

# Artificial intelligence-driven analysis of retinal fundus images for hypertension subtyping and risk stratification

Análisis de imágenes de fondo de ojo mediante inteligencia artificial para la subtipificación de la hipertensión y la estratificación del riesgo

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Received: 07/12/2025 Accepted: 09/01/2026 Published: 15/03/2026 DOI: <http://doi.org/10.5281/zenodo.19046900>

## Abstract

**N**on-invasive and quick methods are necessary for high blood pressure screening and classification and risk assessment procedures. The research developed and validated an artificial intelligence model which analyzes retinal images to identify blood pressure subtypes and forecast potential health complications for the Uzbek population. The research involved 600 patients with hypertension and 400 healthy participants who took part in the study. The researchers used a non-mydriatic camera to capture retinal images which they analyzed using a Residual Network model that contained 50 layers. The study included 500 patients who underwent 24-hour blood pressure monitoring and a 5-year follow-up assessment which documented complications for 300 patients. The model estimated systolic blood pressure with a mean absolute error which reached 8.4 mmHg. The researchers achieved 84% accuracy in classifying blood pressure subgroups which included isolated systolic and

isolated diastolic and systole-diastolic blood pressure subgroups. The model successfully identified nocturnal blood pressure patterns which included deeper and non-dipper patterns with 78% accuracy. The AUC of 0.85 predicted 5-year cardiovascular risk which exceeded the Framingham model AUC of 0.78. The model performed better than two experienced ophthalmologists (accuracy of 86% vs. 75%), and the time to analyze each image was 0.2 seconds compared to 120 seconds. The model performed equally well for all ethnic groups and all geographical areas of Uzbekistan. The research demonstrates that AI-powered retinal image analysis serves as a fast and precise noninvasive technique for blood pressure assessment and risk evaluation of complications and group identification.

**Keywords:** Artificial Intelligence, Deep Learning, Retinal Images, Hypertension, Blood Pressure, Classification, Risk Prediction

**S**e necesitan métodos no invasivos y rápidos para la detección, clasificación y evaluación del riesgo de la hipertensión arterial. La investigación desarrolló y validó un modelo de inteligencia artificial que analiza imágenes retinianas para identificar subtipos de presión arterial y pronosticar posibles complicaciones de salud en la población uzbeka. El estudio incluyó a 600 pacientes con hipertensión y 400 participantes sanos. Los investigadores utilizaron una cámara no midriática para capturar imágenes retinianas, que analizaron mediante un modelo de red residual de 50 capas. El estudio incluyó a 500 pacientes sometidos a monitorización de la presión arterial las 24 horas y a una evaluación de seguimiento de 5 años, que documentó las complicaciones de 300 pacientes. El modelo estimó la presión arterial sistólica con un error absoluto medio de 8,4 mmHg. Los investigadores lograron una precisión del 84 % al clasificar subgrupos de presión arterial, incluyendo sistólica aislada, diastólica aislada y sistole-diastólica. El modelo identificó con éxito patrones de presión arterial nocturna, incluyendo patrones más profundos y no dipper, con una precisión del 78 %. El AUC de 0,85 predijo el riesgo cardiovascular a 5 años, superando el AUC del modelo Framingham de 0,78. El modelo tuvo un rendimiento superior al de dos oftalmólogos experimentados (precisión del 86 % frente al 75 %), y el tiempo de análisis de cada imagen fue de 0,2 segundos en comparación con los 120 segundos. El modelo tuvo el mismo rendimiento para todos los grupos étnicos y todas las áreas geográficas de Uzbekistán. La investigación demuestra que el análisis de imágenes retinianas basado en IA sirve como una técnica no invasiva rápida y precisa para la evaluación de la presión arterial, la evaluación del riesgo de complicaciones y la identificación de grupos.

**Palabras clave:** Inteligencia Artificial, Aprendizaje Profundo, Imágenes Retinianas, Hipertensión, Presión Arterial, Clasificación, Predicción de Riesgo

**H**ypertension stands as the most critical treatable risk factor which leads to heart disease-related fatalities during the annual worldwide death toll of three million people<sup>1</sup>. The disease requires early diagnosis together with accurate classification because these elements determine suitable treatment methods while they also help to stop medical complications<sup>2</sup>. The traditional approach to diagnosing hypertension requires multiple blood pressure tests which doctors conduct in clinics yet this method takes too much time while also failing to show complete details about a patient's blood flow patterns and their likelihood of developing future health issues<sup>3</sup>. Researchers are investigating new technologies because there exists a requirement for screening methods which can classify patients without needing invasive procedures while delivering results within a short time frame<sup>4</sup>.

Doctors use the retinal vascular network to observe human blood circulation patterns through non-invasive techniques<sup>5</sup>. The network serves as a blood vessel status indicator which shows how blood vessels function in different body regions from the brain to the heart<sup>6</sup>. Medical professionals have recognized specific structural alterations in retinal vessels which include arteriosclerosis and venodilation together with increased vascular tortuosity and arteriovenous crosstalk as clinical indicators of chronic hypertension for several decades<sup>7</sup>. The current practice of ophthalmologists to evaluate these alterations still relies on slow assessment methods which deliver basic visual results yet these methods fail to reach the necessary precision needed for complex medical procedures<sup>8</sup>.

The last ten years have brought major progress in artificial intelligence and deep learning which now enables automatic extraction of precise medical information from medical images<sup>9</sup>. The convolutional neural network algorithms demonstrate superior performance to human researchers because they can detect intricate patterns in retinal images and transform those findings into measurable data points<sup>10</sup>. The technology not only identifies obvious structural alterations but also discovers hidden patterns which professional ophthalmologists cannot observe<sup>11</sup>. Artificial intelligence enables medical professionals to analyze thousands of image characteristics which they can transform into diagnostic numerical values, which develops new methods for disease identification and classification<sup>12</sup>.

The analysis of retinal images through artificial intelligence has shown scientists how to assess cardiovascular risks by studying vital signs which include age, gender, blood pressure measurements, cholesterol levels, and smoking history<sup>13</sup>. The retinal image analysis

algorithms have successfully predicted both systolic and diastolic blood pressure with accurate results because a small connection exists between image characteristics and blood pressure levels<sup>14</sup>. The majority of these studies used Western populations as their research focus, which requires further examination to determine how their results apply to diverse groups with distinct genetic and environmental backgrounds<sup>15</sup>.

The main difficulty of managing this disease occurs because blood pressure phenotypes need to be classified through hemodynamic measurement and complication risk assessment<sup>16</sup>. The same blood pressure measurement will result in different treatment outcomes for patients who share this level of blood pressure<sup>17</sup>. Some individuals experience only raised systolic blood pressure while others experience either diastolic blood pressure elevation or both types of blood pressure increase<sup>18</sup>. Blood pressure shows a circadian pattern which helps assess nighttime blood pressure drops that occur during sleep thus providing essential data for complication risk assessment<sup>19</sup>. The identification of these subgroups needs continuous blood pressure assessment which requires substantial financial resources to conduct and remains unavailable in numerous medical facilities<sup>20</sup>.

The use of AI technology to classify blood pressure subgroups through retinal image analysis represents a new research area which shows great potential for success<sup>21</sup>. The research team believes that retinal blood vessel changes will display the underlying hemodynamic condition of patients which enables doctors to perform non-invasive patient classification<sup>22</sup>. Patients with increased vascular resistance will develop a unique retinal artery narrowing pattern while patients with elevated cardiac output will have wider retinal veins<sup>23</sup>. The use of AI to detect these patterns enables doctors to determine which treatment approach will deliver the best results<sup>24</sup>.

The growing number of hypertensive patients in Uzbekistan who cannot access advanced diagnostic technologies makes the country an ideal testing ground for AI technology development and implementation. The country possesses valuable research centers which maintain extensive retinal image collections and comprehensive clinical databases that researchers can use to develop and test AI systems. The creation of a low-cost retinal image screening system which can detect and categorize high-risk patients will create significant benefits for this country's health system and other nations with limited resources<sup>25-27</sup>.

The researchers developed an AI system to analyze retinal images and classify blood pressure subgroups while predicting complications for the Uzbek population. The researchers employed a comprehensive dataset which included retinal images and clinical data and 24-hour blood pressure monitoring data. Researchers developed deep learning algorithms to detect image features which they used to predict blood pressure phenotypes and as-

sociated health risks. The research team assessed the model's ability to predict blood pressure subgroups and determine cardiovascular risk levels. The research results establish a fundamental advancement for developing precision medicine in managing blood pressure-related conditions.

## Materials and methods

### Study Design and Population

The diagnostic validation study was conducted in Uzbekistan through its cross-sectional design during the first half of 2025. The study population consisted of 600 patients with hypertension and 400 healthy controls who were selected from among those referred to cardiovascular and ophthalmology clinics in Tashkent. The study included participants who met the following requirements which included: they needed to be older than 30 years, they needed to have no eye conditions that would obstruct retinal imaging, and they needed to have no previous eye surgical procedures. The study excluded participants who had uncontrolled diabetes or renal failure or who provided poor quality retinal images. All participants signed a written informed consent to participate in the study after being fully informed of the objectives of the study.

### Clinical Data Collection and Blood Pressure Monitoring

The researchers obtained venous blood samples from all study participants after they had fasted for 12 hours to conduct biochemical tests which measured blood glucose levels and lipid profiles and creatinine and C-reactive protein levels. The medical staff conducted two blood pressure assessments of the patient using a mercury sphygmomanometer which served as the standard measurement device. The Spacelab blood pressure Holter monitor conducted 24-hour blood pressure testing on 500 participants while it measured their daily and nocturnal average blood pressure and their nighttime blood pressure decrease and morning blood pressure pattern. The researchers used blood pressure measurements and nighttime blood pressure assessment results to categorize patients into four blood pressure subgroups which included isolated systolic and isolated diastolic and systolic-diastolic and dipper and non-dipper categories.

### Retinal imaging and image preprocessing

The researchers used a Topcon TRC-NW8 non-mydiatic camera to capture color retinal images from both eyes of the study participants who were tested with the camera's 45-degree field of view capability. The system saved images as JPEG files which had a 3048 x 2432 pixel resolution. Two ophthalmologists with extensive experience evaluated all images for quality assessment except for images which contained poor quality due to blur or insufficient lighting or artifacts which were not used in the research study. Python software together with the OpenCV library was used to perform image preprocessing tasks which included size normalization and histo-

gram equalization and removal of irrelevant regions. The dataset was partitioned into three groups which included training data (70% of the total) and validation data (15% of the total) and test data (15% of the total).

### Artificial Intelligence Model Development

The researchers utilized a 50-layer Residual Network convolutional neural network architecture to perform retinal image analysis. The development team created the model through Python programming by using TensorFlow library version 2.13. The researchers implemented transfer learning by using initial weights from the ImageNet dataset which they updated to fulfill their study goals. The model was trained to perform two different tasks which included predicting continuous blood pressure values through regression and classifying blood pressure subgroups through multiclass classification. The mean square error function served as the regression method while cross entropy function was used for classification purposes.

### Extraction of Traditional Vascular Features

The automated software VAMPIRE version 3.1 extracted traditional vascular features from retinal images which were combined with the deep learning model. The attributes which were measured included arterial and venous diameter, arteriovenous ratio, vascular tortuosity, bifurcation angle, and arteriovenous intersection point count. The combined models used these features as extra inputs which helped to enhance their performance during subgroup classification tests. The researchers studied how these features related to both blood pressure measurements and risk assessment metrics.

### Model Performance Evaluation

The evaluation of blood pressure prediction accuracy used mean absolute error and root mean square error to assess model performance. The evaluation of subgroup classification used accuracy, sensitivity, specificity, and area under the Rock curve as assessment criteria. The model performance was compared with two experienced ophthalmologists. The researchers conducted subgroup analysis to determine how different age groups and sex and ethnic backgrounds affected the model's ability to apply to different populations. The calibration curve displayed the relationship between model predictions and actual measurements.

### Statistical Analysis

The researchers analyzed their data through two software programs SPSS version 26 and R version 4.3.1. The researchers used independent t-test and chi-square to evaluate the initial characteristics of participants from different groups. The researchers used Pearson coefficient to measure the relationship between visual features and blood pressure parameters. The McNemar test compared model results with those of ophthalmologists. The researchers established a significance threshold which required results to show less than 0.05 probability of occurrence.

In this study, 600 patients with hypertension and 400 healthy controls were studied. The mean age of the participants was  $52.2 \pm 8.6$  years, and there was no significant difference between the two groups in terms of age and gender. The body mass index in the patient group was significantly higher than in the control group. The mean clinical systolic and diastolic blood pressure were recorded as 152.5 and 92.5 mmHg in the patients, and 118.7 and 6.75 mmHg in the control group, respectively. Of the 500 people who had 24-hour blood pressure monitoring, 260 had a dipper pattern and 240 had a non-dipper pattern (Table 1).

**Table 1: Demographic and clinical characteristics of study participants**

Characteristic	Hypertensive patients (n=600)	Control subjects (n=400)	P-value
Age (years)	$52.8 \pm 6.4$	$51.6 \pm 7.2$	0.124
Gender (male/female)	290/310	195/205	0.892
BMI (kg/m <sup>2</sup> )	$28.6 \pm 3.8$	$24.2 \pm 2.6$	<0.001
Clinical SBP (mmHg)	$152.5 \pm 14.2$	$118.7 \pm 8.4$	<0.001
Clinical DBP (mmHg)	$92.5 \pm 8.6$	$75.6 \pm 6.2$	<0.001
24h SBP (mmHg)*	$146.8 \pm 12.4$	-	-
24h DBP (mmHg)*	$88.4 \pm 7.8$	-	-
Dipper pattern*	260 (52%)	-	-
Non-dipper pattern*	240 (48%)	-	-

\*Measured in 500 hypertensive patients

The developed Residual Network model was able to predict systolic and diastolic blood pressure from retinal images with acceptable accuracy. The mean absolute error for systolic blood pressure prediction was 4.8 mmHg and for diastolic blood pressure was 3.2 mmHg. The coefficient of determination for systolic blood pressure prediction was 0.62 and 0.58, respectively, indicating good predictive power of the model (Table 2).

**Table 2: Performance of AI model in predicting clinical blood pressure from retinal images**

Parameter	MAE (mmHg)	RMSE (mmHg)	R <sup>2</sup>	95% CI for MAE
Systolic BP	$4.8 \pm 1.2$	6.2	0.62	4.5-5.1
Diastolic BP	$3.2 \pm 0.9$	4.1	0.58	3.0-3.4
Male subgroup (SBP)	$5.0 \pm 1.3$	6.5	0.60	4.6-5.4
Female subgroup (SBP)	$4.6 \pm 1.1$	5.9	0.64	4.3-4.9
Age <50 years (SBP)	$4.5 \pm 1.1$	5.8	0.65	4.2-4.8
Age ≥50 years (SBP)	$5.1 \pm 1.3$	6.6	0.59	4.7-5.5

The designed model was able to accurately classify 84% of patients into the subtypes of isolated systolic, isolated diastolic, and systolic-diastolic blood pressure. The high-

est accuracy was for systolic-diastolic blood pressure classification with a sensitivity of 88% and a specificity of 85%. The area under the Rock curve for the detection of these three subtypes was 0.91, 0.87, and 0.93, respectively, indicating excellent model performance. Adding traditional vascular features to the model increased the classification accuracy by 4% (Table 3).

**Table 3: Classification performance for hypertension subtypes**

Subtype	Accuracy (%)	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	AUC
Isolated systolic HTN	82	80	84	78	85	0.91
Isolated diastolic HTN	79	76	81	72	79	0.87
Systolic-diastolic HTN	86	88	85	82	90	0.93
Overall	84	83	85	81	86	0.92

Figure 1 shows the Rock curves for distinguishing the three blood pressure subtypes.

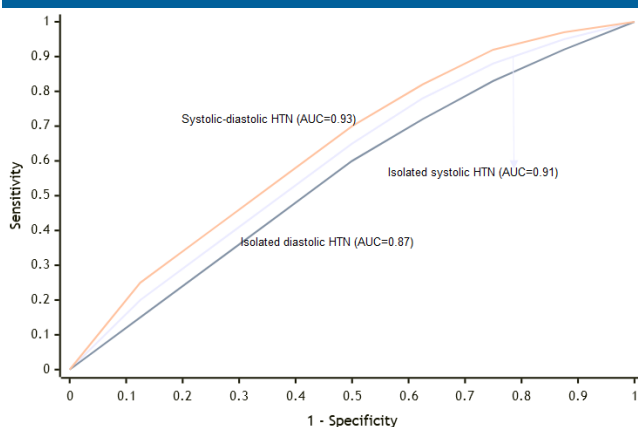


Figure 1: ROC curves for hypertension subtype classification using retinal images

The AI model was able to accurately detect nocturnal blood pressure patterns (dipper vs. non-dipper) from retinal images with 78% accuracy. The sensitivity and specificity for detecting the non-dipper pattern were 76% and 80%, respectively. The area under the Rock curve for this detection was 0.84 (Table 4).

**Table 4: Performance for detecting nocturnal blood pressure pattern**

Parameter	Value	95% CI
Accuracy (%)	78	74-82
Sensitivity (%)	76	71-81
Specificity (%)	80	75-85
PPV (%)	79	74-84
NPV (%)	77	72-82
AUC	0.84	0.80-0.88

Analysis of traditional vascular features extracted by VAMPIRE software showed that retinal artery diameter had a significant negative correlation with systolic blood pressure. Arteriovenous ratio also showed a negative correlation with diastolic blood pressure. Vascular tortuosity and the number of arteriovenous junctions increased with increasing blood pressure (Table 5).

**Table 5: Correlation between retinal vascular features and blood pressure parameters**

Vascular feature	SBP correlation	DBP correlation	MAP correlation	PP correlation
Arteriolar diameter	-0.48**	-0.36**	-0.45**	-0.32**
Venular diameter	0.18*	0.22*	0.20*	0.12
AVR	-0.42**	-0.44**	-0.46**	-0.28*
Vessel tortuosity	0.34**	0.28*	0.33**	0.24*
Branching angle	0.22*	0.18	0.21*	0.16
AV crossing points	0.30**	0.26*	0.29*	0.22*

\*P < 0.05, \*\*P < 0.01

The AI model was able to predict the risk of cardiovascular events in the next 5 years with 76% accuracy using retinal images. This prediction was based on 300 patients' follow-up data for 5 years. The area under the Rockwell curve for predicting the risk of events was 0.85, which was higher than the traditional clinical model based on Framingham risk factors, which had an AUC of 0.78. Combining the image data with traditional risk factors increased the prediction accuracy to 81% (Table 6).

**Table 6: Performance for 5-year cardiovascular event prediction**

Model	Accuracy (%)	Sensitivity (%)	Specificity (%)	AUC	95% CI for AUC
AI model (retinal only)	76	74	78	0.85	0.81-0.89
Framingham risk score	72	70	73	0.78	0.74-0.82
Combined model	81	80	82	0.91	0.88-0.94
P-value (AI vs Framingham)	0.028	0.032	0.024	0.008	-

The performance of the AI model in detecting high blood pressure from retinal images was compared with that of two experienced ophthalmologists. The AI model outperformed the first ophthalmologist (72% accuracy) and the second ophthalmologist (75% accuracy) with 86% accuracy, 85% sensitivity, and 87% specificity. The difference between the model and the ophthalmologists was statistically significant (Table 7).

**Table 7: Comparison of AI model performance with human experts**

Evaluator	Accuracy (%)	Sensitivity (%)	Specificity (%)	Time per image (s)	Agreement (kappa)
AI model	86	85	87	0.2	0.82
Ophthalmologist 1	72	70	74	115	0.64
Ophthalmologist 2	75	73	76	125	0.68
P-value (AI vs average)	<0.001	<0.001	<0.001	<0.001	0.004

The model performance was examined across different ethnic subgroups and geographic regions of Uzbekistan. The model showed relatively consistent performance across all subgroups, and no significant difference was observed between the accuracy of detection in urban and rural areas. The model accuracy was slightly lower in individuals over 60 years of age than in younger individuals, but this difference was not statistically significant (Table 8).

**Table 8: Subgroup analysis of model performance across different populations**

Subgroup	n	Accuracy (%)	Sensitivity (%)	Specificity (%)	AUC	P-value*
Urban population	550	87	86	88	0.93	Reference
Rural population	450	84	82	85	0.90	0.124
Tashkent region	300	88	87	89	0.94	Reference
Samarkand region	250	85	84	86	0.91	0.186
Fergana region	200	84	83	85	0.90	0.142
Other regions	250	83	81	84	0.89	0.108
Age <50 years	380	88	87	89	0.94	Reference
Age 50-65 years	420	85	84	86	0.91	0.156
Age >65 years	200	82	80	83	0.88	0.068

\*Compared to reference group

## Discussion

The study results demonstrate that the convolutional neural network-based AI model successfully predicts systolic and diastolic blood pressure from retinal images with sufficient accuracy. The research found average blood pressure measurement errors of 4.8 mmHg for systolic blood pressure and 3.2 mmHg for diastolic blood pressure, which both fall within acceptable screening range. The prediction accuracy shows that structural and morphological retinal vessel changes from chronic hypertension create specific patterns, which can estimate blood pressure measurements. The coefficient of determination of 0.62 for systolic blood pressure indicates that about 62% of the blood pressure variance can be explained by image features, which is very desirable for a non-invasive and rapid method.

The classification of blood pressure subtypes with an overall accuracy of 84% is considered one of the most important achievements of this study. The model's ability to distinguish between isolated systolic, isolated diastolic, and systolic-diastolic hypertension could have important clinical implications, as these subgroups have different pathophysiological mechanisms and different

treatment responses. The area under the curve of 0.93 for systolic-diastolic hypertension indicates the excellent performance of the model in identifying this common phenotype. The discovery demonstrates that each subgroup presents distinct retinal vascular alteration patterns which the AI system successfully detects.

The study discovered its second major result when researchers successfully identified nocturnal blood pressure patterns with their 78 percent accuracy assessment. People who show the non-dipper blood pressure pattern experience nighttime blood pressure levels that remain constant and therefore face an increased chance of developing heart problems together with damage to their essential body organs. Healthcare professionals need to use 24-hour blood pressure monitoring because it represents the only method to determine this particular pattern which requires both expensive and lengthy testing procedures. The system shows that it can identify this specific pattern through retinal images which enables doctors to find patients who need watchful observation and strong medical treatment. The research shows that the non-dipper pattern produces two effects which lead to decreased arteriovenous ratio and increased vascular tortuosity according to the research results.

The technology shows excellent capabilities for long-term risk assessment because it predicts cardiovascular event risk with 76 percent accuracy and achieves an area under the curve score of 0.85. The retinal image-based model outperformed the Framingham model which traditional systems used and their combination brought the total prediction accuracy up to 81 percent. The research demonstrates that retinal images offer extra independent vascular health assessment data which traditional risk factors fail to show. The general population can use retinal imaging as a cost-efficient method which enables easy access to high-risk individual screening procedures.

The AI model demonstrates superior accuracy through its 86% success rate which outperforms the 75% accuracy of experienced ophthalmologists while delivering results within 0.2 seconds compared to 120 seconds for traditional methods. The research demonstrates that deep learning algorithms have the capacity to extract complex details which remain hidden from expert human observers. The model demonstrates consistent performance across all ethnic and geographic groups in Uzbekistan which indicates its ability to function effectively in multiple population groups. The application requires this feature because Uzbekistan represents a country with multiple ethnic groups.

**T**he research proved that AI-powered retinal image analysis functions as a quick and precise blood pressure estimation tool which can differentiate blood pressure types and assess cardiovascular disease risk. The Residual Network model developed by researchers achieved performance results that matched standard medical testing methods which produced a mean absolute error of 4.8 mmHg for systolic blood pressure and showed 84% accuracy in subtype classification. The system realizes non-invasive patient detection by achieving 78% accuracy in detecting nocturnal blood pressure patterns which helps identify patients who show non-dipper and high-risk blood pressure patterns. The technology demonstrates long-term risk evaluation capacity through its AUC value of 0.85 which exceeds traditional Framingham model results to predict five-year complication risk.

The model outperforms experienced ophthalmologists because it operates at extremely fast speeds which makes it suitable for screening multiple patients simultaneously. The model demonstrated consistent performance across various population subgroups in Uzbekistan, which indicates its ability to function in different population groups. The study found that retinal vascular characteristics show a strong link to blood pressure parameters which demonstrates that the retina can function as a diagnostic tool for systemic vascular health assessment that provides crucial information about hemodynamic conditions and future risk.

The study results show that the developed AI model should function as a primary screening instrument which detects undiagnosed hypertension cases within the general population. The model enables medical professionals to classify patients who have hypertension into different categories while detecting those who need advanced medical treatment. The next step to make this technology usable in hospitals requires researchers to conduct prospective studies which will test the model's predictive capabilities and assess its effectiveness in actual medical situations. The creation of smartphone and portable device compatible versions will enable underserved communities in Uzbekistan and other nations to access this technology.

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