37% (17/76), malignant lesions (breast cancer) is 77.63% (59/76). According to puncture and pathological findings after operation, the standard of the molecular subtypes of breast cancer, triple negative account for 13.6% (8/59), non-triple negative account for 86.4% (51/59). The value of mean Ktrans and Kep were lower in benign than malignant lesions ($P \leq .001$). The AUC of the 3 indicators are significantly improved after adjusting for age (AUC = 0.858 for Ktrans, AUC = 0.926 for Kep, and AUC = 0.827 for Ve). Moreover, the Ve index showed better discrimination performance than other indicators in identifying patients with triple-negative subtypes. Similarly, the identification ability came to the highest when combing Kep and Ve.

Perfusion parameters on dynamic enhanced magnetic resonance imaging are statistically significant in distinguishing benign from malignant breast lesion, and may potentially be used as biomarkers in discriminating patients with triple-negative molecular subtypes of breast cancer.

Abbreviations: AUC = area under the curve, DCE-MRI = dynamic enhanced magnetic resonance imaging, ER = estrogen receptor, FOV = field of view, HER-2 = human epidermal growth factor receptor-2, MRI = magnetic resonance imaging, PR = progesterone receptor, ROC = receiver operating characteristic, TE = echo time, TR = repetition time.

Keywords: area under the curve, breast cancer, dynamic contrast-enhanced MRI

1. Introduction

Breast cancer has become the most common malignancy among women in China. Angiogenesis is an independent risk factor for breast cancer, it is proved to correlate with the prognostic factors of tumor size, histologic type, and axillary lymph node metastasis.[1–3] The association of breast cancer subtypes with angiogenesis was identified by Kraby et al,[4] who observed that high microvessel density was associated with poor prognosis in luminal A.

Magnetic resonance imaging (MRI) is widely used in the discovery, diagnosis, and staging of breast cancer. MRI has a

Editor: Maya Saranathan.

XL and PF contributed equally to this work.

This study was funded by Wuhan Municipal Health Commission, Grant/Award Number: WX19Q49; Health Commission of Hubei province, Grant/Award Number: WJ2019H396.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

The authors have no conflicts of interest to disclose.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

[a] *Department of Thyroid and Breast Surgery, The Central Hospital of Wuhan, Tongji Medical College, Huazhong University of Science and Technology, 26 Shengli Street, Wuhan, China,* [b] *Department of Cardiology, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Jiefang Avenue, Wuhan, China,* [c] *Department of Imaging Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Jiefang Avenue, Wuhan, China,* [d] *Department of Thyroid and Breast Surgery, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Jiefang Avenue, Wuhan, China.*

[*] *Correspondence: Xingrui Li, Department of Thyroid and Breast Surgery, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Jiefang Avenue, Wuhan 430030, China (e-mail: 283326710@qq.com).*

Copyright © 2021 the Author(s). Published by Wolters Kluwer Health, Inc.
This is an open access article distributed under the terms of the Creative Commons Attribution-Non Commercial License 4.0 (CCBY-NC), where it is permissible to download, share, remix, transform, and buildup the work provided it is properly cited. The work cannot be used commercially without permission from the journal.

How to cite this article: Li X, Fu P, Jiang M, Zhang J, Tan L, Ai T, Li X. The diagnostic performance of dynamic contrast-enhanced MRI and its correlation with subtypes of breast cancer. Medicine 2021;100:51(e28109).

Received: 14 July 2021 / Received in final form: 22 October 2021 / Accepted: 16 November 2021

http://dx.doi.org/10.1097/MD.0000000000028109

unique role in the pre-operative assessment of multifocal, occult, and breast conserving surgery. Although it has a very high sensitivity in the diagnosis of breast cancer, the specificity is relatively low. Contrast-enhanced MRI was first applied to breast cancer in 1986. The principle of dynamic enhanced magnetic resonance imaging (DCE-MRI) is angiogenesis, which is an independent and important risk factor for breast cancer. It had greatly improved radiological diagnosis. The diffusion parameters for evaluating tumor angiogenesis by DCE-MRI were initially identified by Tofts et al.[5] Then, with breast cancers, there has been a rising interest in the correlation between perfusion parameters and prognostic factors.[6–8] Kim et al[7] reported that correlations between a higher Ktrans and Kep or lower Ve and poor prognostic factors or triple negative subtypes. Tofts et al[6] reported that there was no statistical significance between perfusion parameters and subtypes of breast cancer.

The aim of our study is to evaluate whether a correlation exists between the prognostic factors or subtypes of breast cancers and perfusion parameters from DCE-MRI, and to assess the diagnostic accuracy of perfusion-weighted imaging in differentiating benign from malignant breast lesions using DCE-MRI.

2. Methods

2.1. Study population

This study was approved by the institutional review board of our hospital, and the informed consent form were waived. Between January 2019 and July 2020, 98 consecutive patients with breast lesions underwent DCE-MRI for pre-operative evaluation at our hospital. After excluding 22 cases (9 of them transferred to another hospital and 13 were lost to follow-up), we included 76 patients in the final analysis, with 59 cases confirmed as breast cancer. All patients are female and the median age of our participants is 41.0 years (ranging from 13–67 years).

2.2. MRI techniques

All breast MR examinations were performed using a 3.0T system (Verio; Siemens Healthcare, Erlangen, Germany) with a dedicated 16-channel phased-array breast coil. The imaging sequences and parameters were as follows: Axial bilateral turbo spin-echo T2-weighted imaging: repetition time (TR) = 3700 ms, echo time (TE) = 101 ms, flip angle = 120°, field of view (FOV) = 320 × 320 mm, matrix = 224 × 320, average = 1, slice thickness = 4 mm, acquisition time = 2 minutes 20 seconds. Diffusion-weighted imaging with readout-segmented echo-planar technique: TR = 5000 ms, TE = 70 ms, FOV = 169 × 280, matrix = 114 × 188, flip angle = 180°, slice thickness = 5 mm, b-value = 0, 50, 1000, 2000 s/mm^2, readout segments = 5, acquisition time = 4 minutes 27 seconds. T1-mapping and fast dynamic T1-weighted DCE-MRI based on 3D volumetric interpolated breath-hold examinations sequence: TR = 5.40 ms, TE = 2.46/3.69 ms, FOV = 320 × 320 mm, matrix = 320 × 320, slice thickness = 1.5 mm, no gap. The variable flip angle method was used to calculate T1 maps (2° and 14°). After T1-mapping scan, 35 consecutive phases were acquired for DCE-MRI, with a temporal resolution of 11.2/phase. Gadodiamide contrast medium (Omniscan; GE Healthcare, Milwaukee, WI) was intravenously administrated at a dose of 0.1 mmol/kg of body weight and a rate of 2.5 mL/s by a power injector at the end of the third phase of dynamic acquisitions, followed by a 20-mL saline flush. The total scan time of DCE-MRI was 6 minutes 58 seconds.

2.3. Image analysis

Data processing was performed by 2 independent radiologists with more than 5 years of breast MRI experience. They were both blinded to the patients' clinical history and histopathological results. The T1 mapping and 35-phase dynamic series were transferred to a workstation and subsequently processed with commercial software Tissue 4D (Siemens Healthcare). After motion correction and registration were automatically performed, a series of ROIs was manually drawn on the continuous levels for each lesion, avoiding visible necrosis, vessels, calcifications, and cystic appearing areas by referring to T2-weighted images. The pharmacokinetic parameters were analyzed based on the Tofts model. The arterial input function was set to "intermediate" type (population arterial input function) which is built in Tissue 4D. The perfusion parameters including Ktrans, Kep, and Ve for the whole enhanced lesion were then generated for each voxel defined by the ROIs.

2.4. Statistical analysis

According to histopathological prognostic factors and immunohistochemical subtypes, all cases with malignant lesions were divided into 1 of 2 groups: tumor size (≤2 cm vs >2 cm), histologic grade (grades 1 and 2 vs 3), estrogen receptor (ER) or progesterone receptor (PR), or human epidermal growth factor receptor-2 (HER-2) expression (negative vs positive), Ki-67 (≤14% vs >14%), and lymph node metastasis (negative vs positive). Subtypes based on the immunohistochemical profile were categorized as follows: luminal (ER or PR-positive), triple negative (ER or PR-negative, HER-2-negative), or HER-2 (ER and PR-negative with HER-2 overexpression).

Since the skew distributions of perfusion parameters, we adopted the Wilcoxon rank-sum test or the Kruskal–Wallis test for comparisons according to the dichotomous histopathologic prognostic factors or immunohistochemical subtypes. Receiver operating characteristic (ROC) curves were used to determine the area under the curve (AUC) values for perfusion parameters to assess discrimination ability. The above analyses were all performed using Stata 12.0, the statistically significant difference was determined to be 2-sided $P < .05$.

3. Results

Totally, 76 patients who underwent DCE-MRI in our hospital were selected. Among them, 59 cases were confirmed as breast cancer and 17 were benign masses. The age of breast cancer patients is 19 to 67 years (with a mean age of 43.0 years), and the age of benign breast patients is 13 to 49 years (with a mean age of 29.0 years).

As shown in Table 1, the average values of Ktrans and Kep of breast cancer were greater than that of benign, and the differences were statistically significant ($P < .001$ for Kep and $P = .001$ for Ktrans). Besides, we also found age of breast cancer patients is

Table 1

The distributions of quantitative parameters for benign and malignant lesions.

	Kep	Ktrans	Ve	Age
Benign	0.44 ± 0.21	0.20 ± 0.13	0.46 ± 0.10	29.76 ± 10.09
Malignant	0.84 ± 0.25	0.35 ± 0.15	0.42 ± 0.11	42.81 ± 10.03
P value	<.001	.001	.192	<.001

Table 2

The ROC curves of quantitative indicators used to distinguish the benign and malignant lesions.

Parameters	AUC	Cut-off	Sensitivity	Specificity
Ktrans	0.780	0.205	84.7	58.8
Kep	0.892	0.581	86.4	82.4
Ve	0.624	0.384	88.2	40.7
Age	0.824	33.5	79.7	76.5
Ktrans+age	0.858	-	78.0	82.4
Kep+age	0.926	-	79.7	94.1
Ve+age	0.827	-	83.1	70.6
Ktrans+Kep+Ve+age	0.934	-	94.9	82.4

AUC = area under the curve, ROC = receiver operating characteristic.

elder than patients with benign breast masses (which seemed to be a confounding factor when distinguishing tumors from benign masses).

As is shown in Table 2 and Figure 1, Kep has the highest ability to distinguish malignant lesions from benign masses, with the sensitivity and specificity 86.4% and 82.4%, respectively. The AUC of the 3 indicators are significantly improved after adjusting for age (AUC=0.858 for Ktrans, AUC=0.926 for Kep, and AUC=0.827 for Ve). And combining the 3 indicators, the discrimination ability came to the highest, with the AUC of 0.934.

As shown in Table 3, the mean value of Ve in low histological grade is greater than that in high histological grade ($P=.011$); the mean value of Kep in patients with PR positive is lower than patients with PR negative ($P=.023$). Except these, there is no significant difference in other clinical characteristics.

The comparison results of the DCE-MRI quantitative parameters among different molecular types are shown in Table 4. There is no statistical difference in any quantitative parameter among the 4 different molecular expression types (luminal A, luminal B, HER2 overexpression and triple negative, all $P>.05$). Interestingly, the average value of Kep for triple-negative breast cancer is higher than that for non-triple negative patients, while the Ve index showed the opposite result, with a border significant P value of .055 (Table 5). Similarly, the Ve index showed better discrimination performance than other indicators, and the identification ability came to the highest when combing Kep and Ve (Fig. 2).

4. Discussion

DCE-MRI is an important part of breast magnetic resonance examination, which can provide the morphological and hemodynamic characteristics of the lesion. Time resolution is an important factor affecting the results of quantitative DCE-MRI analysis.[7,8] The quantitative parameters obtained through the high time resolution scanning sequence can improve the accuracy of breast lesion diagnosis. The occurrence, development and metastasis of tumors are closely related to angiogenesis. The number of blood vessels in the tumor is huge, and the microcirculation blood volume increases easily. However, the vascular shape of benign tumors is relatively mature and the permeability is better, while the permeability of malignant tumors is lower than that of normal breast parenchyma. ER, PR, HER-2, Ki-67, and other related factors directly affect the prognosis of breast cancer.[9–12] Therefore, the DCE-MRI related parameters for evaluating tumor formation may be closely related to the biological characteristics of breast cancer.

The application of DCE-MRI quantitative analysis provides an extremely important diagnostic basis for the identification of benign and malignant breast lesions. First, DCE-MRI judges the nature of the lesion mainly by observing the amount of neovascularization of the mass, permeability, and the micro-structure of basement membrane development.[13–15] This study found that the Ktrans and Kep values of benign breast lesions were both lower than that of malignant lesions, which was supported by other studies. Compared with breast cancer tissue, there are fewer micro-vessels, complete vascular wall structure,

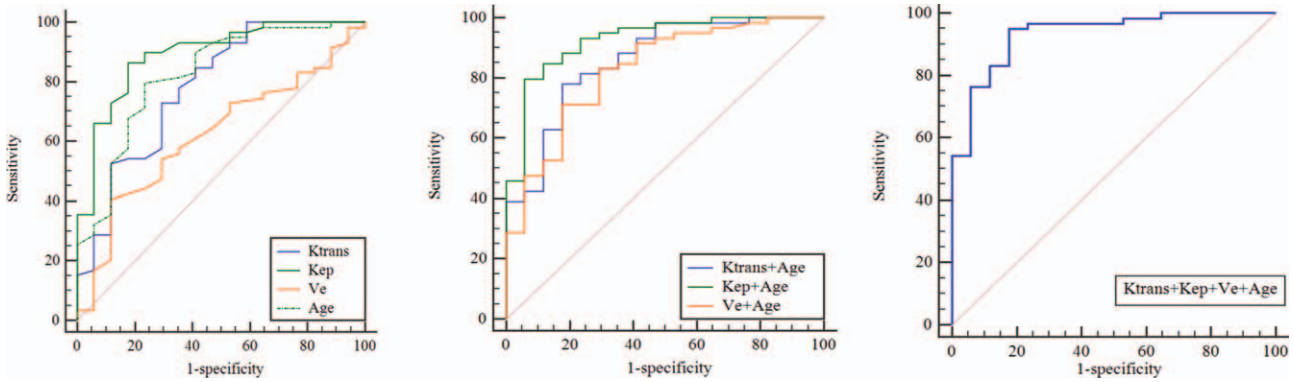

Figure 1. The ROC curve of various parameters in distinguishing malignant lesions from benign masses. ROC = receiver operating characteristic.

Table 3

Correlation of quantitative perfusion parameters with prognostic factors.

	Ktrans	*P* value	Kep	*P* value	Ve	*P* value
Tumor size						
≤2	0.39 ± 0.15	.155	0.87 ± 0.28	.553	0.46 ± 0.11	.122
>2	0.33 ± 0.15		0.83 ± 0.24		0.41 ± 0.11	
Histological grade						
Non-high (grade 1–2)	0.36 ± 0.14	.469	0.82 ± 0.23	.250	0.44 ± 0.12	.011
High (grade 3)	0.32 ± 0.09		0.91 ± 0.18		0.36 ± 0.06	
ER						
Negative	0.36 ± 0.19	.764	0.90 ± 0.30	.178	0.40 ± 0.08	.196
Positive	0.34 ± 0.13		0.80 ± 0.22		0.44 ± 0.12	
PR						
Negative	0.39 ± 0.18	.081	0.92 ± 0.28	.023	0.43 ± 0.09	.762
Positive	0.32 ± 0.12		0.77 ± 0.21		0.42 ± 0.12	
Ki-67						
≤15%	0.33 ± 0.11	.734	0.75 ± 0.19	.381	0.44 ± 0.08	.569
>15%	0.36 ± 0.16		0.86 ± 0.26		0.43 ± 0.11	
HER-2						
Negative	0.34 ± 0.12	.994	0.84 ± 0.21	.707	0.42 ± 0.10	.616
Positive	0.37 ± 0.20		0.84 ± 0.31		0.43 ± 0.12	
Lymph node metastasis						
Negative	0.39 ± 0.17	.223	0.87 ± 0.31	.708	0.44 ± 0.08	.275
Positive	0.34 ± 0.14		0.83 ± 0.23		0.42 ± 0.12	

ER = estrogen receptor, HER-2 = human epidermal growth factor receptor-2, PR = progesterone receptor.

low blood perfusion, and light enhancement for benign lesions.[16–19] However, the Ve value is less significant in distinguishing benign and malignant lesions, which is also similar to the research results of some scholars. Most of them tend to be related to 2 factors, which are the different degrees of edema of the tissues around the malignant transformation or the different arteries. Due to the differences in the distribution of age between benign and malignant patients, we draw 3 separately integrated ROC curves of a single index and 3 comprehensive indexes, and the results showed that the AUC of a single index increased significantly after adjusting for age, and the AUC of the 3 comprehensive indexes was the highest, which greatly improved the ability to distinguish benign and malignant breasts.

Previous studies have shown that according to the metabolism of drugs and contrast agents in breast cancer tissues, the metabolic parameters of drugs and contrast agents in these types of breast cancer are not different in size. This study showed similar results. Studies have shown that the Kep value of triple negative is higher, indirectly reflects the higher contrast agent outflow rate in triple negative.[20–22] Although the differences between the groups in this study were not statistically significant, the Ktrans and Kep of triple negative were higher, indicating that triple negative has higher local blood perfusion and vascular permeability, so it may be more sensitive to chemotherapy. At the same time, the area under the ROC curves of Ve in distinguishing triple-negative from non-triple-negative breast cancer was significantly higher than that of Ktrans and Kep, and the AUC of the combined index was significantly higher. This may provide a highly discriminating method for patients with triple-negative molecular subtypes of breast cancer.[23,24]

There are some limitations in this study. The first is the limitation of MRI technology. The conclusions drawn by different mathematical models are different. The selection of the most appropriate mathematical model is still in the process of groping. The selection of contrast agents also has major limitations. At present, most of the contrast agents used in clinical practice are metal gadolinium-based contrast agents, which are small molecule contrast agents. The study found that when the macromolecular contrast agent is used for enhancement, the relevant parameters obtained are significantly correlated with the histological grades of benign, malignant and malignant tumors, but after switching to small molecule contrast agents, this correlation it is not obvious.[25] Secondly, the sample size of our study is relatively small, thus the results are warranted to be further verified by studies with larger sample size.

Table 4

Correlation of perfusion parameters and immunohistochemical subtypes.

	Ktrans	Kep	Ve
Luminal A	0.31 ± 0.13	0.74 ± 0.20	0.43 ± 0.10
Luminal B	0.36 ± 0.11	0.82 ± 0.20	0.45 ± 0.11
HER-2 overexpression	0.35 ± 0.20	0.84 ± 0.32	0.42 ± 0.12
Triple negative	0.42 ± 0.14	0.94 ± 0.22	0.36 ± 0.05
P value	.714	.627	.199

HER-2 = human epidermal growth factor receptor-2.

Table 5

The distribution differences of quantitative parameters between triple negative and non-triple negative lesions.

	Ktrans	Kep	Ve
Non-triple negative	0.35 ± 0.15	0.82 ± 0.25	0.44 ± 0.11
Triple negative	0.42 ± 0.14	0.94 ± 0.22	0.36 ± 0.05
P value	.778	.250	.055

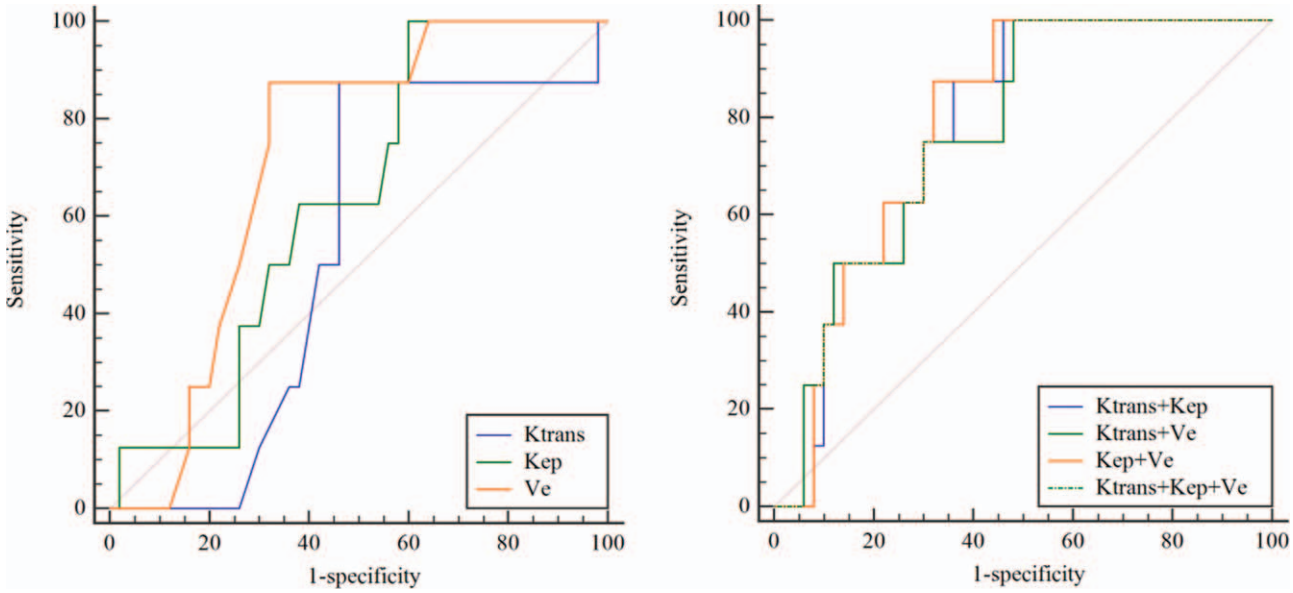

Figure 2. The ROC curve of various parameters in discriminating patients with triple-negative molecular subtypes of breast cancer. AUC for Ktrans+Kep: 0.783; AUC for Ktrans+Ve: 0.770; AUC for Kep+Ve: 0.790; AUC for Ktrans+Kep+Ve: 0.770. AUC = area under the curve, ROC = receiver operating characteristic.

5. Conclusion

The quantitative parameters, Ktrans, Kep, and Ve values of DCE-MRI are statistically significant in distinguishing benign from malignant breast lesion, as well as shows satisfactorily good sensitivity and specificity in discriminating patients with triple-negative molecular subtypes of breast cancer. Further studies with larger sample size are warranted to externally evaluate and validate our results.

Author contributions

Conceptualization: Xingrui Li, Jiaming Zhang.
Data curation: Xun Li, Xingrui Li, Ming Jiang, Tao Ai.
Formal analysis: Xun Li, Peng Fu, Jiaming Zhang, Lun Tan.
Funding acquisition: Xingrui Li.
Investigation: Xun Li, Peng Fu, Ming Jiang, Lun Tan, Tao Ai.
Methodology: Xun Li, Xingrui Li, Jiaming Zhang, Lun Tan, Tao Ai.
Project administration: Xingrui Li, Ming Jiang, Tao Ai.
Resources: Xun Li, Peng Fu, Jiaming Zhang, Lun Tan.
Software: Xun Li, Ming Jiang, Tao Ai.
Supervision: Xun Li, Jiaming Zhang, Lun Tan.
Validation: Xun Li, Peng Fu, Ming Jiang, Jiaming Zhang, Tao Ai.
Visualization: Peng Fu, Ming Jiang, Jiaming Zhang, Lun Tan, Tao Ai.
Writing – original draft: Xun Li, Xingrui Li, Peng Fu, Ming Jiang.
Writing – review & editing: Xingrui Li.

References

[1] Weidner N, Folkman J, Pozza F, et al. Tumor angiogenesis: a new significant and independent prognostic indicator in early-stage breast carcinoma. J Natl Cancer Inst 1992;84:1875–87.
[2] Goede V, Fleckenstein G, Dietrich M, Osmers RG, Kuhn W, Augustin HG. Prognostic value of angiogenesis in mammary tumors. Anticancer Res 1998;18:2199–202.
[3] Nakamiya N, Ueda S, Shigekawa T, et al. Clinicopathological and prognostic impact of imaging of breast cancer angiogenesis and hypoxia using diffuse optical spectroscopy. Cancer Sci 2014;105:833–9.
[4] Kraby MR, Kruger K, Opdahl S, Vatten LJ, Akslen LA, Bofin AM. Microvascular proliferation in luminal A and basal-like breast cancer subtypes. J Clin Pathol 2015;68:891–7.
[5] Kraby MR, Krüger K, Opdahl S, et al. Microvascular proliferation in luminal A and basal-like breast cancer subtypes. J Clin Pathol 2015;68:891–7.
[6] Tofts PS, Brix G, Buckley DL, et al. Estimating kinetic parameters from dynamic contrast-enhanced T (1)-weighted MRI of a diffusable tracer: standardized quantities and symbols. J Magn Reson Imaging 1999;10:223–32.
[7] Kim JY, Kim SH, Kim YJ, et al. Enhancement parameters on dynamic contrast enhanced breast MRI: do they correlate with prognostic factors and subtypes of breast cancers? Magn Reson Imaging 2015;33:72–80.
[8] Koo HR, Cho N, Song IC, et al. Correlation of perfusion parameters on dynamic contrast-enhanced MRI with prognostic factors and subtypes of breast cancers. J Magn Reson Imaging 2012;36:145–51.
[9] Li L, Wang K, Sun X, et al. Parameters of dynamic contrast-enhanced MRI as imaging markers for angiogenesis and proliferation in human breast cancer. Med Sci Monit 2015;21:376–82.
[10] Han M, Kim TH, Kang DK, Kim KS, Yim H. Prognostic role of MRI enhancement features in patients with breast cancer: value of adjacent vessel sign and increased ipsilateral whole-breast vascularity. AJR Am J Roentgenol 2012;199:921–8.
[11] Sardanelli F, Iozzelli A, Fausto A, Carriero A, Kirchin MA. Gadobenate dimeglumine-enhanced MR imaging breast vascular maps: association between invasive cancer and ipsilateral increased vascularity. Radiology 2005;235:791–7.
[12] Wright H, Listinsky J, Quinn C, Rim A, Crowe J, Kim J. Increased ipsilateral whole breast vascularity as measured by contrast-enhanced magnetic resonance imaging in patients with breast cancer. Am J Surg 2005;190:576–9.
[13] Huang X, Dugo M, Callari M, et al. Molecular portrait of breast cancer in China reveals comprehensive transcriptomic likeness to Caucasian breast cancer and low prevalence of luminal A subtype. Cancer Med 2015;4:1016–30.
[14] Bosari S, Lee AK, DeLellis RA, Wiley BD, Heatley GJ, Silverman ML. Microvessel quantitation and prognosis in invasive breast carcinoma. Hum Pathol 1992;23:755–61.

[15] Li SP, Makris A, Beresford MJ, et al. Use of dynamic contrast-enhanced MR imaging to predict survival in patients with primary breast cancer undergoing neoadjuvant chemotherapy. Radiology 2011;260:68–78.
[16] Pickles MD, Manton DJ, Lowry M, Turnbull LW. Prognostic value of pre-treatment DCE-MRI parameters in predicting disease free and overall survival for breast cancer patients undergoing neoadjuvant chemotherapy. Eur J Radiol 2009;71:498–505.
[17] Li L, Wang K, Sun X, et al. Parameters of dynamic contrast enhanced MRI as imaging markers for angiogenesis and proliferation in human breast cancer. Med Sci Monit 2015;21:376–82.
[18] Huang W, Tudorica LA, Li X, et al. Discrimination of benign and malignant breast lesions by using shutter-speed dynamic contrast-enhanced MR imaging. Radiology 2011;261:394–403.
[19] Rahbar H, Partridge SC. Multiparametric MR imaging of breast cancer. Magn Reson Imaging Clin N Am 2016;24:223–38.
[20] Kuhl CK, Kooijman H, Gieseke J, Schild H. Effect of B1 inhomogeneity on breast MR imaging at 3. 0T. Radiology 2007;244:929–30.
[21] Ihemenopausal Cu, Leffall LD, Dewitty RL, et al. Molecular breast cancer subtypes in premenopausal and postmenopausal African-American women: age-specific prevalence and survival. J Surg Reg 2007;143:109–18.
[22] Carey LA, Perou CM, Livasy CA, et al. Race, breast cancer subtypes, and survival in the Carolina Breast Cancer Study. JAMA 2006;295:2492–502.
[23] Baek HM, Yu HJ, Chen JH, Nalcioglu O, Su MY. Quantitative correlation between l HMRS and dynamic contrast — enhanced MRI of human breast cancer. Magn Reson Imaging 2008;26:523–31.
[24] Li J, Zhu P, Wang L, Yang L, Zou L, Gao F. Study of diffusion-weighted magnetic resonance imaging in the evaluation of the response to AAV2-VEGF-Trap neoadjuvant treatment in a triple-negative breast cancer animal model. Cancer Med 2019;8:1594–603.
[25] Mema E, Schnabel F, Chun J, et al. The relationship of breast density in mammography and magnetic resonance imaging in women with triple negative breast cancer. Eur J Radiol 2020;124:108813.
[26] Baker JHE, McPhee KC, Moosvi F, et al. Multi-modal magnetic resonance imaging and histology of vascular function in xenografts using macromolecular contrast agent hyperbranched polyglycerol (HPG-GdF). Contrast Media Mol Imaging 2016;11:77–88.