

Deep Learning Architectures for Urolithiasis Classification: A Comparative Analysis of DNN, MLP, and Autoencoder-based Models

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Abstract. Renal calculus is a common urological condition that necessitates an accurate and effective diagnostic methodology. This study examines three deep learning architectures applied to the classification of kidney stone images: the Deep Neural Network (DNN), the Multi-Layer Perceptron (MLP), and the Autoencoder-based Deep Neural Network (AE-DNN). A rigorous training and assessment system utilizing a publicly available dataset of 9,416 images is presented. This study offers a comprehensive comparison of performance and clinical measures, emphasizing the trade-off between model complexity and efficiency. The results indicate that all models achieve outstanding performance, with the MLP model being the most efficient and precise, attaining a validation accuracy of 99.67%, precision of 99.67%, and specificity of 99.44%. AE-DNN exhibits a competitive performance with an accuracy of 99.47%. A key finding is the enhanced computational efficiency of the MLP, which trains significantly faster than alternative architectures. Supplementing the promising results, this work acknowledges limitations stemming from the binary classification task and image down-sampling, as well as the necessity for external validation to establish clinical usefulness.

Keywords: Kidney Stone Classification · Deep Learning · Medical Imaging · Neural Networks · Computer-Aided Diagnosis

1 Introduction

1.1 Background and Motivation

Kidney stone disease is a significant global health issue, with incidence rates rising and impacting approximately 10-15% of the worldwide population [1,2].

Traditional diagnostic techniques, such as ultrasound scans, standardized clinical biomarker analysis, and manual interpretation by radiologists, can be time-consuming and prone to interobserver variability. Deep learning-based automated systems offer the opportunity to enhance diagnostic accuracy, thereby reducing interpretation time and increasing access to healthcare. Recent research in medical imaging and computational techniques has shown great promise for enhancing kidney stone categorization and detection, potentially leading to the development of effective and precise diagnostic instruments.

1.2 Challenges and Research Contribution

Classical kidney stone diagnosis presents challenges, including stone variability, limited access to imaging, and subjective interpretation. Computational approaches to kidney stone diagnosis have been explored, but comprehensive comparisons of deep learning architectures for kidney stone classification remain limited. This research evaluates the three neural network architectures (DNN, MLP, and AE-DNN) and provides insight into their performance and efficiency for kidney stone detection.

1.3 Related Work in Kidney Stone Classification

Recent advancements have shown the effectiveness of machine learning and deep learning approaches for kidney stone classification across multiple data modalities and imaging techniques. Several studies have focused on traditional machine learning approaches using custom features. Asaye et al. [3] employed a machine learning approach to detect kidney stones in ultrasound images, utilizing 410 labeled samples. This approach incorporated Gabor filtering and threshold-based segmentation, along with GLCM texture features. Their approach achieved 98.4% accuracy with the KNN algorithm, illustrating the potential of traditional feature-based methods. Iparraguirre-Villanueva et al. [4] evaluated multiple ML algorithms using non-imaging clinical parameters, with Logistic Regression achieving 78% accuracy. Furthermore, Panda et al. [5] reported 93% accuracy using urine analysis data, which included physical features such as pH and calcium concentration. Khan et al. [6] developed an automated detection system employing median filtering for noise reduction and adaptive thresholding for segmentation. By achieving 96.82% accuracy and 92.16% sensitivity, their method demonstrated computational efficiency while overcoming challenges such as speckle noise and low contrast in ultrasound images.

Deep learning approaches have shown great potential in addressing the challenges of kidney stone classification and diagnosis. Kumar et al. [7] proposed a hybrid CNN-ResNet model that achieved 90.9% accuracy by leveraging the capabilities of CNN feature extraction and the advantages of ResNet in deep learning. Further advancing deep learning applications, Liu et al. [8] developed an integrated radiomics and deep learning model for classifying kidney stone types on CT urography, achieving exceptional performance with an AUC of 0.95. Jacob et al. [9] compared three deep learning models for kidney stone identification from

CT scans, finding that ResNet50 outperformed both VGG16 and standard CNN by 7.7% and 4.5%, respectively. Despite these advancements, a need remains for comparative studies of different neural network architectures specifically optimized for kidney stone classification using clinical biomarkers and imaging data. Our research addresses this gap by providing an evaluation of DNN, MLP, and AE-DNN architectures on a dataset of kidney images, offering information on their relative strengths, limitations, and clinical applicability for kidney stone detection.

2 Methodology

This study investigates deep learning techniques for the binary classification of kidney stone images, employing a methodology that encompasses data preprocessing, model development, and a comprehensive evaluation strategy. Three neural network architectures are implemented and evaluated: DNN, MLP, and AE-DNN. The experimental workflow, illustrating the data pipeline and model training process, is shown in Figure 1. To guarantee reproducibility, all random seeds were set to 123 at the beginning of the execution.

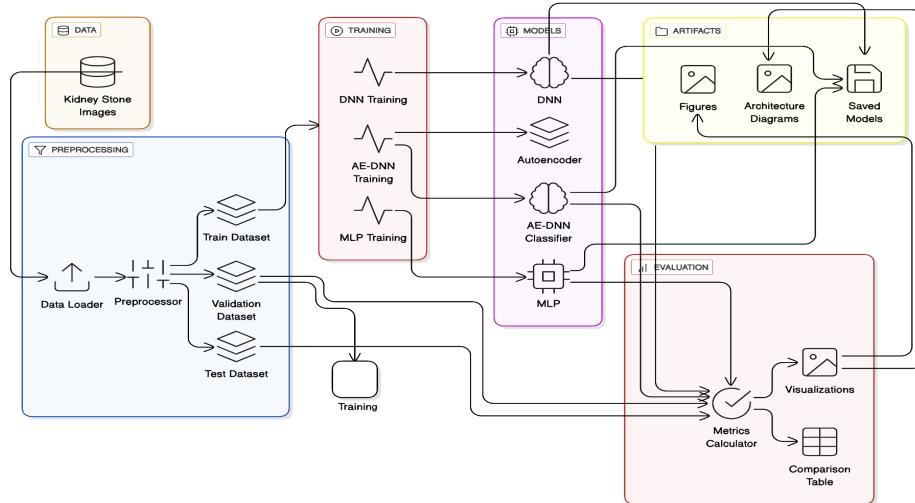


Fig. 1. Methodological Framework for Kidney Stone Classification using Deep Learning Approaches

2.1 Dataset Description and Preprocessing

Data Collection and Characteristics The study utilized the publicly available Kidney Stone Classification dataset from Kaggle [10], comprising 9,416 high-

quality labeled images categorized into two distinct classes: **Normal** (4,708 images) and **Stone** (4,708 images). The dataset exhibits a balanced class distribution, hence mitigating class imbalance bias during model training and ensuring robust performance evaluation. Moreover, images are systematically collected from multiple clinical sources under uniform acquisition conditions. All images are standardized to a resolution of 64×64 pixels with RGB color channels, resulting in an input dimension of 12,288 features per sample ($64 \times 64 \times 3$). The resolution reduction was incorporated to ensure computational efficiency while maintaining diagnostic relevance. Preliminary analysis confirmed that stone characteristics remained discernible at this scale. The dataset splitting followed a structured approach with stratified sampling to maintain class distribution integrity across all subsets:

Training Set	6,026 images $\approx 64\%$
Validation Set	1,507 images $\approx 16\%$
Test Set	1,883 images $\approx 20\%$

$$\text{Total} = 6,026 + 1,507 + 1,883 = \mathbf{9,416}$$

Data Cleaning, Validation and Preprocessing Comprehensive data validation confirmed that there were no missing values or corrupted files within the dataset. Image preprocessing included pixel normalization to scale intensity values to the range [0,1] by the following transformation:

$$I_{\text{normalized}} = \frac{I_{\text{original}}}{255} \quad (1)$$

where I_{original} signifies original pixel intensity values. This normalization ensured stable gradient computation during neural network training and accelerated convergence. For model training, images were flattened into one-dimensional vectors to suit fully connected neural network architectures.

$$X_{\text{flat}} = \text{flatten}(I_{\text{normalized}}) \in \mathbb{R}^{12288} \quad (2)$$

Data Augmentation and Training Strategy Given the size and inherent balance of the dataset, explicit data augmentation techniques were not employed. This decision was made to allow the models to learn from authentic clinical representations without synthetic alterations. The dataset was processed using TensorFlow's data pipeline, which includes automatic caching and prefetching, to optimize training efficiency. The dataset splits were created with a fixed random seed (123) to ensure consistency across experiments. The validation set was used for model selection and hyperparameter tuning, while the final held-out test set provided an unbiased estimate of model performance.

2.2 Deep Learning Architectures

Three neural network architectures were designed with varying complexities to facilitate robust comparison. All models were implemented using TensorFlow/Keras and shared the same experimental setup: an input dimension of 12,288 (flattened $64 \times 64 \times 3$ images), ReLU activation functions for hidden layers, a softmax output layer for the 2-class classification, Adam optimizer, a fixed training schedule of 10 epochs, a batch size of 32, and a random seed of 123 for reproducibility.

Deep Neural Network (DNN) Architecture The DNN was designed as a high-capacity model with two hidden layers comprising 512 and 256 neurons. Each layer employed ReLU activation, followed by batch normalization for stable training, and utilized Dropout regularization ($p = 0.3$) to mitigate overfitting. L2 weight regularization ($\lambda = 10^{-4}$) was also applied to all layers. The model was compiled with Adam optimizer and sparse categorical cross-entropy loss, $\mathcal{L} = \mathcal{L}_{\text{CE}} + \lambda \|\mathbf{W}\|_2^2$, resulting in a total of approximately 6.5 million trainable parameters. This architecture aimed to use its depth and breadth to learn complex, hierarchical features directly from the pixel data.

Multi-Layer Perceptron (MLP) Architecture The MLP was designed as a more efficient and compact architecture featuring two hidden layers with 128 and 64 neurons. It maintained use of ReLU, batch normalization, and L2 regularization ($\lambda = 10^{-4}$), but utilized a lower Dropout rate ($p = 0.2$), reflective of its reduced capacity, and had approximately 1.6 million parameters. The objective of this model was to determine whether a more basic network could match or surpass the performance, aiming to achieve a favorable balance between computational cost and performance.

Autoencoder-based DNN (AE-DNN) Architecture The AE-DNN employed a hybrid two-stage training process. A symmetric autoencoder was trained in an unsupervised manner to reconstruct its input, learning a compressed latent representation. The encoder consisted of layers with 512, 256, and 128 neurons (ReLU activation), with the 128-neuron layer serving as the latent space. The decoder mirrored this structure. The autoencoder was trained using Mean Squared Error (MSE) loss: $\mathcal{L}_{\text{recon}} = \text{MSE}(\mathbf{x}, \hat{\mathbf{x}})$. Subsequently, a classifier, which shared the encoder weights, was attached to the latent space and trained using the labeled data with sparse categorical cross-entropy loss, $\mathcal{L}_{\text{class}} = \mathcal{L}_{\text{CE}}$. The total parameter count for the full AE-DNN system was approximately 7.2 million. This allowed for an investigation into whether features learned through unsupervised reconstruction could enhance the performance of the downstream classifier.

2.3 Experimental Setup

Training Configuration and Hyperparameters All models are trained for 10 epochs using a batch size of 32, and the Adam optimizer was used with its

default parameters (learning rate $\alpha = 0.001$, $\beta_1 = 0.9$, $\beta_2 = 0.999$). The primary loss function for classification tasks (DNN, MLP, and the second stage of AE-DNN) was sparse categorical cross-entropy:

$$\mathcal{L}_{\text{CE}} = -\frac{1}{N} \sum_{i=1}^N \sum_{c=1}^2 y_{i,c} \log(\hat{y}_{i,c}) \quad (3)$$

Mean squared error loss was used during the autoencoder pretraining phase of the AE-DNN model:

$$\mathcal{L}_{\text{MSE}} = \frac{1}{N} \sum_{i=1}^N \|\mathbf{x}_i - \hat{\mathbf{x}}_i\|_2^2 \quad (4)$$

To optimize convergence, learning rate scheduling was implemented with a reduction on plateau (factor = 0.5, tolerance = 5 epochs).

Evaluation Metrics and Validation Strategy A comprehensive set of metrics was used to assess model performance from multiple perspectives. The primary metrics included accuracy, precision, recall, and F1 score, calculated as follows:

1. Performance Metrics:

- **Accuracy:** The proportion of correctly classified samples

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \quad (5)$$

- **Area Under the ROC Curve (AUC):** The area under the Receiver Operating Characteristic curve, measuring the model's ability to distinguish between classes across all classification thresholds.

2. Clinical Metrics:

- **Sensitivity (Recall):** The true positive rate, measuring the model's ability to correctly identify positive cases

$$\text{Sensitivity} = \frac{TP}{TP + FN} \quad (6)$$

- **Specificity:** The true negative rate, measuring the model's ability to correctly identify negative cases

$$\text{Specificity} = \frac{TN}{TN + FP} \quad (7)$$

- **Precision:** The positive predictive value, measuring the proportion of true positives among all predicted positives

$$\text{Precision} = \frac{TP}{TP + FP} \quad (8)$$

- **F1-Score:** The harmonic mean of precision and recall, providing a balanced measure

$$\text{F1-Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (9)$$

3. Error Analysis:

- **Error Rate:** The proportion of incorrectly classified samples

$$\text{Error Rate} = \frac{FP + FN}{TP + TN + FP + FN} \quad (10)$$

- **False Negative Rate (FNR):** The proportion of actual positives incorrectly classified as negative

$$\text{FNR} = \frac{FN}{TP + FN} \quad (11)$$

- **False Positive Rate (FPR):** The proportion of actual negatives incorrectly classified as positive

$$\text{FPR} = \frac{FP}{TN + FP} \quad (12)$$

Supplementary metrics such as Cohen’s Kappa and Matthews Correlation Coefficient were also computed, and Cohen’s Kappa (κ) measures inter-rater agreement for categorical items, accounting for chance agreement:

$$\kappa = \frac{p_o - p_e}{1 - p_e} \quad (13)$$

where p_o is observed agreement and p_e is expected agreement by chance. Matthews Correlation Coefficient provides a balanced measure even with imbalanced classes:

$$\text{MCC} = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \quad (14)$$

The validation strategy followed a standard supervised learning protocol. Models were trained on the designated training set, while model selection and hyperparameter tuning were guided by performance on the validation set. Final comparative results were reported based on the validation outcomes, consistent with established practice. An independent test set was subsequently employed as an unbiased evaluation, with results (e.g., Test Accuracy: MLP = 99.31%) showing the model’s generalizability within the dataset.

Table 1. Comprehensive Kidney Stone Classification Performance Analysis and Clinical Evaluation Metrics

Model	Performance Metrics		Clinical Metrics				Error Analysis		
	Acc (%)	Time (s)	Sen (%)	Spe (%)	Pre (%)	F1 (%)	Err (%)	FN (%)	FP (%)
AE-DNN	99.47	4.2	99.47	98.87	99.48	99.47	0.53	0.53	1.13
MLP	99.67	1.5	99.67	99.44	99.67	99.67	0.33	0.33	0.56
DNN	98.95	5.3	98.95	97.75	98.97	98.94	1.05	1.05	2.25

3 Results and Analysis

3.1 Overall Performance and Computational Efficiency

The results shows that our all three deep learning models achieved high performance on kidney stone classification task and comprehensive summary of results including performance, clinical and error metrics calculated on validation set and that is presented in Table 1. The Multi Layer Perceptron emerged as the top performing model, achieving highest validation accuracy of 99.67% and it was closely followed by Autoencoder based DNN at 99.47% accuracy while Deep Neural Network established strong baseline with 98.95% accuracy. This schema was consistent across all primary clinical metrics with MLP also attaining highest sensitivity (99.67%) specificity (99.44%) precision (99.67%) and F1-score (99.67%). Critical differentiator was computational efficiency and the MLP compact architecture resulted in dramatically faster training time of 0.58 seconds per epoch which is order of magnitude more efficient than DNN (6.34 s/epoch) and AE-DNN (8.42 s/epoch)

3.2 Comprehensive Model Evaluation and Clinical Relevance

The confusion matrix presented in Figure 2 provides view of classification performance across all models and the matrix shows average normalized confusion values and absolute counts (in parentheses) confirming high accuracy and low error rates reported in Table 1. The minimal off diagonal values visually corroborate low false negative and false positive rates achieved by all models particularly the MLP. High sensitivity (Recall) of all models (98.95-99.67%) is essential as it minimizes false negatives critical factor where missing kidney stone diagnosis could have serious consequences for the patient. The specificity (97.75-99.44%) is equally important reducing false positives that could lead to unnecessary follow up procedures and patient anxiety. The MLP balanced performance with near perfect sensitivity of 99.67% and highest specificity of 99.44% positions it the most clinically reliable model in this study

3.3 Limitations and Statistical Considerations

While results demonstrates strong performance several limitations warrant consideration. The perfectly balanced 50:50 class distribution while methodologi-

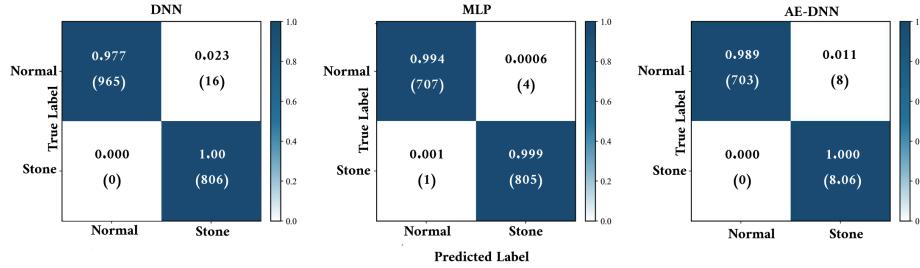


Fig. 2. Confusion Matrix for All Models

cally appropriate for comparative analysis does not reflect real world clinical prevalence rate, potentially affecting predictive values in practical deployment and the decision to flatten images and employ fully connected networks though intentional for architectural comparison discarded valuable spatial information that the convolutional networks typically exploit. The consistent high performance across all model while promising raises questions about potential ceiling effects in specific dataset and the perfect scores could indicate exceptional model performance or binary classification task may be relatively straightforward for deep learning models given the current data characteristics.

4 Conclusion and Future Work

This study demonstrated effectiveness of three deep learning architectures for kidney stone classification with the MLP achieving the highest accuracy (99.67%) while maintaining the superior computational efficiency and the consistent high performance across all models highlights their potential for clinical deployment. Future work will focus on the developing of an integrated diagnostic tool implementing Explainable AI techniques including SHAP and LIME for model interpretability conducting multi center validation and expanding to multi class classification for different stone types and this research contributes to AI powered diagnostic tools that can enhance precision and efficiency in urological practice.

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