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Potential use of radiomics analysis of cine-mode cardiac MRI to detect post-infarction lesions in the left ventricular myocardium

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ABSTRACT

BACKGROUND: The size and location of an infarct lesion and its clear differentiation from normal tissue are important for clinical diagnosis and precision medicine. This paper is based on the study of radiomic attributes for differentiation of infarct and non-infarct tissue using non-contrast-enhanced cine-mode cardiac magnetic resonance imaging (MRI) data.

AIM: The aim of the study was to evaluate the potential use and informative value of radiomics analysis to identify post-infarction lesions in the left ventricular myocardium in patients with ischemic cardiomyopathy (ICM) using non-contrast-enhanced cine-mode cardiac MRI.

MATERIALS AND METHODS: Results of contrast-enhanced cardiac MRI were evaluated in 33 patients following surgical treatment for ICM. Texture analysis was performed on 66 lesions in cine-mode cardiac MRI images, and 105 texture attributes were determined for each lesion. Cardiac MRI was performed according to a standard technique using a Vantage Titan 1.5 T MRI scanner (Toshiba). For texture analysis, 3D Slicer version 5.2.2 (Pyradiomics) was used.

RESULTS: During the study, attribute collinearity diagrams were plotted, zero-significance attributes were identified, and attribute significance was determined using a gradient boosting algorithm, and the cumulative significance of attributes was estimated as a function of their total number. By identifying low-significance attributes, the least significant parameters that did not affect the overall significance level were determined. When single-valued attributes were extracted, no corresponding attributes were found. Based on the analysis results, an ROC curve was constructed for Lasso logistic regression (Se=57.14%, Sp=71.43%, AUC=0.76). The main result of this study was to determine radiomic attributes that characterized lesions corresponding to post-infarction cardiosclerosis and intact left ventricular wall based on cine-mode cardiac MRI images.

CONCLUSION: This study demonstrated that radiomics analysis of non-contrast-enhanced cine-mode cardiac MRI images is a promising approach to identify lesions corresponding to myocardial infarction and intact wall. This method may potentially be used to identify lesions of post-infarction cardiosclerosis in patients with ICM without contrast enhancement.

Keywords: radiomics; texture analysis; cardiac magnetic resonance imaging; myocardial infarction; ischemic cardiomyopathy.

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Возможности радиомического анализа МРТ-изображений сердца в кино-режиме в определении постинфарктных областей миокарда левого желудочка

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АННОТАЦИЯ

Обоснование. Размер и локализация, а также чёткая дифференциация между интактной тканью и областью инфаркта важны для клинической диагностики и прецизионной медицины. В основе данной работы лежит исследование радиомических признаков, которые позволяют дифференцировать участки инфарктной и удалённой от области инфаркта ткани по данным бесконтрастных изображений магнитно-резонансной томографии (МРТ) сердца в кино-режиме.

Цель. Оценка возможностей и информативности радиомического анализа в выявлении постинфарктных областей миокарда левого желудочка у пациентов с ишемической кардиомиопатией (ИКМП) по данным бесконтрастных изображений МРТ сердца в кино-режиме.

Материалы и методы. Мы проанализировали результаты МРТ сердца с контрастированием 33 пациентов, которым провели хирургическое лечение по поводу ИКМП. Текстурный анализ выполнили для 66 участков изображений МРТ сердца в кино-режиме, для каждого из них определяли 105 текстурных характеристик. МРТ сердца проводили по стандартной методике на магнитно-резонансном томографе Vantage Titan (Toshiba) 1,5 Тл. Для текстурного анализа использовали программное обеспечение 3D slicer-version 5.2.2, Pyradiomics.

Результаты. В ходе исследования мы построили диаграммы коллинеарности признаков, определили признаки с нулевой важностью и установили важность признаков с помощью алгоритма градиентного бустинга, а также оценили кумулятивную важность признаков в зависимости от их общего количества. С помощью метода выявления признаков с низкой важностью определили параметры с наименьшей значимостью, которые не влияют на указанный общий уровень. Используя метод выявления признаков с единственным значением, мы не нашли соответствующих функций. По результатам анализа сформирована ROC-кривая для логистической регрессии Lasso (Se=57,14%, Sp=71,43%, AUC=0,76). Основным результатом данного исследования является определение радиомических признаков, характеризующих на основе изображений МРТ сердца в кино-режиме участки, соответствующие постинфарктному кардиосклерозу и интактной стенке левого желудочка.

Заключение. Данное исследование показало, что применение радиомического анализа на бесконтрастных изображениях МРТ сердца в кино-режиме — перспективный подход для выявления участков, соответствующих инфаркту миокарда и интактной стенке. Метод потенциально может быть использован для идентификации областей постинфарктного кардиосклероза у пациентов с ИКМП без применения контрастных препаратов.

Ключевые слова: радиомика; текстурный анализ; магнитно-резонансная томография сердца; инфаркт миокарда; ишемическая кардиомиопатия.

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在胶片模式下对心脏磁共振图像进行放射组学分析以确定左心室心肌梗死后区域的可能性

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摘要

论证。这项工作的基础是对放射组学特征的研究，通过使用胶片模式下的非对比心脏磁共振成像（MRI）图像，可以区分梗死组织区域和远离梗死区域的组织。尺寸和定位，以及完整组织和梗死区域的明确区分对于临床诊断和精准医疗非常重要。

目的。根据胶片模式下的非对比心脏MRI图像数据，评估放射组学分析在检测缺血性心肌病（ICM）患者左心室心肌梗死后区域方面的能力和信息量。

材料和方法。我们分析了33名接受ICM手术治疗的患者的心脏磁共振成像造影结果。在胶片模式下，对66幅心脏 MRI 图像进行了纹理分析，并确定了每幅图像的 105 个纹理特征。心脏磁共振成像是在Vantage Titan（Toshiba）1.5 Tesla磁共振成像仪上按照标准方法进行的。纹理分析使用的是3D slicer-version 5.2.2, Pyradiomics。

结果。在研究中，我们构建了特征共线性图，识别了重要性为零的特征，并使用梯度提升算法确定了特征的重要性，并根据特征总数估计了特征的累积重要性。使用识别低重要性特征的方法，我们识别出不影响指定总体水平的最低重要性的参数。使用单值特征检测方法，我们没有发现任何相关特征。根据分析结果，生成用于Lasso逻辑回归的ROC曲线（Se=57.14%，Sp=71.43%，AUC=0.76）。该研究的主要成果是在胶片模式的心脏磁共振成像基础上，确定心肌梗塞后心肌梗死和左心室壁完整区域的放射组学特征。

结论。该研究表明，在胶片模式下非对比心脏磁共振图像进行放射组学分析是一种很有前途的方法，可用于识别心肌梗死和完整壁的相应区域。这种方法可用于识别 ICM 患者梗死后心脏硬化的区域，而无需使用造影剂。

关键词：放射组学；纹理分析；心脏磁共振成像；心肌梗死；缺血性心肌病。

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BACKGROUND

The incidence of cardiovascular diseases continues to rise each year. Coronary artery disease is the most prevalent cardiovascular complication and the leading cause of death and disability in adults globally [1]. Myocardial infarction (MI), the most common form of coronary artery disease, is characterized by irreversible cardiac muscle necrosis caused by an acute disruption of coronary circulation [2, 3]. The size and location of the lesion, along with its distinction from normal tissue, are critical for accurate clinical diagnosis and treatment planning [4]. MI is often followed by left ventricular (LV) remodeling, a progressive condition that involves changes in LV size and function within hours after the coronary circulation disturbance [5]. Post-ischemic LV remodeling has a complex pathophysiology, involving various ultrastructural, metabolic, and neurotransmitter processes in the affected and surrounding myocardial tissue. Cardiac remodeling is thought to influence the clinical progression of heart failure [6].

Contrast-enhanced cardiac MRI is widely used and is an important tool for assessing the presence, prevalence, and severity of post-infarction changes in the myocardium. It is also employed to assess myocardial viability and LV remodeling. This technique provides a qualitative assessment of MI and detects microvascular obstruction and hyperemia, which are key factors for determining unfavorable remodeling and predicting adverse cardiovascular outcomes [7–9]. However, this technique has several limitations, including a high dependency on subjective physician judgment and intraoperator variability. Additionally, gadolinium-based contrast agents can lead to nephrogenic systemic fibrosis in patients with renal insufficiency [10], a significant concern given the high prevalence of concurrent renal disorders in patients with cardiovascular diseases [11].

To address these challenges, emerging techniques such as radiomics and texture analysis offer promising alternatives for extracting quantitative data from digital medical images. Radiomics enables a reliable assessment of abnormal changes detected in medical imaging by transforming image data into quantitative measures. Previous studies have explored the potential of texture analysis in cardiac MRI images to differentiate between conditionally normal and nonviable myocardial segments [12]. Some investigations have focused on detecting cicatricial changes in the LV myocardium using non-contrast-enhanced cardiac cine-MRI [13]. Given the morphological differences between affected and healthy myocardium, the corresponding texture features of these areas will also differ [14]. It was assumed that subtle differences between nonviable and conditionally normal segments could be detected on cardiac cine-MRI images using radiomics analysis, based on variations in gray level nonuniformity. However, few studies have confirmed this hypothesis [15, 16]. This theory suggests that post-infarction cardiosclerosis areas could be identified using only non-contrast-enhanced cardiac cine-MRI images, reducing the risks associated with gadolinium-based contrast agents and significantly lowering both the cost and time of analysis. Currently, no such studies have been conducted in patients with ischemic cardiomyopathy (ICM).

AIM

To assess the potential and diagnostic value of radiomics analysis in detecting post-infarction lesions in the LV myocardium in patients with ICM using non-contrast-enhanced cardiac cine-MRI.

MATERIALS AND METHODS

Study design

This observational, single-center, retrospective, cross-sectional, single-arm study involved male and female patients aged 52–65 years who underwent surgical treatment for ICM. All patients received a contrast-enhanced cardiac MRI either as part of their clinical care or according to the study protocol.

Eligibility criteria

The study included patients who met the established criteria for ICM [17]:

1) A history of MI

2) Multivessel coronary artery disease, confirmed by invasive coronary angiography

3) Left ventricular ejection fraction (LVEF) of <40%

4) Increased end-systolic volume (ESV) >60 mL/m^2

5) Heart failure classified as New York Heart Association (NYHA) class II–IV

Patients with infectious and rheumatic heart diseases, stroke, acute MI, and right ventricular failure were extracted from the study.

The study used contrast-enhanced cardiac MRI images from patients who underwent surgical treatment for ICM between 2019 and 2023.

Study setting

Patients were enrolled at the Research Institute of Cardiology, Tomsk National Research Medical Center, Russian Academy of Sciences.

The study included patients who underwent cardiac MRI with paramagnetic contrast to assess myocardial viability.

Main study outcome

The primary outcome was the difference in radiomic features between intact myocardium and post-infarction cardiosclerosis (PICS) areas on cardiac cine-MRI images.

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Outcomes registration

Contrast-enhanced cardiac MRI

The study reviewed patients' medical records to gather data from cardiac MRIs with paramagnetic contrast agents, performed to assess myocardial viability. ECG- and respiratory-gated MRI scans were conducted according to standard procedures using a *Vantage Titan 1.5-T scanner* (Toshiba). Short- and long-axis myocardial images were acquired before and after gadolinium-based contrast injection (gadobutrol 0.1–0.15 mmol/kg body weight). The slice thickness was 7–8 mm, and images were acquired using a 256 × 256 matrix. The MRI protocol included T1- and T2-weighted images, fat-suppressed images to assess the myocardium, dynamic SSFP sequences for LV volume and function assessment, and gradient inversion-recovery (GR-IR) sequences to identify areas of abnormal contrast uptake. The inversion time was selected individually for each case (mean TI, 300 ± 10 ms). Abnormal myocardial changes were assessed using a standardized 17-segment system for LV myocardium segmentation. The primary LV parameters were calculated using segment post-processing software (version 2.2, Medviso AB).

Radiomics analysis

Texture analysis was performed using non-contrast-enhanced cardiac cine-MRI images. All images were segmented using *3D slicer software* (version 5.2.2), and radiomic features were automatically extracted using the *SlicerRadiomics extension* (version aa418a5).

The radiomic features of intact myocardium were compared with those of the PICS areas on non-contrast-enhanced cine-MRI images.

Regions of interest (ROIs) were manually selected to assess differences in radiomic features between intact myocardium and PICS areas. The size and position of the ROIs corresponded to the PICS areas and intact myocardium regions based on time-delayed contrast-enhanced MRI images. Initially, ROIs were manually selected on MRI slices along the short axis (in SSFP mode) that matched the PICS areas on post-contrast MRI images. Texture features were then extracted using the PyRadiomics library. The ROI selection process is illustrated in Fig. 1.

Texture analysis was performed on 66 areas from the cardiac cine-MRI images, with 105 texture features calculated for each area. These texture features were categorized as follows:

- First-order features (Energy, Entropy, Range, Kurtosis, etc.)
- 3D shape features (Mesh Volume, Voxel Volume, Sphericity, etc.)
- 2D shape features (Perimeter, Pixel Surface, Elongation, etc.)
- Gray Level Co-occurrence Matrix
- Gray Level Run Length Matrix
- Gray Level Size Zone Matrix
- Neighboring Gray Tone Difference Matrix
- Gray Level Dependence Matrix

Ethical review

The study was conducted in accordance with Good Clinical Practice and the Declaration of Helsinki. All patients provided written informed consent. The study received approval from the Institutional Review Board of the Research Institute of Cardiology, Tomsk National Research Medical Center (Minutes No. 210, dated February 18, 2021).

Statistical analysis

Statistical processing included the following steps: selection of significant texture features, plotting of feature collinearity diagrams, feature selection based on significance, and application of Lasso regression. Features selection was performed using the following *Python* functions: *identify_collinear*, *identify_zero_importance*, *identify_low_importance*, *identify_single_unique*, and *identify_all*. The sample size was not predetermined.

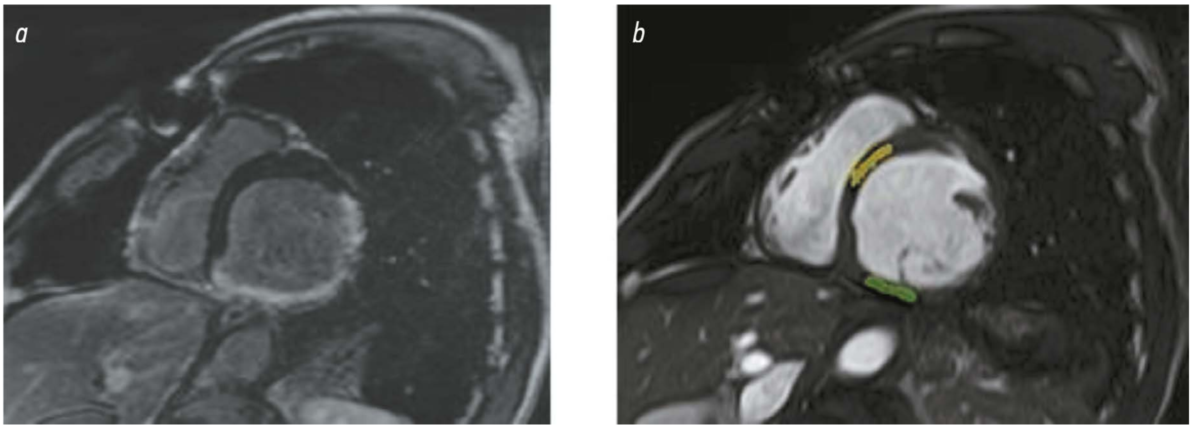

Fig. 1. Selection of regions of interest in post-contrast and non-contrast-enhanced cardiac MRI images, short axis view. *a*: time-delayed contrast-enhanced MRI showing transmural contrast uptake along the LV inferior wall with no signs of damage in the interventricular septum. *b*: cardiac cine-MRI showing regions of interest in the posterior wall (green), corresponding to a PICS area in the inferior segment at the middle LV level, and in the anteroseptal segment at the middle level (yellow), corresponding to an intact interventricular septum.

RESULTS

Participants

Study sample characteristics

The study included 33 patients with ICM. The mean age was 58.3 ± 5.7 years, and 94% of the patients were male. All patients had angina pectoris and heart failure, with NYHA class III being the most prevalent (67% and 61%, respectively). Hypertension was present in 85% of the patients, dyslipidemia in 73%, and diabetes mellitus in 24%. The clinical characteristics of these patients are shown in Table 1.

Contrast-enhanced cardiac MRI

Table 1. Clinical characteristics of the patients

Parameter	Value
Age, years	58.3 ± 5.7
Male, *n* (%)	31 (94%)
BMI, kg/m^2	27.5 ± 3.9
History of hypertension, *n* (%)	28 (85%)
Heart failure NYHA class, *n* (%):	
• I	0 (0%)
• II	12 (39%)
• III	20 (61%)
• IV	0 (0%)
Angina pectoris NYHA class, *n* (%):	
• I	1(3%)
• II	10 (30%)
• III	22 (67%)
• IV	0 (0%)
Diabetes mellitus, *n* (%)	8 (24%)
Dyslipidemia, *n* (%)	24 (73%)

Note. BMI, body mass index; NYHA, New York Heart Association classification.

Table 2. Findings from contrast-enhanced cardiac magnetic resonance imaging

Parameter	Value
LVEF, %	31.5 ± 7.5
ESV, mL/m^2	79.7 ± 16.7
LVMM, g	190.8 ± 2.1
VMM, g	140.8 ± 30.05
Number of segments with transmurality >50%	4.4 ± 2.6
Ratio of myocardial mass with contrast uptake to LVMM, %	27.1 ± 6.9
Thrombosis, n (%)	5 (15)

Note. LVEF, left ventricular ejection fraction; LVMM, left ventricular myocardial mass; VMM, viable myocardial mass.

All patients had a LVEF <40% on contrast-enhanced cardiac MRI. The myocardial mass and LV ESV were elevated. Time-delayed contrast-enhanced MRI identified areas of abnormal contrast uptake corresponding to PICS in all patients. Five (15%) patients had thrombotic masses in a thinned LV wall, and 31 (94%) showed evidence of LV spherical remodeling. The contrast-enhanced cardiac MRI findings are provided in Table 2.

Primary results

Data preprocessing

We removed columns and rows with a missing value rate >0.75. For the remaining data, missing values were imputed using the feature means.

Feature collinearity diagrams

The identify_collinear function was used to detect collinear predictors. For each pair of highly correlated features, the function identified which one to remove. In machine learning, strong correlations between features can increase variance and reduce model interpretability. We identified 33 radiomic features with a correlation coefficient of >0.98. Heat maps were used to visually represent feature collinearity, with columns indicating correlated features and rows indicating the features marked for removal (Fig. 2, 3).

Features with zero importance

The identify_zero_importance function was used to identify features with zero importance. Removing these features does not impact diagnostic performance. Additionally, we applied the FeatureSelector function and a gradient boosting algorithm to assess feature importance. To minimize variance, the importance value was averaged over 10 training iterations. Early stopping with a control dataset was used to prevent overtraining. Fig. 4 shows the normalized importance of the most significant features, with the X-axis representing the normalized importance of each feature.

We also assessed the cumulative importance of the features based on their total number. We found that 27 features contributed to the overall variation (Fig. 5).

Features with low importance

The identification of features with low importance was based on the same approach used previously. *The identify_low_importance function* was used to identify features with minimal importance that do not affect the overall outcome. We found that 27 features were needed to achieve a total importance of 0.98, whereas 78 features contributed no additional value to the total importance.

Features with a single value

To identify features with a single value, we selected columns containing only one distinct value. These features exhibit zero variance and are not informative for machine

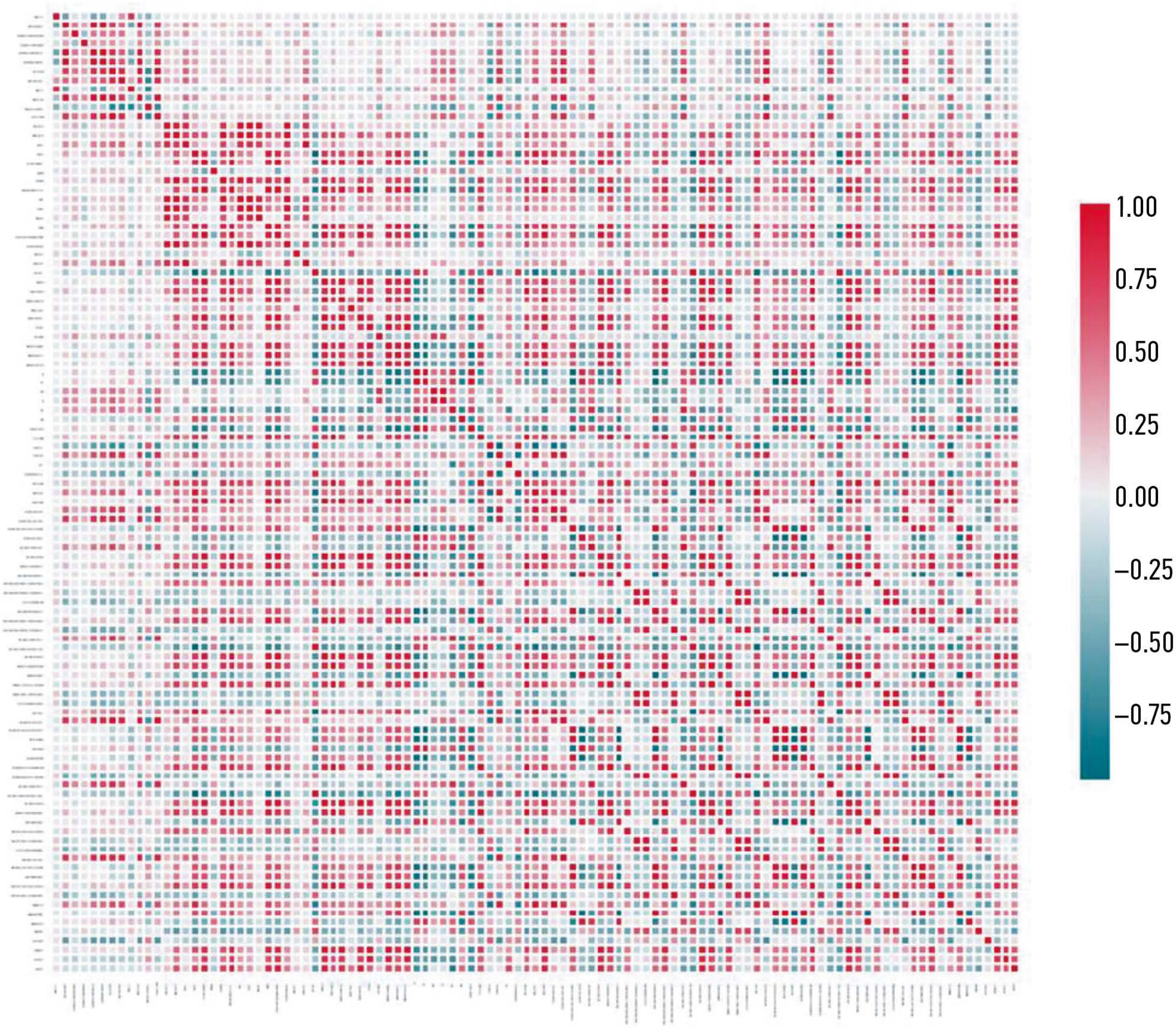

Fig. 2. Heat map showing correlations across the dataset.

learning. Using this method, we found no features with a single unique value (Fig. 6).

We applied Lasso logistic regression to select features and generate a receiver operating characteristic (ROC) curve (Fig. 7). The training accuracy and test accuracy were 0.77 and 0.64, respectively (sensitivity, 57.14%; specificity, 71.43%).

DISCUSSION

Main study outcome

This study assessed the potential of radiomics analysis of non-contrast-enhanced cardiac cine-MRI images for detecting areas corresponding to PICS and intact myocardial tissue in patients with ICM. Using Lasso regression, the method achieved a specificity and sensitivity of 57.14% and 71.43%, respectively. The findings support the ability to differentiate between cicatricial changes in the myocardium and conditionally normal tissue. The relatively low sensitivity and specificity are likely attributable to the small sample size.

Discussion of primary results

The study findings suggest that radiomic features extracted from cine-MRI images can help in identifying post-infarction lesions, thereby potentially improving MI detection and reducing the risks associated with gadolinium-based contrast agents. Few studies have focused on texture analysis of non-contrast-enhanced cardiac cine-MRI images, and none were found in patients with ICM.

These findings align with the study by Smith et al., which showed the significance of machine learning-based radiomic features from non-contrast-enhanced cardiac MRI images for distinguishing between MI and normal myocardial tissue, providing new avenues for clinical diagnosis (AUC 0.88) [16]. Similarly, another study showed that radiomics analysis of non-contrast-enhanced cardiac MRI images in patients with ST-elevation MI (STEMI) helps to assess unfavorable LV remodeling, enhancing diagnostic accuracy and prognosis (AUC 0.82) [18]. Additionally, combining native T1 mapping and extracellular volume mapping in cardiac MRI with radiomics analysis improves the prediction of cardiac function recovery

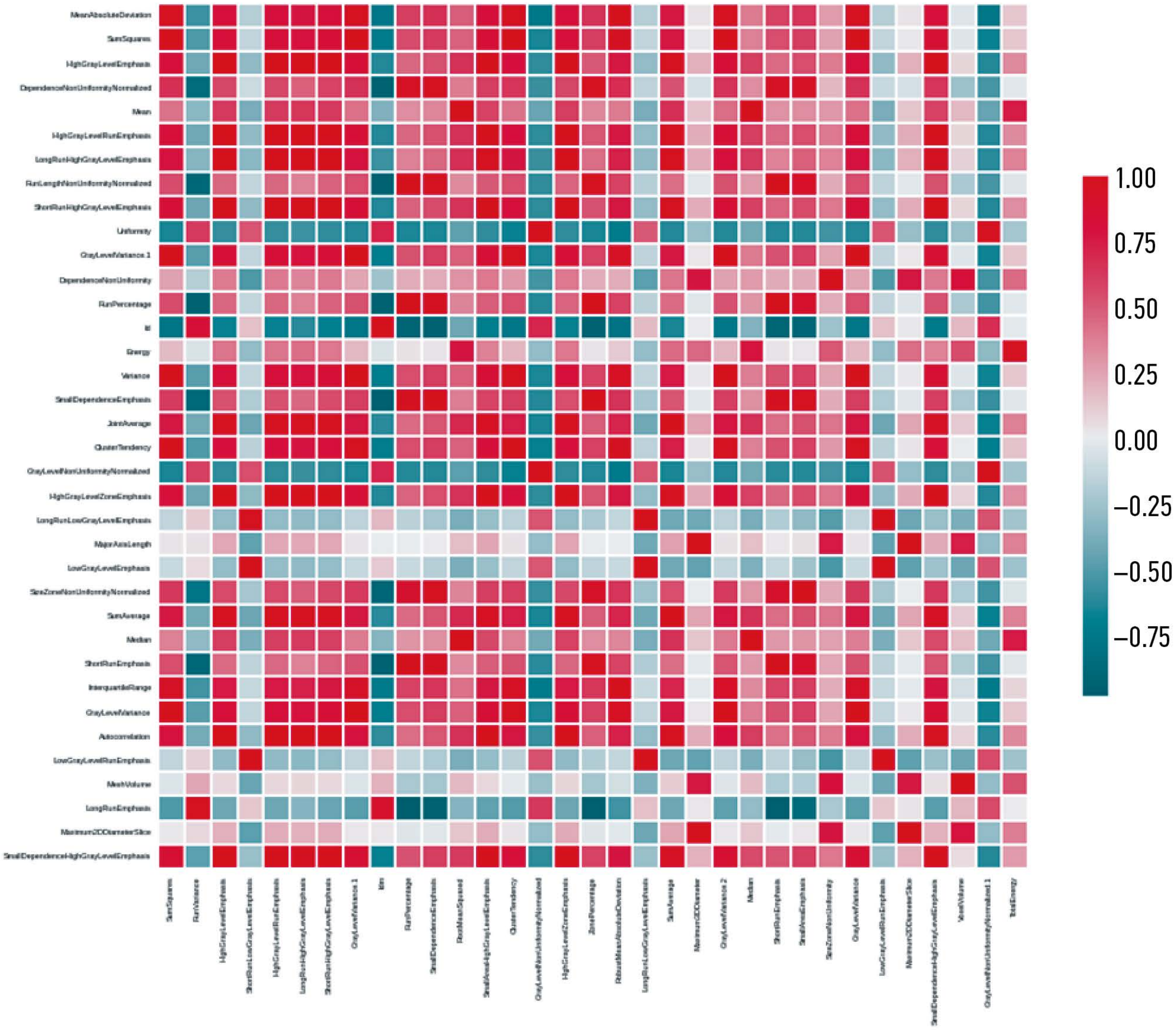

Fig. 3. Correlation heat map for 33 features with a correlation coefficient >0.98.

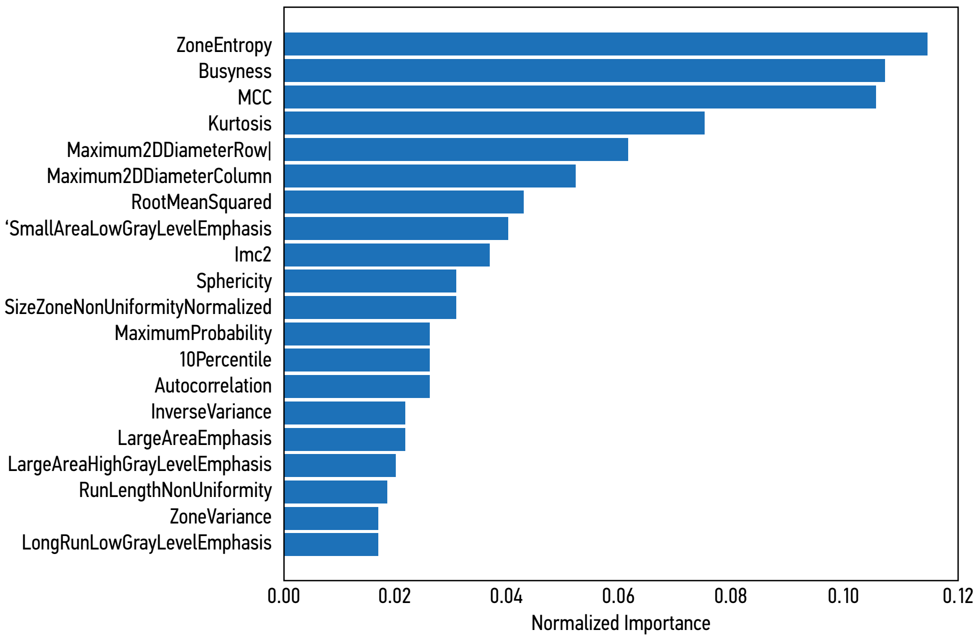

Fig. 4. Normalized importance values.

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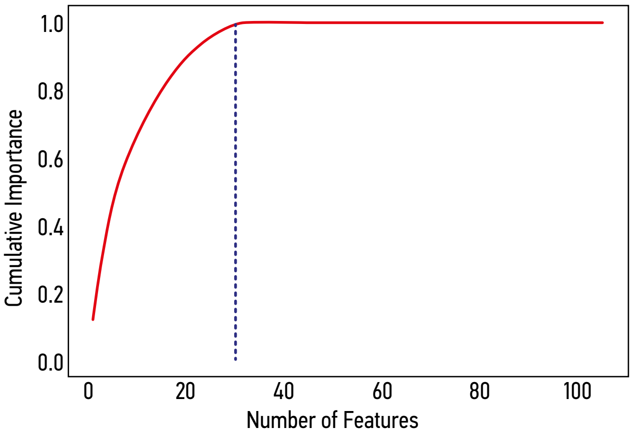

Fig. 5. Changes in cumulative feature importance.

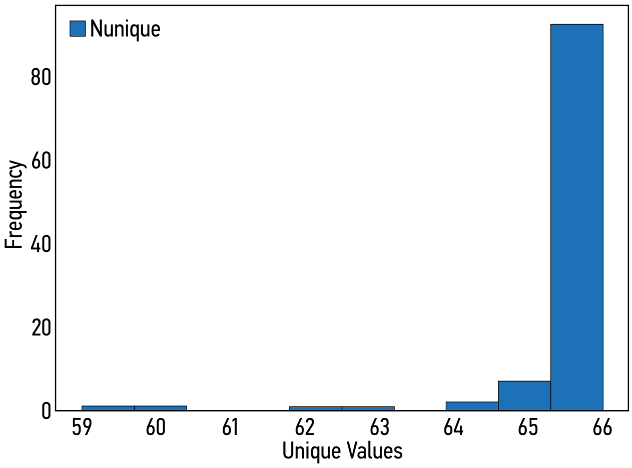

Fig. 6. Number of unique values for each feature.

and microvascular damage. Ma et al. demonstrated that radiomics analysis of non-contrast-enhanced T1 mapping images aids in diagnosing acute MI and predicting myocardial function recovery [19]. This approach improves the accuracy of detecting microvascular obstruction and enhances the long-term prognosis of myocardial contractility. Additionally, native T1 mapping-based radiomics can predict major adverse cardiovascular events in patients with STEMI, aiding in risk stratification [20]. Chen et al. found that extracellular volume mapping-based texture analysis can differentiate between reversible and irreversible myocardial damage in STEMI patients, helping to predict unfavorable LV remodeling, which has clinical significance (AUC 0.91) [21]. Another study showed that native T1 mapping-based radiomic features can predict the risk of unfavorable LV remodeling in patients with non-ischemic dilated cardiomyopathy (AUC 0.81) [22]. Modern mapping techniques can effectively detect various myocardial disorders, but their availability is currently limited. We propose an alternative method using non-contrast-enhanced cardiac cine-MRI images, without the need for mapping or contrast enhancement, which provides sufficient accuracy (AUC 0.77).

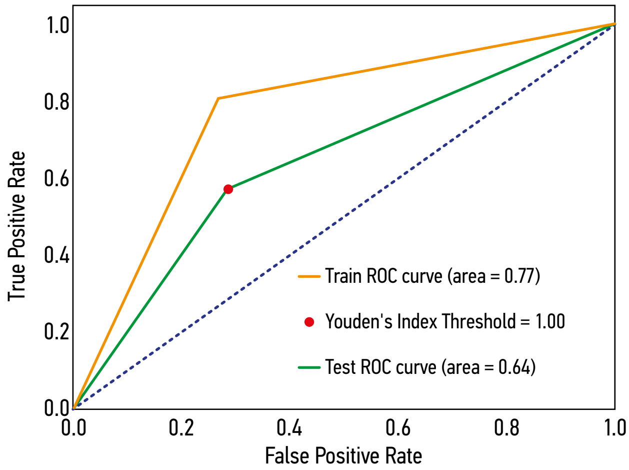

Fig. 7. ROC curves for training accuracy (AUC 0.77) and test accuracy (AUC 0.64).

In recent years, MRI has become the gold standard for noninvasive diagnosis and comprehensive assessment of structural changes in the myocardium [23]. In addition to the well-established diagnostic value of dynamic SSFP sequences for assessing LV volume and function, time-delayed contrast-enhanced MRI is a unique tool for detecting and quantifying PICS areas. The lesion area derived from time-delayed contrast-enhanced MRI findings plays a crucial role in predicting LV remodeling [24]. However, the use of contrast agents is limited to specific patient groups. Many post-infarction patients are clinically unstable during the examination and cannot undergo lengthy procedures. Additionally, gadolinium-based contrast agents may cause side effects, such as renal function impairment, in patients with renal insufficiency.

Study limitations

This study has several limitations, including its retrospective design and small sample size. The sample size required to achieve sufficient statistical power was not determined prior to or during the study. As a result, the sample may not be fully representative, limiting the ability to generalize the findings to the broader population of patients with this condition. Moreover, the study did not include a validation sample to assess the diagnostic value of the model. However, despite the small sample, the study successfully identified significant differences between intact tissue and PICS areas using radiomics analysis of cine-MRI images.

CONCLUSION

Radiomics analysis of non-contrast-enhanced cardiac cine-MRI images can differentiate between PICS areas and viable myocardium. Therefore, this technique could serve as an alternative to time-delayed contrast-enhanced MRI in patients with MI. However, further studies with larger sample sizes and models with stronger prognostic value are needed to identify patients with ICM and support clinical decision-making in their management.

ADDITIONAL INFORMATION

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