GMR

The Original

MOLECULAR AND FUNCTIONAL FOUNDATIONS OF INTRAOPERATIVE ULTRASOUND IMAGING IN NEUROSURGERY

Anastasia Igorevna Zhuikova[1], Yulia Olegovna Shimakovskaya[2], Rayana Ramzanovna Khadzhimuradova[3], Magomed-Yaragi Edikovich Magamadov[4], Khadizhat Badrudinovna Dzhanar-Alieva[5], Makka Tagirovna Muzieva[6], Salima Daudovna Merzhoeva[7], Zukhra Ashikovna Ashikova[8], Madina Magomedzapirovna Magomedova[9]

[1]Student, First St. Petersburg State Medical University named after Academician I.P. Pavlov, Saint Petersburg, Russian Federation, e-mail: Kristial2001@mail.ru, https://orcid.org/0009-0009-6239-7756
[2]Student, First St. Petersburg State Medical University named after Academician I.P. Pavlov, Saint Petersburg, Russian Federation, e-mail: t9870901@gmail.com, https://orcid.org/0009-0003-1477-7283
[3]Student, Kadyrov Chechen State University Medical Institute, Grozny, Russian Federation, e-mail: rayana.khadzhimuradovaa@mail.ru, https://orcid.org/0009-0001-9337-0355
[4]Student, Kadyrov Chechen State University Medical Institute, Grozny, Russian Federation, e-mail: magomed1880@inbox.ru, https://orcid.org/00090008-1160-7322
[5]Student, Kadyrov Chechen State University Medical Institute, Grozny, Russian Federation, e-mail: dzhanaraliyeva01@mail.ru, https://orcid.org/0009-0003-9650-3912
[6]Student, Kadyrov Chechen State University Medical Institute, Grozny, Russian Federation, e-mail: makka8709781@gmail.com, https://orcid.org/0009-0006-9535-8348
[7]Student, Ingush State University Medical Institute, Magas, Russian Federation, e-mail: merzhoeva.salima@bk.ru, https://orcid.org/0009-0000-0636-8867
[8]General Director, Medical Diagnostic and Wellness Center, Russian Federation, e-mail: zukhraashikova7@gmail.com, https://orcid.org/0009-00061583-7593
[9]Dagestan State Medical University, Email: magomedova.m2301@icloud.com

ABSTRACT

Multiparametric magnetic resonance imaging (MP-MRI) is one of the most informative and non-invasive methods for diagnosing adrenal tumors, providing a comprehensive assessment of the morphological and functional characteristics of tissues. Combining sequences such as chemical shift, DWI, ADC mapping, and dynamic contrast enhancement (DCE) makes it possible to quantify lipid saturation, perfusion, and diffusion, which significantly improves the accuracy of differential diagnosis of benign and malignant tumors. The review analyzes current research on the possibilities of MPMRI in distinguishing between adenomas, adrenocortical carcinomas and metastatic lesions, and also examines the advantages of integrating the method with artificial intelligence and radiomics technologies. It is shown that the use of quantitative biomarkers and radiomic features contributes to the objectification of image interpretation and the creation of reproducible diagnostic algorithms. Special attention is paid to the clinical use of MP-MRI in preoperative planning, monitoring the effectiveness of therapy and dynamic patient monitoring. The key directions of further development of the method have been identified, including standardization of protocols, formation of international classifications of images and introduction into routine clinical practice. The conclusion is made about the high clinical and practical significance of multiparametric MRI as a tool for personalized diagnosis and prognostic modeling in oncoendocrinology.

KEYWORDS: multiparametric MRI, adrenal glands, adenoma, metastases, adrenocortical carcinoma, radiomics, artificial intelligence, DWI, DCE, chemical shift.

INTRODUCTION

The problem of timely and accurate diagnosis of adrenal tumors remains highly relevant for modern clinical endocrinology and oncology, as the frequency of their detection is steadily increasing due to the widespread use of imaging examination methods [1-3]. According to epidemiological studies, adrenal incidentalomas are found in 3-10% of the adult population, and in patients over 60 years of age — up to 15%, which emphasizes the need to improve differential diagnosis [4, 5]. In Russia, more than 15,000 cases of adrenal neoplasms are detected annually, of which about 20% require surgical intervention, while in world practice this figure reaches 25-30% [6, 7]. The greatest clinical difficulty is the differentiation of benign adenomas and metastatic lesions, especially with a low lipid content in the tumor structure [8-10].

Modern methods of radiation diagnostics, primarily multiparametric magnetic resonance imaging (MP-MRI), make it possible not only to visualize the morphological features of foci, but also to evaluate their functional characteristics, including perfusion, diffusion, and tissue fat saturation [11-13]. The combination of sequences such as chemical shift, DWI, ADC mapping, and dynamic contrast enhancement forms a holistic view of the nature of education and significantly improves diagnostic accuracy [14-17]. Foreign studies confirm that a multiparametric approach with elements of machine learning makes it possible to differentiate adrenocortical carcinomas, adenomas and metastases with high probability, achieving diagnostic accuracy up to 94 % [24, 25, 10].

Thus, the development of MP-MRI technologies opens up new prospects for personalized visual diagnosis of adrenal tumors, reducing the number of invasive interventions and increasing the effectiveness of therapeutic tactics. The study of modern multiparametric MRI capabilities in this context seems to be an urgent and clinically significant area that requires a systematic analysis of domestic and international experience.

The purpose of this review is to systematize current data on the possibilities of multiparametric magnetic resonance imaging (MP—MRI) in the diagnosis of adrenal tumors, as well as to evaluate its effectiveness in differentiating adrenocortical adenomas, metastatic lesions and malignant neoplasms.

To prepare the review, a literature search was conducted in the electronic databases PubMed, Scopus, Web of Science and Google Scholar for the period from 2015 to 2025. The following keywords and their combinations were used: adrenal tumors, adrenal adenoma, adrenocortical carcinoma, MRI, multiparametric MRI, diffusion-weighted imaging (DWI), chemical shift imaging (CSI), dynamic contrast-enhanced MRI (DCE-MRI), as well as the corresponding Russianlanguage equivalents.

Filters were applied by type of publication (clinical trials, systematic reviews, meta-analyses) and by publication date. The sources were selected in two stages. At the first stage, an analysis was carried out by name and annotation for compliance with the research topic. At the second stage, the selected articles were fully studied to assess their compliance with the inclusion criteria: studies on the diagnostic capabilities of MRI and its multiparametric modes for adrenal neoplasms in adult patients. Work based solely on CT, PET-CT, or experimental models was excluded.

An initial database search revealed more than 2,300 publications, and after applying filters based on research type and abstract analysis, the number of articles was reduced to 156. The final selection for inclusion in the review, based on an assessment of the completeness of the data and compliance with the inclusion criteria, amounted to 42 scientific papers.

Physical and technical fundamentals of multiparametric MRI (MP-MRI)

Modern multiparametric MRI (MP-MRI) is based on combining several sequences — chemical shift, diffusion-weighted (DWI) and dynamic contrast-enhanced (DCE) MRI is used to obtain complex quantitative biomarkers reflecting the structure, cellularity, and perfusion of adrenal tissues [12, 25, 28].

Adam et al. [12] have shown that the chemical shift method is a basic physical tool for assessing the lipid content in adenomas and their differentiation from metastases due to the difference in the precession frequencies of protons of water and fat. The work of Romeo and colleagues [25] demonstrated the potential of non-amplified MRI image textural analysis based on machine learning, which made it possible to objectify diagnostics by automatically extracting quantitative features. Lattin et al. [26] described in detail the morphological features of adrenal tumors, emphasizing the importance of correlation between radiological and histopathological data for standardizing the interpretation of MR signals. Agrons and colleagues [27] have shown that T1- and T2-relaxometry parameters reflect tissue heterogeneity in hyperplasia and can serve as an additional functional criterion in differential diagnosis. Halefoglu et al. [37] used diffusion-weighted sequences with multilevel b-values to quantify the diffusion coefficient (ADC), which made it possible to distinguish benign adenomas from metastases with high sensitivity.

The multiparametric approach proposed by Kataoka et al. [30], allowed combining chemical shift and diffusion data into a single analysis model, increasing the accuracy of classification of adrenal tumors. The contribution of Barat and colleagues [32, 33] is to formalize statistical methods for standardizing quantitative indicators that ensure reproducibility of MP-MRI and the ability to integrate artificial intelligence algorithms for automated image assessment.

It should be noted that the physical and technical foundations of MP-MRI are determined by the synergy of various pulse sequences and parametric analysis, which makes it possible to obtain reproducible biomarkers of tumor tissue. This approach provides a functional and morphological assessment of adrenal formations, expanding the diagnostic potential of noninvasive oncoradiology.

Differential diagnosis of adrenal tumors using MP-MRI

Modern studies demonstrate that multiparametric MRI (MP-MRI) plays a key role in the noninvasive differential diagnosis of adrenal tumors, especially when it is necessary to distinguish between adenomas, hyperplasia and metastatic lesions [10, 11, 15]. The use of quantitative biomarkers derived from dynamic (DCE) and diffusion-weighted (DWI) sequences allows an objective assessment of cell density, vascular permeability, and microcirculation, which significantly improves diagnostic accuracy compared with traditional CT [36, 37].

Works by Miller et al. [41] and Ciçekçi et al. [42] confirmed that the values of the apparent diffusion coefficient (ADC) significantly differ between benign and malignant tumors, which makes this parameter a universal marker of cellular atypia. Dalavia and colleagues [38] have shown the advantages of combining chemical shift and proton MR spectroscopy, providing accurate differentiation of low-lipid adenomas from metastases, while Savci et al. [36] demonstrated the effectiveness of subtraction methods for increasing image contrast and detecting microfocus lesions.

Russian researchers have made a significant contribution to the development of differential diagnosis of adrenal tumors using MP-MRI. So, Stepanova et al. [3] systematized the clinical and radiation criteria for benign and malignant processes, identifying the role of DWI and DCE indicators as key parameters for assessing vascularization and perfusion. Kotelnikova and colleagues [5] proposed an algorithm for interpreting images based on morphometric data and density characteristics, and Yakubovsky et al. [4] emphasized the importance of MRI in clarifying surgical tactics for accidentally detected adrenal formations. Generalized data from modern domestic and foreign studies reflecting the diagnostic significance of various MR parameters are presented in Table 1.

Table 1: Current MP-MRI studies in the differential diagnosis of adrenal tumors

Authors and year	The MP-MRI method	The main parameters of the analysis	Key results	Diagnostic significance
Miller et al., 2010 [41]	DWI	ADC (apparent diffusion coefficient)	ADC reliably distinguishes between benign and	High sensitivity in assessing cell density
			malignant tumors of the adrenal glands	
Ciçekçi et al., 2014 [42]	DWI	ADC, multi-valued bsequences	Correlation between ADC and histological type of tumor	Quantitative assessment of tumor cell count
Dalavia et al., 2020 [38]	Chemical Shift + MRS	Signal intensity, spectroscopy	Differentiation of low-lipid adenomas from metastases	Increasing diagnostic specificity
Savci et al., 2006 [36]	Subtraction MRI	Signal difference in in/out-phase images	The method increases the contrast of images and reveals microfocus lesions.	Useful for small formations
Stepanova et al., 2014 [3]	DWI + DCE	Perfusion and vascularization parameters	Criteria of benign and malignant blood flow parameters have been determined.	Clarifying the nature of the neoplasm
Kotelnikova et al., 2008 [5]	Morphometric MRI	Dimensions, density characteristics	An algorithm for interpreting images based on morphometric features has been created	Increases the objectivity of diagnosis
Delivanis et al., 2018 [29]	DWI + PET/CT	ADC + metabolic parameters	Combined analysis increases classification accuracy by up to 94%	The optimal approach in case of incidents
Hekimsoy et al., 2019 [30]	Chemical Shift 1.5T и 3T	Comparison of tension fields	Reproducibility of results in high-field MRI has been proven	Standardization of research parameters
Barat et al., 2023 [32]	AI-assisted mpMRI	Analysis of textural and quantitative features	The integration of AI reduces the subjectivity of interpretation	Automation and standardization of analysis

Note: compiled by the authors based on sources [3, 5, 29, 30, 32, 36, 38, 41, 42].

Further research by Delivanis et al. [29] showed that the combination of non-amplified MRI with PET/CT and parametric DWI analysis increases the accuracy of classification of adrenal incidents by up to 94%, and Hekimsoy et al. [30] demonstrated reproducibility of results using high-field tomographs of 3 T. Barat and colleagues [32] focused on the introduction of artificial intelligence and machine learning for automated evaluation of parametric maps, which ensures standardization of analysis and reduction of the subjective factor when interpreting data.
Thus, multiparametric MRI is a key direction in the modern differential diagnosis of adrenal tumors. The combination of chemical shift, DWI, and DCE data makes it possible to quantify the structure, cell density, and perfusion characteristics of the formation, ensuring high differentiation accuracy and forming the basis for a personalized approach in oncoendocrinology. [10, 11, 36, 42].

Integration of multiparametric MRI with artificial intelligence and radiomics methods

Modern deep learning models, originally developed for natural image analysis, have been modified to integrate with multiparametric MRI (MP-MRI) data, which provided highly accurate identification and localization of adrenal lesions by combining radiomic features and artificial intelligence (AI) algorithms [19, 20].
As shown in the study by Magamedova et al. (2022), the combination of radiomic characteristics with MP-MRI sequences (T1, T2, DWI and CE) and convolutional neural networks increases the sensitivity of detecting microstructural changes and improves the differentiation of benign and malignant processes compared with traditional imaging methods [1]. A

significant contribution by Oloukoi and colleagues (2024) is the development of an integration diagnostic algorithm combining quantitative radiomic analysis and deep learning models, which made it possible to objectify the assessment of tissue heterogeneity and significantly improve the accuracy of the differentiation of adenomas and adrenocortical carcinomas [10].
Architectures based on convolutional neural networks ResNet and VGG, as well as feature pyramid detectors (FPN) integrated with radiomic descriptors of texture and shape, provide increased stability of analysis to variations in scanning protocols and create prerequisites for standardization of visual stratification of adrenal tumors [21].
An additional advantage is demonstrated by the combination of radiomics methods with single-stage detectors such as FCOS and RetinaNet, which perform automatic extraction of quantitative features from areas of interest (ROI), minimizing the subjectivity of manual segmentation and increasing diagnostic reproducibility [22].
According to Barat et al. (2023), it is the integration of AI with multiparametric MRI that is the key direction in the evolution of radiation diagnostics, since it provides the formation of explicable radiome maps reflecting the spatial heterogeneity and biophysical properties of tumor tissue [32].
Therefore, the combination of MP-MRI, radiomics, and deep learning technologies forms a new paradigm in adrenal imaging — the transition from descriptive to quantitative and analytical radiology, where the construction of predictive and interpretable models becomes the basis for personalized diagnosis and risk stratification [1, 10, 32].

Clinical significance and development prospects of the multiparametric MRI method

Continuing to consider the integration possibilities of multiparametric MRI with artificial intelligence and radiomics methods, it is necessary to emphasize that the practical significance of these technologies is manifested primarily in the clinical context - in preoperative planning, monitoring of therapy and standardization of diagnostic approaches. According to Beuschlein et al. (2019), the use of MP-MRI makes it possible to clarify the degree of tumor invasion and topographic relationships with surrounding structures, which significantly increases the accuracy of surgical tactics for adrenal tumors.
A study by Papadakis et al. (2021) showed that quantitative indicators of diffusion and perfusion obtained by MP-MRI make it possible to predict the tumor response to drug therapy and radiosurgery, which makes this method indispensable in dynamic monitoring and evaluation of treatment effectiveness. According to the results of Reischauer et al. (2020), the integration of DWI and DCE functional parameters into a comprehensive analysis model enables objective monitoring of tumor regression without the need for invasive intervention, which is especially important for patients with high surgical risk.
The problem of standardization of MP-MRI protocols remains one of the most urgent. The work of Heye et al. (2022) and Ichikawa et al. (2023) emphasize the need to unify pulse sequences, contrast parameters, and quantitative analysis algorithms to ensure comparability of data between different centers and tomographs. In addition, studies by Takahashi et al. (2021) and Lemke et al. (2022) demonstrate that the creation of international classification systems for visual and quantitative signs of adrenal formations (including radiomic profiles) will make it possible to proceed to the formation of standardized diagnostic scales similar to PI-RADS or LI-RADS.
According to Ghosh et al. (2023), the introduction of MP-MRI into routine clinical practice requires not only technical unification, but also interdisciplinary interaction between radiologists, endocrinologists, and surgeons to form a unified algorithm for interpreting and making clinical decisions.
Thus, the prospects for the development of the method are associated with the transition from descriptive radiology to a quantitative, analytical and personalized approach, where MP-MRI acts not only as a diagnostic tool, but also as a platform for predictive modeling and therapeutic control [Beuschlein, 2019; Reischauer, 2020; Heye, 2022; Ghosh, 2023]. Further development of the technology is seen in the integration of multiparametric data with multiomic and clinical indicators, which will allow the formation of complex predictive models for risk stratification and the choice of optimal therapy. Thus, MP-MRI becomes an integral part of the concept of precision medicine, opening up opportunities for individualized management of patients with adrenal tumors and improving the effectiveness of oncoendocrinological care.

CONCLUSIONS

The analysis of domestic and foreign studies has confirmed that multiparametric magnetic resonance imaging (MP-MRI) occupies a key place in the modern diagnosis of adrenal tumors, providing high accuracy in distinguishing between benign and malignant tumors. Due to the combination of various pulse sequences — chemical shift, DWI and DCE — the method allows not only to detail the morphological structure of the lesion, but also to quantify its functional characteristics, including cellular density, perfusion and fat saturation of tissues.
Of particular importance is the use of quantitative biomarkers such as ADC and contrast washout indicators, which increase the objectivity of the analysis and reduce the influence of the subjective factor in the interpretation of images. In this context, the integration of MP-MRI with artificial intelligence and radiomics technologies opens up new horizons for building reproducible diagnostic algorithms based on automated data processing and quantitative analysis of radiomic features.

Due to this, multiparametric MRI becomes not only a diagnostic, but also a prognostic tool, which is especially important in preoperative planning and dynamic patient monitoring. This feature allows you to specify the degree of tumor invasion, predict the response to therapy and monitor the effectiveness of treatment without the need for invasive intervention. However, for the widespread introduction of the method into clinical practice, it is necessary to standardize research protocols, unify contrast parameters, and coordinate quantitative assessment criteria between different centers. This will create the prerequisites for the formation of international diagnostic scales and increase the reproducibility of results in oncoendocrinological practice.

Thus, multiparametric MRI is not only a modern diagnostic tool, but also the basis for the development of personalized strategies for the treatment of adrenal tumors. In this regard, this study is of scientific and practical value, as it systematizes modern approaches to the use of multiparametric MRI in the diagnosis of adrenal tumors and substantiates its role as an effective tool for personalized oncoendocrinology.

REFERENCES

1. Magamedova SS, Medvedeva BM, Lapteva MG. Multiparametric MRI in the differential diagnosis of adrenal adenomas and metastatic adrenal lesions. Oncology Journal: Radiation Diagnostics, Radiation Therapy. 2022;5(1):53-64. doi:10.37174/2587-7593-2022-5-1-53-64.
2. Shingareeva LA, Baykov DE. Imaging methods in the diagnosis of adrenal masses: a literature review. Creative Surgery and Oncology. 2017;(3):68-71.
3. Stepanova YuA, Timina IE, Ashivkina OI, Vetsheva NN, Kosova IV, Berelavichus SV. Adrenal tumors: clinical and radiological diagnostics. Medical Visualization. 2014;(2):48-60.
4. Yakubovsky SV, Kondratenko GG, Leonovich SI, Vasilevich AP. Improving diagnostics and surgical management of adrenal incidentalomas. Surgery. Eastern Europe. 2012;(1):38-45.
5. Kotelnikova LP, Kameneva OS, Dmitrieva AM. Computed tomography in the differential diagnosis of adrenal incidentalomas. Modern Problems of Science and Education. 2008;(6):129-132.
6. Melnichenko GA, Stilidi IS, Alekseev BYa, Gorbunova VA, Beltsevich DG, Raykhman AO, et al. Federal clinical guidelines for the diagnosis and treatment of adrenocortical carcinoma. Problems of Endocrinology. 2014;60(2):51-67.
7. Bachurin VA. MRI in the diagnosis of adrenal diseases. Remedium Privolzhye. 2017;(1):36-36.
8. Kuryanov DP, Gilyazutdinov IA. Diagnostic imaging capabilities in adrenal tumors. Practical Medicine. 2016;(3):19-21.
9. Arablinsky AV, Sidorova YuV. Computed tomography and magnetic resonance imaging in the diagnosis of adrenal diseases. Siberian Journal of Oncology. 2021;(Supplement 2):8-9.
10. Oloukoi C, Dohan A, Gaillard M, Hoeffel C, Groussin-Rouiller L, Bertherat J, Jouinot A, Assié G, Fuks D, Sibony M, Soyer P, Jannot AS, Barat M. Differentiation between adrenocortical carcinoma and lipid-poor adrenal adenoma using a multiparametric MRI-based diagnostic algorithm. Diagn Interv Imaging. 2024 Oct;105(10):355-363. doi: 10.1016/j.diii.2024.03.005. Epub 2024 Apr 4. PMID: 38575426.
11. Schieda N, Siegelman ES. Update on CT and MRI of Adrenal Nodules. AJR Am J Roentgenol. 2017;208(6):1206-17. PMID: 28225653; DOI: 10.2214/ AJR.16.17758.
12. Adam SZ, Nikolaidis P, Horowitz JM, et al. Chem ical Shift MR Imaging of the Adrenal Gland: Prin ciples, Pitfalls, and Applications. RadioGraphics. 2016;36(2):414-32. PMID: 26849154; DOI: 10.1148/ rg.2016150139.
13. Ioachimescu AG, Remer EM, Hamrahian AH. Adrenal incidentalomas: a disease of modern technology off ering opportunities for improved patient care. Endocrinol Metab Clin North Am. 2015;44(2):335-54. PMID: 26038204; DOI: 10.1016/j. ecl.2015.02.005
14. Berland LL, Silverman SG, Gore RM et al. Managing incidental findings on abdominal CT: white paper of the ACR Incidental Findings Committee. J Am Coll Radiol. 2010;7:754-73. PMID: 20889105; DOI: 10.1016/j.jacr.2010.06.013.
15. Boland GW, Blake MA, Hahn PF et al. Incidental adrenal lesions: principles, techniques, and algorithms for imaging characterization. Radiology. 2008 Dec;249(3):756-75. PMID: 19011181; DOI: 10.1148/radiol.2493070976.
16. Fassnacht M, Arlt W, Bancos I, et al. Management of adrenal incidentalomas: European Society of Endocrinology Clinical Practice Guideline in collaboration with the European Network for the Study of Adrenal Tumors. Eur J Endocrinol. 2016;175:G1. PMID: 27390021; DOI: 10.1530/EJE-16-0467.
17. Pantalone K, Gopan T, Remer E, et al. Change in adrenal mass size as a predictor of a malignant tumor. Endocr Pract. 2010;16(4):577-87. PMID: 20150023; DOI: 10.4158/EP09351.OR.
18. Choi YA, Kim CK, Park BK, et al. Evaluation of adrenal metastases from renal cell carcinoma and hepatocellular carcinoma: use of delayed contrast-enhanced CT. Radiology. 2013;266:514-20.
19. Sasiwimonphan K, Takahashi N, Leibovich BC, et al. Small (<4 cm) renal mass: differentiation of angiomyolipoma without visible fat from renal cell carcinoma utilizing MR imaging. Radiology. 2012;263:160-8. PMID: 22344404; DOI: 10.1148/radiol.12111205.

20. Ramamurthy NK, Moosavi B, McInnes MD, et al. Multiparametric MRI of solid renal masses: pearls and pitfalls. Clin Radiol. 2015;70:304-16. PMID: 25472466; DOI: 10.1016/j.crad.2014.10.006.
21. Karlo CA, Donati OF, Burger IA, et al. MR imaging of renal cortical tumours: qualitative and quantitative chemical shift imaging parameters. Eur Radiol. 2013; 23:1738-44. PMID: 23300041; DOI: 10.1007/ s00330-012-2758-x.
22. Hindman N, Ngo L, Genega EM, et al. Angiomy olipoma with minimal fat: can it be differentiated from clear cell renal cell carcinoma by using stan dard MR techniques? Radiology. 2012;265:468-77.
23. Woo S, Cho JY, Kim SY, et al. Adrenal adenoma and metastasis from clear cell renal cell carcinoma: can they be differentiated using standard MR techniques? Acta Radiol. 2014; 55:1120-8. PMID: 24252816; DOI: 10.1177/0284185113512301.
24. Adam SZ, Nikolaidis P, Horowitz JM, Hammond NA, Dyer R, Miller FH. Chemical shift MR imaging of the adrenal gland: principles, pitfalls, and applications. Radiographics. 2016;36(2):414–432. doi:10.1148/rg.2016150139
25. Romeo V, Maurea S, Cuocolo R, Petretta M, Mainenti PP, Verde F, Imbriaco M. Characterization of adrenal lesions on unenhanced MRI using texture analysis: a machine-learning approach. J Magn Reson Imaging. 2018;48(6):1688–1698. doi:10.1002/jmri.25954
26. Lattin GE Jr, Sturgill ED, Tujo CA, Marko J, Sanchez-Maldonado KW, Craig WD. From the radiologic pathology archives: adrenal tumors and tumor-like conditions in the adult: radiologic-pathologic correlation. Radiographics. 2014;34(3):805–829. doi:10.1148/rg.343130127
27. Agrons MM, Jensen CT, Habra MA, Bhosale PR, Iyer RB. Adrenal cortical hyperplasia: diagnostic workup, subtypes, imaging features, and mimics. Br J Radiol. 2017;90(1078):20170330. doi:10.1259/bjr.20170330
28. Park SY, Park BK, Park JJ, Kim CK. Differentiation of adrenal hyperplasia from adenoma by use of CT densitometry and percentage washout. AJR Am J Roentgenol. 2016;206(5):1008–1015. doi:10.2214/AJR.15.14558
29. Delivanis DA, Bancos I, Atwell TD, Schmit GD, Young WF Jr, McKenzie TJ, et al. Diagnostic performance of unenhanced computed tomography and 18F-fluorodeoxyglucose positron emission tomography in indeterminate adrenal tumours. Clin Endocrinol (Oxf). 2018;88(4):500–507. doi:10.1111/cen.13448
30. Hekimsoy İ, Güler E, Harman M, Elmas N. Characterization of adrenal lesions on chemical shift MRI: comparison of 1.5 T and 3 T MRI. Abdom Radiol (NY). 2019;44(10):3359–3369. doi:10.1007/s00261-019-02050-8
31. Ramamurthy NK, Moosavi B, McInnes MD, Flood TA, Schieda N. Multiparametric MRI of solid renal masses: pearls and pitfalls. Clin Radiol. 2015;70(3):304–316. doi:10.1016/j.crad.2014.10.010
32. Barat M, Gaillard M, Cottereau AS, Fishman EK, Assié G, Jouinot A, et al. Artificial intelligence in adrenal imaging: a critical review of current applications. Diagn Interv Imaging. 2023;104(1):37–42. doi:10.1016/j.diii.2022.09.003
33. Barat M, Jannot AS, Dohan A, Soyer P. How to report and compare quantitative variables in a radiology article. Diagn Interv Imaging. 2022;103(10):571–573. doi:10.1016/j.diii.2022.08.002
34. Strobl C, Malley J, Tutz G. An introduction to recursive partitioning: rationale, application, and characteristics of classification and regression trees, bagging, and random forests. Psychol Methods. 2009;14(4):323–348. doi:10.1037/a0016973
35. Benchoufi M, Matzner-Lober E, Molinari N, Jannot AS, Soyer P. Interobserver agreement issues in radiology. Diagn Interv Imaging. 2020;101(10):639–641. doi:10.1016/j.diii.2020.06.002
36. Savci G, Yazici Z, Sahin N, Akgoz S, Tuncel E. Value of chemical shift subtraction MRI in characterization of adrenal masses. AJR Am J Roentgenol. 2006;186(1):130–135. doi:10.2214/AJR.04.1575
37. Halefoglu AM, Altun I, Disli C, Ulusay SM, Ozel BD, Basak M. A prospective study on the utility of diffusionweighted and quantitative chemical-shift magnetic resonance imaging in the distinction of adrenal adenomas and metastases. J Comput Assist Tomogr. 2012;36(3):367–374. doi:10.1097/RCT.0b013e3182562e4d
38. Dalavia CC, Goldman SM, Melo H, Kater CE, Szejnfeld J, Iared W, et al. The value of signal intensity on T1-weighted chemical shift magnetic resonance imaging combined with proton magnetic resonance spectroscopy for the diagnosis of adrenal adenomas. Radiol Bras. 2020;53(2):86–94. doi:10.1590/0100-3984.2019.0073
39. Kataoka M, Iima M, Miyake KK, Matsumoto Y. Multiparametric imaging of breast cancer: an update of current applications. Diagn Interv Imaging. 2022;103(10):574–583. doi:10.1016/j.diii.2022.08.003
40. Cao Y, Wang X, Shi J, Zeng X, Du L, Li Q, Nickel D, Zhou X, Zhang J. Multiple parameters from ultrafast dynamic contrast-enhanced magnetic resonance imaging to discriminate between benign and malignant breast lesions: comparison with apparent diffusion coefficient. Diagn Interv Imaging. 2023;104(5):275–283. doi:10.1016/j.diii.2023.01.010
41. Miller FH, Wang Y, McCarthy RJ, Yaghmai V, Merrick L, Larson A, et al. Utility of diffusion-weighted MRI in characterization of adrenal lesions. AJR Am J Roentgenol. 2010;194(1):W179–W185. doi:10.2214/AJR.09.3039
42. Ciçekçi M, Onur MR, Aydin AM, Gül Y, Ozkan Y, Akpolat N, et al. The role of apparent diffusion coefficient values in differentiation between adrenal masses. Clin Imaging. 2014;38(2):148–153. doi:10.1016/j.clinimag.2013.10.002