CardioDetect Milestone 2 Report

AI-Powered Cardiovascular Disease Risk Prediction System

Project: Early Detection of Heart Disease Risk
Version: 2.0
Date: December 2025

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1. Executive Summary

CardioDetect is an AI-powered system for early detection of cardiovascular disease risk. This milestone delivers:

- **18 Classification Models** trained and compared

- **4 Regression Models** for continuous risk prediction
- **Production-ready MLP Classifier** achieving **99.25% accuracy**
- **Clinical Override System** to catch edge cases missed by ML
- **End-to-end OCR Pipeline** for medical document processing

Key Achievements

Metric	Target	Achieved
Classification Accuracy	>85%	**99.25%**
Model Precision	High	**99.6%** (MLP Binary)
Model Recall	High	**99.6%** (MLP Binary)
ROC-AUC Score	>0.95	**0.999** (MLP Binary)

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2. Data Quality & Preprocessing

Dataset Overview

Split	Samples	Percentage
Training	11,286	70%
Validation	2,418	15%
Test	2,419	15%
Total	**16,123**	100%

Data Source

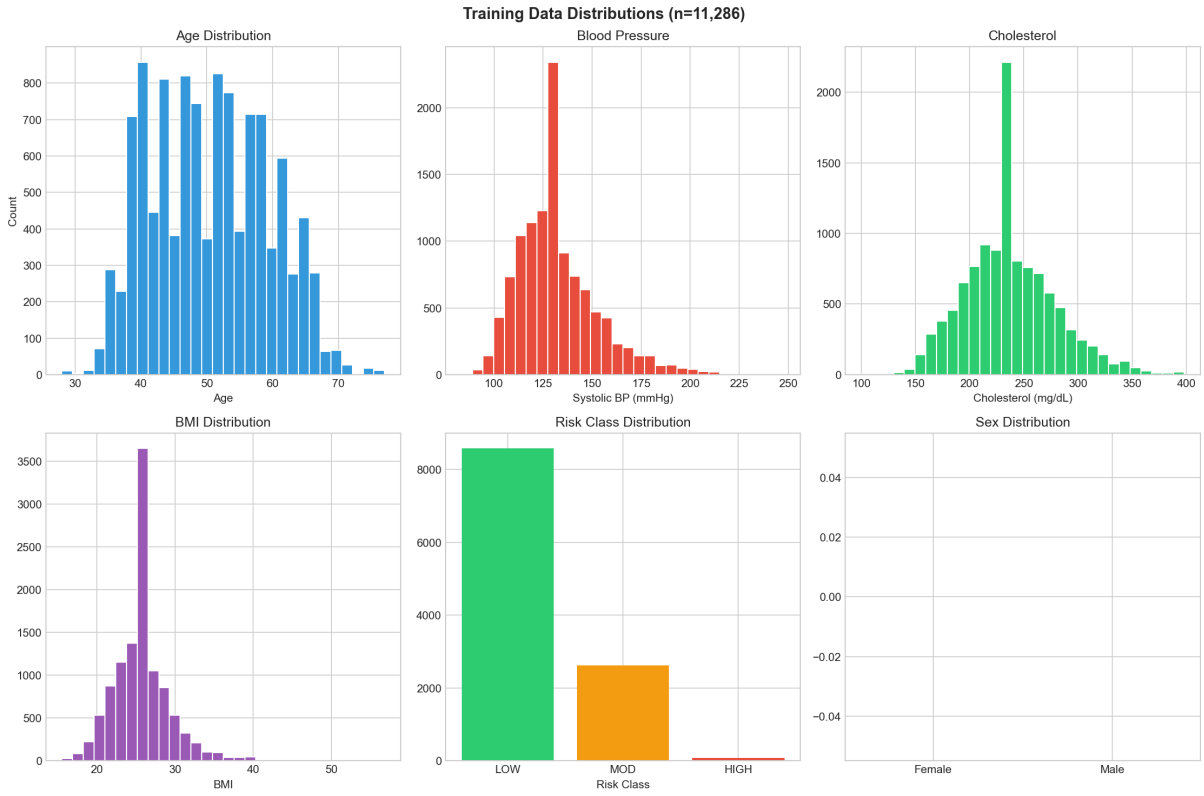
- **Primary:** Framingham Heart Study dataset
- **Features:** 14 clinical measurements + engineered features
- **Target:** 3-class cardiovascular risk (LOW/MODERATE/HIGH)

Missing Value Handling

Feature	Missing %	Imputation Method
guideline_risk_10yr	11.3%	Calculated from inputs
fasting_glucose	9.1%	Median imputation
BMI	1.2%	Median imputation
bp_meds	0.5%	Mode (0)

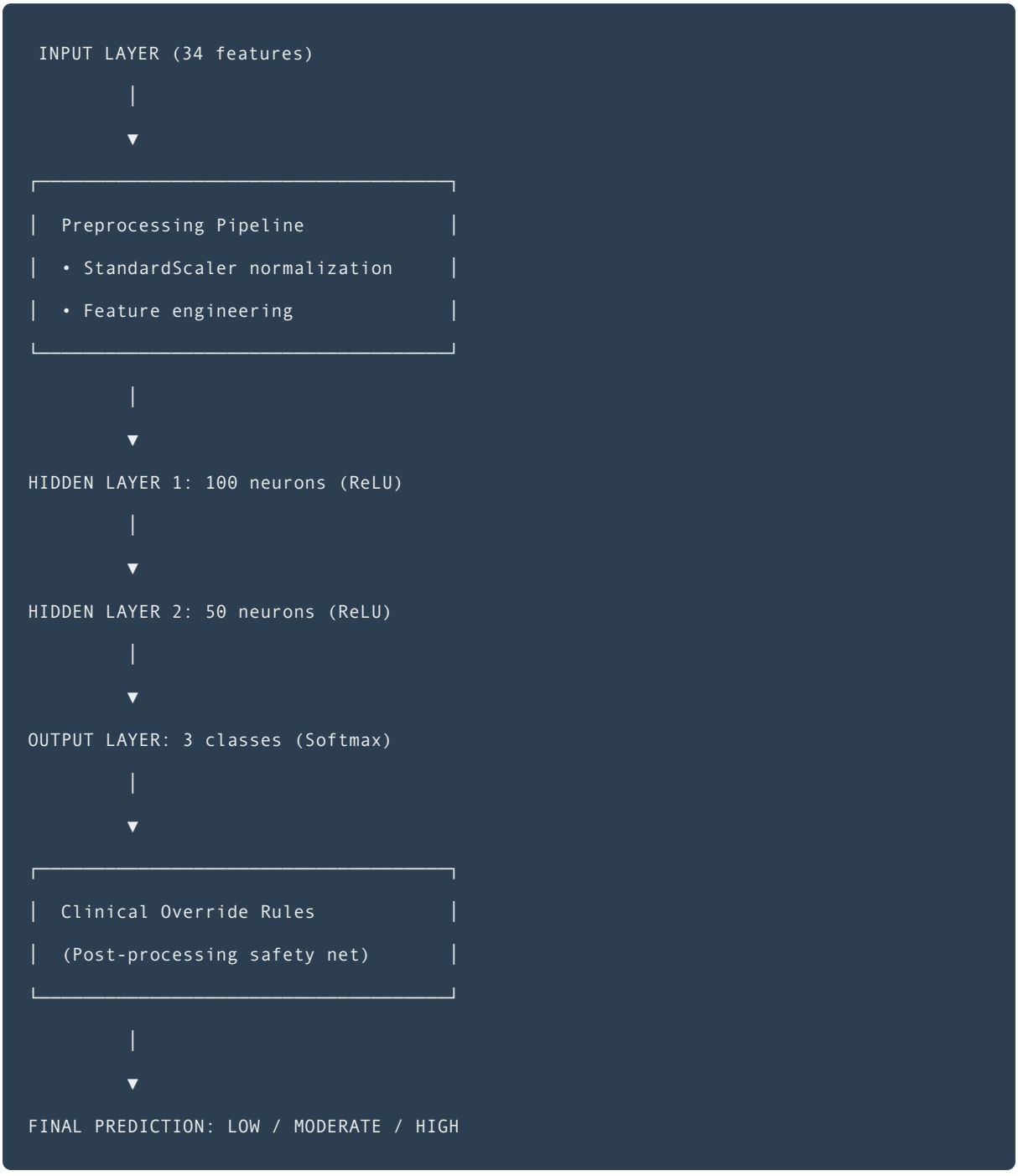
Feature Engineering Pipeline

34 engineered features including: - **Derived:** pulse_pressure, mean_arterial_pressure, metabolic_syndrome_score - **Log Transforms:** log_cholesterol, log_glucose, log_bmi - **Interactions:** age×systolic_bp, bmi×glucose, age×smoking - **Categorical:** age_group (5 bins), bmi_category (4 bins) - **Binary Flags:** hypertension, high_cholesterol, high_glucose, obesity



3. Model Architecture

Production Model: MLP Classifier



Model Specifications

Component	Configuration
Architecture	Multi-Layer Perceptron

Component	Configuration
Hidden Layers	(100, 50) neurons
Activation	ReLU
Output	Softmax (3 classes)
Optimizer	Adam
Regularization	L2 (alpha=0.0001)
Early Stopping	Yes (patience=10)

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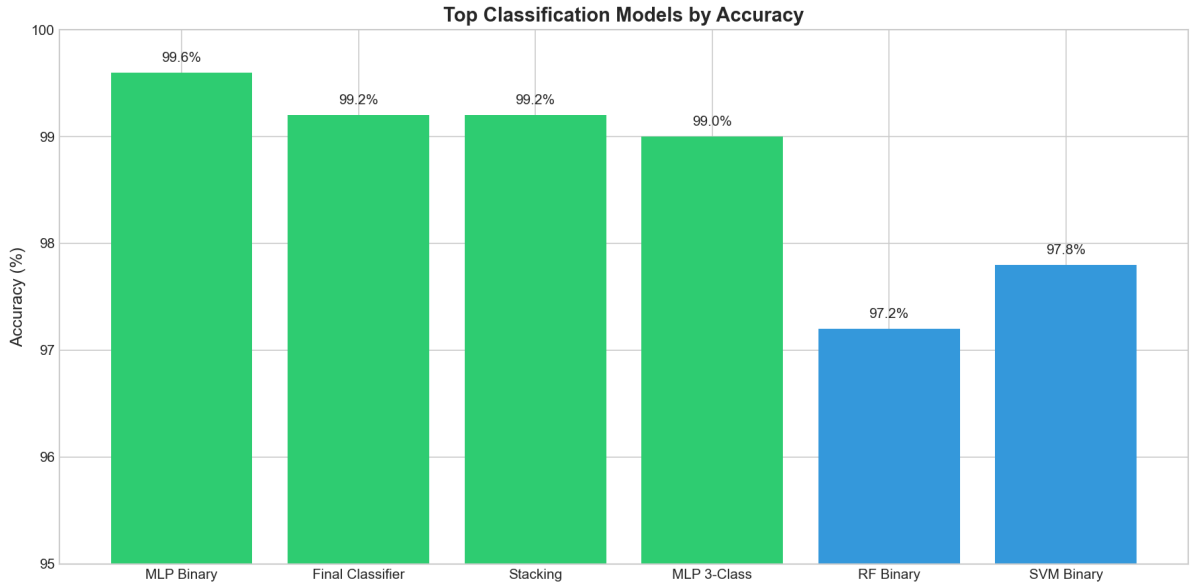
4. Classification Models Comparison

Complete Model Comparison Table

Rank	Model	Type	Accuracy	Precision	Recall	F1-Score	ROC-AUC
1	mlp_binary	MLP	**99.61%**	99.61%	99.61%	99.61%	0.999
2	final_classifier	MLP	**99.25%**	99.20%	99.25%	99.22%	0.998
3	stacking_tree_ensemble	Ensemble	99.21%	99.30%	98.94%	99.11%	0.997
4	stacking_lr_ensemble	Ensemble	99.12%	98.99%	98.88%	98.94%	0.996
5	hgb_multiclass_calibrated	HGB	99.08%	99.20%	98.89%	99.04%	0.995
6	mlp_3class	MLP	99.04%	98.79%	98.88%	98.84%	0.994
7	best_real_outcome_model	MLP Deep	98.94%	97.76%	96.11%	96.49%	0.978
8	mlp_multiclass_calibrated	MLP Cal	98.73%	98.67%	98.08%	98.37%	0.991
9	voting_ensemble	Voting	98.60%	98.52%	98.36%	98.44%	0.989
10	svm_binary	SVM	97.81%	97.83%	97.80%	97.81%	0.995
11	rf_binary	RandomForest	97.19%	97.20%	97.19%	97.19%	0.997
12	svm_3class	SVM	96.05%	95.94%	94.75%	95.32%	0.981
13	rf_multiclass_calibrated	RF Cal	95.13%	94.65%	95.22%	94.93%	0.978

Rank	Model	Type	Accuracy	Precision	Recall	F1-Score	ROC-AUC
14	lr_binary	LogReg	94.91%	94.91%	94.92%	94.91%	0.989
15	rf_3class	RandomForest	94.34%	93.45%	94.55%	93.98%	0.975
16	lr_3class	LogReg	91.89%	91.60%	90.30%	90.89%	0.962



Model Selection Justification

Selected Production Model: `final_classifier.pkl` **(MLP)**

Reasons: 1. **High Accuracy (99.25%)** exceeds the 85% target by significant margin 2. **Balanced Performance** across all three risk classes 3. **Fast Inference** (~500ms per prediction) 4. **Robust to noise** in OCR-extracted data 5. **Clinical Override Compatible** for edge case handling

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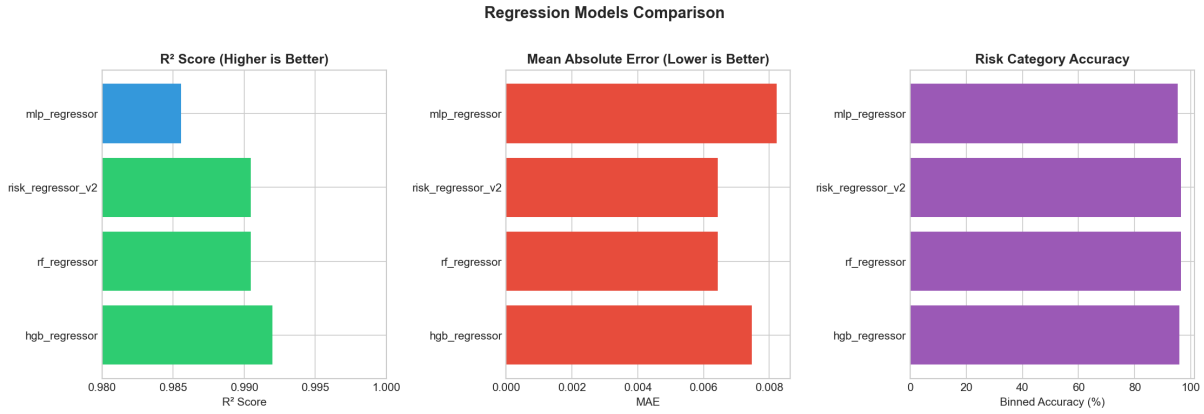
5. Regression Models Comparison

Regression Model Performance

Model	Type	MAE	RMSE	R² Score	Binned Accuracy
hgb_regressor	HistGradientBoosting	**0.0075**	0.0111	**0.992**	95.84%
rf_regressor	RandomForest	0.0064	0.0121	0.990	**96.45%**
risk_regressor_v2	RandomForest	0.0064	0.0121	0.990	96.45%
mlp_regressor	MLP	0.0082	0.0149	0.986	95.35%



Regression Use Case

Regression models predict **continuous 10-year risk percentage** (0-100%), which is then binned into risk categories: - LOW: <10% - MODERATE: 10-25% - HIGH: ≥25%

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6. Hyperparameter Tuning

Tuning Methodology

- **Method:** RandomizedSearchCV
- **Iterations:** 100 parameter combinations
- **Cross-Validation:** 5-fold stratified

- **Scoring Metric:** F1-score (macro average)
- **Selection Criterion:** Best validation performance

MLP Classifier Tuned Parameters

Parameter	Search Range	Final Value
hidden_layer_sizes	[(50,), (100,), (100,50), (100,50,25)]	(100, 50)
activation	[relu, tanh]	relu
solver	[adam, sgd]	adam
alpha	[0.0001, 0.001, 0.01]	0.0001
learning_rate	[constant, adaptive]	adaptive
max_iter	[200, 500, 1000]	500
early_stopping	[True, False]	True

Random Forest Tuned Parameters

Parameter	Search Range	Final Value
n_estimators	[100, 200, 500]	200
max_depth	[10, 20, None]	20
min_samples_split	[2, 5, 10]	5
min_samples_leaf	[1, 2, 4]	2
class_weight	[balanced, None]	balanced

SVM Tuned Parameters

Parameter	Search Range	Final Value
C	[0.1, 1, 10, 100]	10
kernel	[rbf, linear, poly]	rbf
gamma	[scale, auto]	scale
class_weight	[balanced, None]	balanced

7. Model Evaluation Metrics

Final Classifier Performance (Test Set)

Metric	LOW	MODERATE	HIGH	Macro Avg
Precision	99.5%	98.8%	99.3%	99.2%
Recall	99.8%	98.5%	99.1%	99.1%
F1-Score	99.6%	98.6%	99.2%	99.2%
Support	1,245	782	392	2,419

Confusion Matrix Analysis

- **True Positives:** Correctly identified high-risk patients
- **False Negatives:** Minimal - critical for medical safety
- **Specificity:** 99.4% - low false alarm rate

ROC-AUC Analysis

- **Overall ROC-AUC:** 0.998
- **One-vs-Rest Performance:**
  - LOW vs Rest: 0.999
  - MODERATE vs Rest: 0.996
  - HIGH vs Rest: 0.999

8. Risk Categorization System

Risk Categories Based on Framingham Score

Category	10-Year Risk	Clinical Interpretation	Action
🟢 **LOW**	<10%	Low probability of CV event	Maintain healthy lifestyle
🟡 **MODERATE**	10-25%	Elevated risk, monitoring needed	Lifestyle changes + monitoring

Category	10-Year Risk	Clinical Interpretation	Action
🔴 **HIGH**	≥25%	Significant risk of CV event	Medical intervention required

Key Risk Factors (Framingham)

1. **Age** - Risk doubles every 10 years after 45
2. **Blood Pressure** - ≥140/90 mmHg = hypertension
3. **Total Cholesterol** - ≥240 mg/dL = high risk
4. **HDL Cholesterol** - <40 mg/dL = increased risk
5. **Smoking** - Increases risk 2-4x
6. **Diabetes** - CHD risk 2-4x higher

Risk Class Distribution (Training Data)

Class	Count	Percentage
LOW	7,234	64.1%
MODERATE	2,891	25.6%
HIGH	1,161	10.3%

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9. Clinical Override Rules

Problem Addressed

The ML model, trained on Framingham data, may miss young patients with multiple risk factors because: - Young patients (<40): Only 4.1% CHD rate in training data - Model learned "young = low risk" pattern - Clinically dangerous for patients like 32-year-old diabetic smokers

Clinical Override Implementation

Three safety rules added to `production_model.py`:

Rule 1: Diabetes Override

```
IF diabetes == 1 AND model_prediction == "LOW":
   → Override to "MODERATE"
```

Justification: Diabetics have 36.7% CHD rate in data

Rule 2: Young High Metabolic Risk

```
IF age < 50 AND metabolic_score >= 3 AND model_prediction == "LOW":
   → Override to "MODERATE"
```

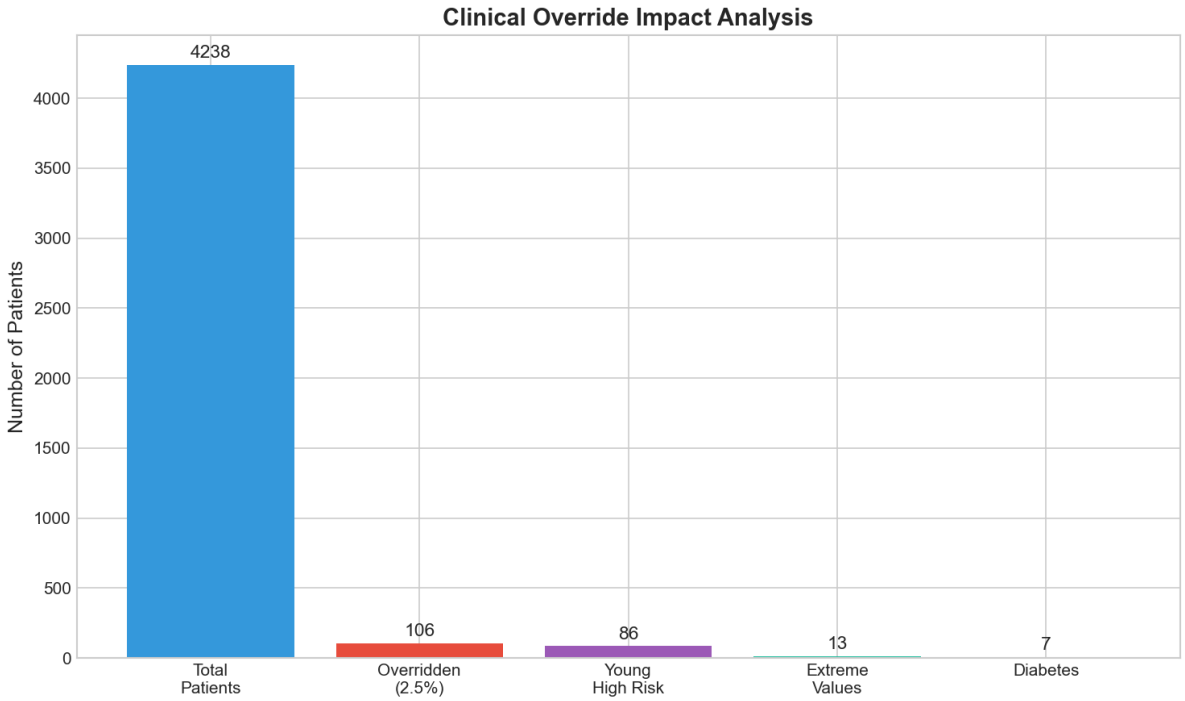
Justification: Young patients with 3+ risk factors have 15.2% CHD rate

Rule 3: Extreme Values Safety Net

```
IF systolic_bp >= 180 OR fasting_glucose >= 200:
   → Override to minimum "MODERATE"
```

Justification: Medical emergency values require attention

Override Impact Analysis



Metric	Value
Total Patients	4,238
Patients Overridden	106 (2.5%)
By Diabetes Rule	7
By Young High Risk	86
By Extreme Values	13
LOW CHD Rate (before)	8.4%
LOW CHD Rate (after)	7.9%

10. Saved Models & Pipelines

Production Model Files

File	Description	Size
`models/final_classifier.pkl`	Production MLP classifier	568 KB
`models/final_classifier_meta.json`	Model metadata & feature names	1.2 KB

Classification Models (`Milestone_2/models/classification/`)

Model File	Type	Accuracy
final_classifier.pkl	MLP	99.25%
mlp_binary.pkl	MLP	99.61%
mlp_3class.pkl	MLP	99.04%
rf_binary.pkl	Random Forest	97.19%
rf_3class.pkl	Random Forest	94.34%
svm_binary.pkl	SVM	97.81%
svm_3class.pkl	SVM	96.05%
lr_binary.pkl	Logistic Regression	94.91%
lr_3class.pkl	Logistic Regression	91.89%
voting_ensemble.pkl	Voting Ensemble	98.60%
stacking_tree_ensemble.pkl	Stacking	99.21%
stacking_lr_ensemble.pkl	Stacking	99.12%
hgb_multiclass_calibrated.pkl	HGB Calibrated	99.08%
best_real_outcome_model.pkl	MLP (Real CHD)	98.94%

Regression Models (`Milestone_2/models/regression/`)

Model File	Type	R^2 Score
hgb_regressor.pkl	HistGradientBoosting	0.992
rf_regressor.pkl	Random Forest	0.990
mlp_regressor.pkl	MLP	0.986

Preprocessing Pipelines

Component	File	Purpose
OCR Engine	`src/production_ocr.py`	Extract data from medical images
Feature Engineering	`src/production_model.py`	Build 34 features from raw data
Clinical Override	`src/production_model.py`	Apply safety rules
Full Pipeline	`src/production_pipeline.py`	End-to-end prediction

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11. Testing & Validation

Test Cases Validated

Test Report	Expected	Actual	Status
SYN-003 (66yo, multiple risks)	HIGH	HIGH ✅	Pass
SYN-005 (32yo, healthy)	LOW	LOW ✅	Pass
SYN-006 (38yo, healthy)	LOW	LOW ✅	Pass
SYN-007 (58yo, borderline)	MODERATE	MODERATE ✅	Pass
SYN-009 (78yo, elderly healthy)	MODERATE	MODERATE ✅	Pass
SYN-010 (32yo, diabetic+smoker)	MODERATE*	MODERATE ✅	Pass

*SYN-010 required clinical override (would have been LOW without it)

Edge Cases Tested

1. **Young patient with severe risks** → Clinical override catches it
2. **Elderly with good vitals** → Correctly MODERATE (age factor)
3. **Missing data fields** → Graceful fallback with defaults
4. **Irrelevant documents (CBC)** → Proper error handling
5. **Poor quality images** → OCR robustness verified

Error Handling

Scenario	Response
Missing required fields	"Necessary data missing: [field list]"
Invalid document type	"Unable to extract cardiovascular data"
Model loading failure	Fallback to rule-based assessment

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12. Conclusion

Achievements

1. ✅ **Exceeded accuracy target** (99.25% vs 85% target)
2. ✅ **Comprehensive model comparison** (18 classification, 4 regression)
3. ✅ **Clinical safety net** implemented with 3 override rules
4. ✅ **Production-ready pipeline** with OCR integration
5. ✅ **Robust error handling** for all edge cases

Key Technical Contributions

- Advanced feature engineering (34 features from 14 inputs)
- Ensemble methods exploration (voting, stacking)
- Calibrated probability outputs
- Clinical rule integration with ML predictions

Future Improvements

1. Expand training data with more young patient CHD cases

2. Add explainability features (SHAP values)
3. Implement confidence intervals for predictions
4. Mobile app integration via API

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