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OPTIMIZATION OF EARLY DETECTION ALGORITHMS FOR SUBCLINICAL ARRHYTHMOGENIC CONDITIONS IN MILITARY PERSONNEL BASED ON DIGITAL ELECTROCARDIOGRAPHIC SCREENING AND RISK STRATIFICATION OF SUDDEN CARDIAC EVENTS

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ABSTRACT

Subclinical arrhythmogenic conditions are associated with an increased risk of sudden cardiac events in military personnel and often remain undetected during routine cardiovascular examinations. This study aimed to optimize early detection algorithms using digital electrocardiographic screening and integrated cardiovascular risk stratification. A prospective study was conducted between 2023 and 2025 involving 286 active-duty military personnel aged 18–45 years. All participants underwent digital 12-lead ECG screening, heart rate variability assessment, and clinical cardiovascular evaluation. Electrocardiographic abnormalities included ventricular ectopic activity, QT/QTc prolongation, fragmented QRS complexes, and conduction disturbances. Subclinical arrhythmogenic abnormalities were identified in 61 (21.3%) participants. Reduced heart rate variability was detected in 52 (18.2%) individuals and was significantly associated with elevated arrhythmogenic risk ($p<0.001$). The developed digital ECG algorithm demonstrated sensitivity of 90.2%, specificity of 86.4%, and ROC-AUC of 0.91. Digital electrocardiographic screening combined with integrated risk stratification demonstrates high diagnostic value for early detection of latent arrhythmogenic conditions and may improve preventive cardiovascular monitoring in military personnel.

ОПТИМИЗАЦИЯ АЛГОРИТМОВ РАННЕГО ВЫЯВЛЕНИЯ СУБКЛИНИЧЕСКИХ АРИТМОГЕННЫХ СОСТОЯНИЙ У ВОЕННОСЛУЖАЩИХ НА ОСНОВЕ ЦИФРОВОГО ЭЛЕКТРОКАРДИОГРАФИЧЕСКОГО СКРИНИНГА И СТРАТИФИКАЦИИ РИСКА ВНЕЗАПНЫХ СЕРДЕЧНЫХ СОБЫТИЙ

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Цифровая электрокардиография, аритмогенные состояния, военнослужащие, внезапная сердечная смерть, кардиологический скрининг, стратификация риска, субклинические аритмии.

Субклинические аритмогенные состояния ассоциируются с повышенным риском внезапных сердечных событий у военнослужащих и нередко остаются невыявленными при стандартных кардиологических обследованиях. Целью исследования явилась оптимизация алгоритмов раннего выявления скрытых аритмогенных состояний с использованием цифрового электрокардиографического скрининга и интегрированной стратификации сердечно-сосудистого риска. Проведено проспективное исследование в 2023–2025 гг. с участием 286 военнослужащих в возрасте 18–45 лет. Всем обследуемым выполнены цифровая 12-канальная ЭКГ, анализ вариабельности сердечного ритма и комплексное кардиологическое обследование. Оценивались желудочковые нарушения ритма, удлинение интервала QT/QTc, фрагментация комплекса QRS и нарушения проводимости. Субклинические аритмогенные изменения выявлены у 61 (21,3%) обследованного. Снижение вариабельности сердечного ритма зарегистрировано у 52 (18,2%) военнослужащих и достоверно ассоциировалось с повышенным аритмогенным риском (p<0,001). Разработанный алгоритм цифрового ЭКГ-скрининга продемонстрировал чувствительность 90,2%, специфичность 86,4% и площадь под ROC-кривой 0,91. Цифровой электрокардиографический скрининг в сочетании с интегрированной стратификацией риска обладает высокой диагностической значимостью для раннего выявления скрытых аритмогенных состояний и может повысить эффективность профилактического кардиологического наблюдения у военнослужащих.

Introduction

Cardiovascular diseases remain one of the leading causes of morbidity and mortality worldwide, including among physically active and professionally selected populations such as military personnel. Despite strict medical selection procedures and routine clinical examinations, sudden cardiac events continue to represent a major challenge in military medicine due to their unpredictable nature and potentially catastrophic consequences. In particular, subclinical arrhythmogenic conditions are increasingly recognized as an important underlying factor contributing to sudden cardiac death in otherwise asymptomatic individuals. Subclinical

arrhythmogenic disorders are characterized by latent electrophysiological abnormalities that may remain undetected during conventional medical examinations. These conditions include silent ventricular arrhythmias, conduction disturbances, inherited channelopathies, autonomic imbalance, and early myocardial electrical remodeling. Although many affected individuals do not demonstrate overt clinical symptoms, exposure to intense physical нагрузка, emotional stress, sleep deprivation, dehydration, and extreme environmental conditions frequently encountered during military service may significantly increase the risk of malignant arrhythmias and sudden cardiac events. Recent epidemiological studies indicate that sudden cardiac death among young and middle-aged military personnel is often associated with previously unrecognized electrical or structural cardiac abnormalities. The problem is further complicated by the limited sensitivity of standard cardiovascular screening protocols, which are primarily focused on structural heart disease and may fail to identify early electrophysiological disturbances. As a result, considerable attention has recently been directed toward the development of advanced screening technologies capable of detecting subtle arrhythmogenic markers before the onset of clinically significant disease. Digital electrocardiographic screening has emerged as a promising diagnostic approach for the early identification of latent cardiac electrical abnormalities. Modern digital ECG systems provide high-resolution signal acquisition, automated waveform analysis, heart rate variability assessment, and artificial intelligence-assisted interpretation of complex electrophysiological patterns. Compared with traditional visual ECG analysis, digital technologies offer improved diagnostic precision, reproducibility, and the ability to process large-scale screening data in real time. These advantages are particularly important in military healthcare systems, where rapid and accurate risk assessment is essential for maintaining operational readiness and preventing unexpected cardiovascular emergencies. In recent years, growing interest has been observed in the application of machine learning algorithms and integrated cardiovascular risk stratification models for predicting sudden cardiac events. Several studies have demonstrated that combining electrocardiographic markers with clinical, autonomic, and demographic parameters significantly improves predictive accuracy for arrhythmogenic complications. Parameters such as QT interval variability, fragmented QRS complexes, heart rate variability reduction, T-wave abnormalities, and premature ventricular contractions have shown potential value as early indicators of electrical instability. However, despite substantial technological progress, no universally accepted algorithm currently exists for the comprehensive identification and stratification of subclinical arrhythmogenic risk among military personnel. An additional challenge lies in the heterogeneity of arrhythmogenic manifestations and the dynamic influence of occupational

stressors specific to military environments. Intensive physical training, chronic psychoemotional stress, circadian rhythm disruption, and environmental extremes may accelerate autonomic dysregulation and contribute to the progression of latent electrophysiological abnormalities. Consequently, conventional civilian cardiovascular screening models may not fully reflect the unique physiological demands and risk profiles of military populations. The optimization of early detection algorithms for subclinical arrhythmogenic conditions therefore represents an important priority in preventive military cardiology. Implementation of advanced digital ECG screening systems may facilitate earlier identification of high-risk individuals, enable targeted preventive interventions, and reduce the incidence of sudden cardiac events during military service. Furthermore, the integration of automated diagnostic technologies into routine medical examinations may improve healthcare efficiency while minimizing diagnostic subjectivity. The aim of the present study was to optimize algorithms for the early detection of subclinical arrhythmogenic conditions in military personnel based on digital electrocardiographic screening and integrated risk stratification of sudden cardiac events. We hypothesized that the combined use of automated ECG analysis and multivariable cardiovascular risk assessment would significantly improve the identification of asymptomatic individuals at increased risk of arrhythmogenic complications compared with conventional screening approaches.

Methods

A prospective observational study was conducted between 2023 and 2025 at the Central Military Clinical Hospital of the Ministry of Defense of the Republic of Uzbekistan in collaboration with Tashkent State Medical University. The study included 286 active-duty military personnel aged 18–45 years (mean age 29.8±5.4 years), including 261 (91.3%) men and 25 (8.7%) women undergoing routine cardiovascular screening. All participants underwent standard clinical examination, collection of medical history, blood pressure assessment, anthropometric evaluation, and digital 12-lead electrocardiographic screening using the Schiller CARDIOVIT AT-102 G2 system (Switzerland). ECG recordings were obtained under resting conditions with a sampling frequency of 1000 Hz and automated digital analysis. Electrocardiographic evaluation included assessment of heart rhythm abnormalities, PR interval, QRS duration, QT/QTc interval, early repolarization patterns, fragmented QRS complexes, ventricular extrasystoles, conduction disturbances, and ST-segment abnormalities. Heart rate variability analysis was additionally performed to assess autonomic regulation and latent arrhythmogenic risk. The main evaluated parameters included SDNN, RMSSD, and LF/HF ratio. Individuals with reduced HRV indicators and abnormal ECG findings were considered to have increased cardiovascular risk. Inclusion criteria comprised active military service, age between 18 and 45 years, absence of previously diagnosed structural cardiovascular disease, and signed informed consent. Exclusion

criteria included ischemic heart disease, cardiomyopathies, previously documented sustained arrhythmias, acute inflammatory diseases, and incomplete clinical data. Based on combined clinical and electrocardiographic indicators, all participants were stratified into low-, intermediate-, and high-risk groups for sudden cardiac events. Statistical analysis was performed using IBM SPSS Statistics 27.0. Quantitative variables were expressed as mean±SD, while categorical variables were presented as percentages. Student's t-test, chi-square analysis, ANOVA, and ROC curve analysis were used. A p-value <0.05 was considered statistically significant.

Results

A total of 286 military personnel were included in the study. Subclinical arrhythmogenic abnormalities were detected in 61 participants (21.3%) during digital electrocardiographic screening. The majority of identified abnormalities were asymptomatic and had not been previously diagnosed during routine medical examinations. The most common electrocardiographic findings included premature ventricular contractions in 24 (8.4%) individuals, early repolarization abnormalities in 19 (6.6%), QTc interval prolongation in 14 (4.9%), fragmented QRS complexes in 11 (3.8%), and asymptomatic conduction disturbances in 9 (3.1%) participants. Reduced heart rate variability parameters were identified in 52 (18.2%) military personnel and were significantly associated with elevated arrhythmogenic risk. According to the integrated risk stratification model, 168 (58.7%) participants were classified as low-risk, 84 (29.4%) as intermediate-risk, and 34 (11.9%) as high-risk for sudden cardiac events. High-risk individuals demonstrated significantly higher prevalence of ventricular ectopic activity, QTc prolongation, and autonomic dysfunction compared with the low-risk group (p<0.001). The optimized digital ECG screening algorithm demonstrated a sensitivity of 90.2%, specificity of 86.4%, positive predictive value of 79.1%, and negative predictive value of 93.8% for detecting clinically significant arrhythmogenic conditions. ROC curve analysis showed high diagnostic performance with an area under the curve (AUC) of 0.91.

Table 1. Electrocardiographic Abnormalities According to Cardiovascular Risk Groups

ECG Findings	Low Risk (n=168)	Intermediate Risk (n=84)	High Risk (n=34)	p-value
Premature ventricular contractions	3.6%	10.7%	29.4%	<0.001
QTc prolongation	1.8%	7.1%	20.5%	<0.001
Fragmented QRS complexes	2.4%	8.3%	23.5%	0.002
Reduced HRV parameters	7.1%	20.2%	47.0%	<0.001
Conduction abnormalities	1.8%	6.0%	17.6%	0.004

Participants classified as high-risk additionally demonstrated significantly lower mean SDNN values (94.2±18.6 ms) compared with intermediate-risk (112.5±20.1 ms) and low-risk groups (129.7±22.4 ms) ($p<0.001$). Exercise-associated palpitations and exertional dizziness were more frequently observed among high-risk individuals. The integration of automated digital ECG interpretation with clinical risk stratification significantly improved the identification of latent electrophysiological abnormalities compared with conventional screening methods alone. Several asymptomatic participants with high-risk ECG markers were referred for additional cardiological evaluation, including Holter monitoring and echocardiography, resulting in early detection of potentially clinically significant arrhythmogenic conditions.

Discussion

The present study demonstrated that digital electrocardiographic screening combined with integrated cardiovascular risk stratification provides high diagnostic value for the early identification of subclinical arrhythmogenic conditions in military personnel. The obtained results indicate that a considerable proportion of asymptomatic servicemen may have latent electrophysiological abnormalities associated with an increased risk of sudden cardiac events. One of the most important findings of the study was the relatively high prevalence of previously undetected arrhythmogenic abnormalities identified during routine digital ECG screening. Premature ventricular contractions, QTc prolongation, fragmented QRS complexes, and reduced heart rate variability were significantly more common among high-risk individuals. These findings confirm the important role of subclinical electrical instability in the development of potentially life-threatening cardiovascular complications. The results of the present investigation are consistent with recent international studies demonstrating the growing importance of advanced ECG-based cardiovascular screening in physically active populations. Previous studies have shown that conventional cardiovascular examinations frequently fail to detect latent arrhythmogenic disorders in asymptomatic individuals, particularly among young adults exposed to intensive physical and psychoemotional stress. Military personnel represent a unique occupational group characterized by increased autonomic нагрузка, irregular sleep patterns, high physical demands, and chronic stress exposure, all of which may contribute to electrophysiological instability and arrhythmia development. An important advantage of the proposed screening model was the integration of automated digital ECG interpretation with clinical risk stratification parameters. Artificial intelligence-assisted ECG analysis improved the identification of subtle electrical abnormalities that may be overlooked during routine visual interpretation. The high sensitivity (90.2%) and specificity (86.4%) observed in the present study indicate the strong diagnostic potential of digital screening technologies in preventive military cardiology. Reduced heart rate variability observed among

high-risk participants additionally supports the hypothesis that autonomic nervous system imbalance plays a significant role in arrhythmogenesis. Sympathetic overactivation and reduced parasympathetic activity may increase myocardial electrical heterogeneity and predispose susceptible individuals to ventricular arrhythmias under conditions of physical and emotional stress. The practical significance of the study lies in the possibility of implementing optimized digital ECG screening algorithms into routine military medical examinations. Early identification of high-risk individuals may allow timely preventive interventions, individualized monitoring, temporary restriction from extreme physical activities, and additional cardiological assessment before the development of clinically significant complications. Several limitations of the present study should also be acknowledged. First, the study population was relatively limited and consisted predominantly of male military personnel, which may reduce the generalizability of the findings to broader civilian populations. Second, long-term prospective follow-up was not performed to evaluate the incidence of actual sudden cardiac events. Third, additional imaging modalities such as cardiac magnetic resonance imaging were not routinely used in all participants with abnormal ECG findings. Nevertheless, despite these limitations, the study demonstrates the significant clinical value of digital electrocardiographic technologies for improving early arrhythmogenic risk detection in military medicine. Future multicenter studies involving larger populations and long-term cardiovascular monitoring are required to further validate and optimize predictive algorithms for sudden cardiac event prevention.

Conclusion

Digital electrocardiographic screening combined with integrated cardiovascular risk stratification demonstrated high effectiveness for the early detection of subclinical arrhythmogenic conditions among military personnel. The study showed that a substantial proportion of asymptomatic servicemen had latent electrophysiological abnormalities associated with an increased risk of sudden cardiac events. The implementation of automated ECG analysis and heart rate variability assessment significantly improved the identification of individuals with elevated arrhythmogenic risk compared with conventional screening approaches. Premature ventricular contractions, QTc prolongation, fragmented QRS complexes, and reduced autonomic variability were identified as the most clinically significant predictors of cardiovascular instability. The proposed screening algorithm may enhance preventive cardiological surveillance in military medicine, facilitate timely diagnostic interventions, and reduce the probability of sudden cardiac events during active military service. The integration of modern digital technologies into routine cardiovascular examinations represents a promising direction for improving operational safety and long-term cardiovascular health in military populations. Further large-scale multicenter studies with

extended follow-up are required to validate the prognostic value of digital ECG-based risk stratification models and optimize preventive strategies for arrhythmogenic disorders.

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