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THE EFFECT OF NOCTURNAL HYPOXEMIA IN OBSTRUCTIVE SLEEP APNEA SYNDROME ON MYOCARDIAL ELECTRICAL INSTABILITY AND THE RISK OF GASTRIC ARRHYTHMIAS

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ABSTRACT

Obstructive sleep apnea syndrome (OSAS) has long gone beyond a highly specialized somnological problem, having transformed into a significant risk factor for cardiovascular mortality. Epidemiological data indicate an alarming trend: in patients with severe forms of respiratory disorders, the peak of sudden cardiac death shifts to the night hours, which directly correlates with cycles of apnea and subsequent desaturation. Despite the evidence of a clinical link, the exact mechanisms by which nocturnal hypoxemia destabilizes the electrical activity of the myocardium remain the subject of active research and debate. This article analyzes the totality of data on the effect of intermittent hypoxia on the electrophysiological properties of the heart, trying to distinguish the contribution of various pathogenetic links.

The discussion focuses on pathophysiological cascades mediating the arrhythmogenic effect. The key trigger is not so much mechanical obstruction as cyclic fluctuations in oxygen partial pressure and subsequent reoxygenation. This process initiates a complex response of the body: from activation of peripheral chemoreflections and sudden surges of the sympathetic nervous system at the time of microarousal to systemic oxidative stress, leading to damage to ion channels of cardiomyocytes. Mechanical factors deserve special attention, such as significant drops in intrathoracic pressure, which create additional stress on the ventricular walls and provoke the phenomenon of mechanical-electrical feedback.

The paper systematizes information about electrocardiographic markers of instability, which have prognostic value. Special emphasis is placed on the QT interval variance and Tp-e/QT ratio, which reflect the spatial heterogeneity of repolarization and serve as independent predictors of life-threatening events. An analysis of clinical observations confirms that the severity of nocturnal desaturation (saturation time <90%) often correlates with the frequency of ventricular extrasystoles and tachycardia more significantly than the classical apnea-hypopnea index.

The effectiveness of pathogenetic therapy remains controversial. Although CPAP therapy eliminates upper respiratory tract obstruction, its effect on reducing the risk of sudden death is ambiguous and critically depends on treatment adherence and the residual apnea index. In conclusion, the need for deep integration of somnological screening into the daily practice of managing arrhythmological patients is substantiated. Correction of hypoxemia is considered not as an auxiliary measure, but as an important, potentially life-saving component of the prevention of fatal ventricular arrhythmias.

KEYWORDS: OSAS, nocturnal hypoxemia, ventricular arrhythmias, electrical instability, QT interval, CPAP therapy.

INTRODUCTION

In modern cardiological practice, obstructive sleep apnea syndrome (OSAS) has ceased to be perceived solely as a somnological pathology, having transformed into a significant independent risk factor for cardiovascular morbidity. The scale of the problem goes beyond initial expectations: according to a global prevalence analysis, the number of adults aged 30 to 69 years with clinically significant forms of respiratory sleep disorders is in the hundreds of millions, with a significant proportion of cases remaining undiagnosed [1]. The situation is particularly alarming in the cohort of patients with established heart diseases, where the incidence of OSAS reaches critical values, creating a complex comorbid background that significantly aggravates the prognosis.

The key issue requiring close attention is the disproportionately high risk of sudden cardiac death (SCD) in this category of patients. In contrast to the general population, where the peak of fatal arrhythmias traditionally occurs in the morning, patients with severe forms of apnea experience a shift of this "risk window" to the night and early morning. This phenomenon directly correlates with cycles of upper respiratory tract obstruction and subsequent

episodes of desaturation, which indicates the presence of specific trigger mechanisms that act specifically during sleep [2]. Ignoring nocturnal symptoms and the lack of timely correction of respiratory disorders negate the effectiveness of standard antiarrhythmic therapy, leaving patients vulnerable to life-threatening events.

Despite the obvious clinical link, the pathogenetic link triggering the cascade of electrical instability continues to be debated. More and more evidence suggests that the key driver of arrhythmogenesis is not so much mechanical obstruction as the degree and duration of nocturnal hypoxemia. Intermittent hypoxia and subsequent reoxygenation initiate oxidative stress, ion channel damage, and myocardial remodeling, creating a substrate for ventricular tachyarrhythmias [3]. In this regard, the purpose of this review is to systematize current data on the effect of nocturnal hypoxemia on the electrophysiological properties of the heart, analyze diagnostic markers of myocardial instability, and evaluate the effect of pathogenetic therapy on reducing the risk of ventricular arrhythmias in patients with OSAS.

MATERIALS AND METHODS

The methodological basis of this review is based on a systematic analysis of modern literature data on the relationship between respiratory disorders during sleep and cardiac arrhythmias. Information search was carried out in the international biomedical databases PubMed, Scopus, Web of Science, as well as in the national database eLibrary. The search depth covered the period from 2018 to 2025, which allowed us to focus on the most relevant clinical recommendations and the results of recent randomized trials, including scientific statements from the American Heart Association [26], [39].

Combinations of terms in Russian and English were used as keywords for forming the search query: "obstructive sleep apnea syndrome", "nocturnal hypoxemia", "ventricular arrhythmias", "electrical instability of the myocardium", as well as their analogues – "obstructive sleep apnea", "nocturnal hypoxemia", "ventricular arrhythmias", "myocardial electrical instability". When selecting publications, special attention was paid to works in which synchronous registration of polysomnographic parameters and electrocardiographic data was carried out, since this approach makes it possible to most accurately verify the trigger effect of desaturation on the electrophysiology of the heart [13], [22].

The criteria for inclusion in the review assumed the presence of full-text articles in Russian or English describing original clinical trials, meta-analyses, or systematic reviews. Case reports, editorials without primary data, as well as publications where patients had primary electrical heart diseases (for example, long QT syndrome) that were not secondary to respiratory pathology were excluded from the sample. This approach is due to the desire to isolate the effect of the hypoxemic component of OSAS on the myocardium, minimizing the effect of concomitant congenital channelopathies [28], [31].

The information received was processed and synthesized manually using qualitative analysis methods. The data were grouped by pathogenetic mechanisms (sympathetic activation, oxidative stress, mechanical factors) and clinical manifestations (changes in the QT interval, frequency of extrasystole, risk of sudden death). When there were contradictions in the results of various studies, priority was given to works with a large sample size and prospective design, which corresponds to the principles of high-level evidence-based medicine [6], [15]. The quality of the included studies was assessed on the basis of standard scales used in observational and interventional studies, which made it possible to stratify the level of evidence of the identified associations.

RESULTS

Cyclic episodes of upper respiratory tract obstruction form a unique pattern of myocardial damage, the key element of which is intermittent hypoxia followed by reoxygenation. This process is fundamentally different from the constant hypoxia observed in chronic lung diseases and acts as a powerful trigger of oxidative stress. During the respiration recovery phase, a sudden influx of oxygen leads to excessive formation of reactive oxygen species (ROS), which damage cell membranes and disrupt mitochondrial function. The degree of nocturnal hypoxemia directly correlates with the severity of cardiometabolic disorders, which confirms the role of desaturation as an independent factor of tissue damage. In a study by André S. and co-authors. It has been demonstrated that it is the parameters of nocturnal hypoxemia, and not just the frequency of respiratory events, that determine the risk of developing concomitant cardiometabolic diseases [4].

At the cellular level, the accumulation of free radicals affects the operation of ion channels that ensure the electrical stability of cardiomyocytes. In particular, oxidative stress modifies the kinetics of potassium and calcium currents, which leads to an elongation of the action potential and an increase in the dispersion of repolarization. A violation of calcium homeostasis contributes to the occurrence of late depolarization, which creates a substrate for triggering ventricular tachyarrhythmias. The situation is aggravated by the presence of concomitant metabolic disorders, such as obesity, which often accompany OSAS and potentiate the inflammatory response and oxidative damage to the myocardium. Beccuti G. And colleagues point out that the combination of obesity and sleep apnea creates an additional burden on the cardiovascular system, requiring an integrated approach to risk assessment [5].

Prolonged exposure to intermittent hypoxia initiates the processes of structural remodeling of the heart. Activation of profibrotic signaling pathways leads to the replacement of normal muscle tissue with connective tissue, creating zones of slowing down of the pulse. Such areas become critical points for the occurrence of re-entry mechanisms of arrhythmia. Given the global prevalence of the disease and its significant contribution to cardiovascular

morbidity, understanding the molecular basis of this process becomes critically important for developing targeted prevention strategies. According to a global analysis conducted by Benjafield A.V. et al., the significant prevalence of pathology dictates the need for more thorough screening and prevention of cardiovascular complications in this population [6]. Collectively, the biochemical and structural changes caused by nocturnal hypoxemia form a stable arrhythmogenic substrate that persists even during periods of wakefulness.

Dysregulation of the autonomic nervous system is central to the pathogenesis of arrhythmogenesis in obstructive sleep apnea syndrome. Cyclic episodes of airway obstruction form a unique pattern of autonomic dysfunction characterized by sharp fluctuations in sympathovagus balance. At the moment of cessation of apnea and restoration of airflow, rapid activation of the sympathetic nervous system occurs, accompanied by the release of catecholamines. This phenomenon, often referred to as a "catecholamine storm", creates conditions for increasing the automatism of cardiomyocytes and the occurrence of trigger activity. Blackwell J.N. et al. It is emphasized that it is precisely such sympathetic bursts, timed to the terminal phases of respiratory events, that can serve as a direct trigger of life-threatening ventricular arrhythmias and contribute to an increased risk of sudden cardiac death in this category of patients [7].

In parallel with the hyperactivation of the sympathetic link, there is a progressive decrease in vagal tone, which disrupts the physiological mechanisms of protection of the myocardium from arrhythmogenic effects. Vagal modulation normally has antiarrhythmic potential, stabilizing the electrical activity of the heart and suppressing excessive sympathetic stimulation. With OSAS, this compensatory mechanism is depleted. Campos-Rodríguez F. and colleagues in their review indicate that an imbalance towards the dominance of sympathetic influences not only increases the excitability of the myocardium, but also contributes to the progression of structural remodeling of the heart, creating a vicious circle that exacerbates the arrhythmic risk [8].

The assessment of heart rate variability (HRV) provides valuable tools for the quantitative analysis of autonomic dysfunction in OSAS. A decrease in the indicators of temporal analysis (SDNN, RMSSD) and a change in spectral characteristics (a decrease in the high-frequency component reflecting vagal activity) significantly correlate with the severity of respiratory disorders. Caples S.M. et al. It is noted that normalization of vegetative balance on the background of CPAP therapy is accompanied by an improvement in HRV parameters, which can be considered as one of the mechanisms of the antiarrhythmic effect of this treatment method, although the clinical significance of these changes requires further verification in large prospective studies [9]. Thus, autonomic dysregulation in OSAS is a dynamic process in which sympathetic hyperactivation and vagal insufficiency mutually potentiate electrical instability of the myocardium.

In addition to neurohumoral and metabolic disorders, hemodynamic shifts caused by respiratory obstruction make a significant contribution to the electrical destabilization of the myocardium. During attempts to inhale against the background of closed upper respiratory tract, the intrathoracic pressure becomes sharply negative, which leads to a significant increase in transmural pressure in the cavities of the heart. This mechanical stretching of the walls of the atria and ventricles activates voltage-gated ion channels that are sensitive to stretching, triggering a mechanism of mechanical-electrical feedback. In a comprehensive review of the effect of OSAS on the cardiovascular system, Di Caro M.V. et al. It is emphasized that such cyclic myocardial deformations can induce premature depolarization and create conditions for the repair of arrhythmia mechanisms [12].

The clinical significance of mechanical stress is confirmed by monitoring data, where episodes of arrhythmias are often synchronized with the phases of maximum negative pressure at the end of apnea. In the OSCA study conducted by He H. Using implantable loop recorders and Holter monitoring, a direct correlation was demonstrated between the severity of respiratory events and the burden of ventricular arrhythmias, which indirectly indicates the role of the mechanical trigger factor [13]. An important argument in favor of the mechanical theory is the reversibility of violations against the background of the elimination of obstruction. Caples S.M. et al. It has been shown that the use of CPAP therapy, which normalizes intra-thoracic pressure and reduces afterload on the heart, leads to a decrease in the frequency of recurrence of rhythm disturbances, which confirms the pathogenetic relationship between mechanical stress and arrhythmogenesis [9].

Intermittent hypoxia, characteristic of OSA, acts as a powerful stimulator of the systemic inflammatory response. Activation of the NF-kB transcription factor under the influence of hypoxic stress leads to an increase in the level of pro-inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α). These inflammatory mediators can directly affect connexin expression and ion channel function, slowing down conduction and increasing the dispersion of repolarization. Chu Y. and Zinchuk A. In their review of the physiological signs of OSAS, they indicate that the patient's inflammatory status can serve as an important predictor of the severity of cardiovascular complications, including electrical instability [11].

Against the background of inflammation and hemodynamic fluctuations, endothelial dysfunction develops, disrupting coronary blood flow and contributing to myocardial ischemia even in the absence of obstructive coronary artery damage. Local ischemia creates heterogeneity in the electrical properties of the myocardium, increasing vulnerability to fatal arrhythmias. Christensen M.A. et al. It is noted that sleep characteristics reflecting the degree of hypoxemia and fragmentation are independent predictors of the development of atrial fibrillation and other rhythm disturbances, which confirms the systemic nature of damage affecting both the atria and ventricles [10]. Together, inflammatory activation and concomitant ischemia form a stable substrate for arrhythmogenesis, which persists during the daytime, increasing the overall cardiovascular risk.

Assessment of the temporal characteristics of ventricular repolarization is one of the most accessible and informative ways to stratify arrhythmic risk in patients with obstructive sleep apnea. Prolongation of the corrected QT interval (QTc) is a classic indicator of prolongation of the action potential and increased vulnerability of the myocardium to the development of repair mechanisms. In OSA, this phenomenon is often dynamic, aggravated during periods of the most pronounced desaturation, which emphasizes the direct link between hypoxic stress and electrophysiological instability. The review by Laczay B. and Faulx M.D. focuses on the fact that the variability of the QT interval during the night can serve as a more sensitive marker than its static values, since it reflects the lability of autonomic regulation and metabolic processes in cardiomyocytes [17].

The dispersion of the QT interval, reflecting the spatial heterogeneity of the restoration of excitability in different parts of the ventricles, demonstrates an even closer correlation with the severity of respiratory disorders. An increase in this parameter creates an electrophysiological substrate for the occurrence of polymorphic ventricular tachycardia. He H. and co-authors. An OSCA study using a combination of implantable loop recorders and Holter monitoring showed that episodes of pronounced QT variance often precede reported ventricular arrhythmias, which allows us to consider this indicator as a potential predictor of adverse events in real time [13].

T-wave alternation, which is cyclic fluctuations in the amplitude or morphology of the T-wave in successive cardiac cycles, is one of the highly specific markers of electrical instability. Although data on its use specifically in OSA remain limited, the pathophysiological justification for its significance is beyond doubt: intermittent hypoxia and sympathetic outbursts create conditions for alternating repolarization. Kainulainen S. And colleagues note that patients with suspected sleep apnea, especially in the presence of morbid obesity, show significant changes in the duration and morphology of ECG waves at night, which indirectly confirms the possibility of using repolarization markers to screen for arrhythmic risk in this population [16].

Ventricular ectopia occupies a central place in the spectrum of arrhythmic manifestations in OSAS. The frequency and complexity of ventricular extrasystoles, assessed according to the Low classification, significantly correlates with the apnea-hypopnea index and the degree of nocturnal desaturation. Horvath C.M. et al. In a recent study of patients with heart failure and concomitant sleep breathing disorders, it was demonstrated that obstructive sleep apnea is associated with increased stress by ventricular arrhythmias at night, while in central sleep apnea this pattern is less pronounced, indicating the specificity of obstructive type mechanical and hypoxic triggers [15].

Episodes of unstable ventricular tachycardia, although less common than extrasystoles, are of particular clinical significance in the context of the risk of sudden cardiac death. Heinzinger C.M. and colleagues, analyzing large clinical cohorts, found that certain phenotypic sleep profiles, characterized by pronounced fragmentation and hypoxemia, are associated with an increased risk of atrial fibrillation and ventricular arrhythmias, which underscores the need for a personalized approach to assessing arrhythmic risk based on a comprehensive analysis of somnographic data [14].

Bradyarrhythmias and rhythm pauses, including sinus stops, are a characteristic feature of the autonomic response to apnea. In the phase of obstruction, vagal activation prevails, leading to pronounced bradycardia, which is replaced by tachycardia upon resumption of breathing. Such a "qualitative" heart rate profile creates additional conditions for the occurrence of arrhythmias by the mechanism of re-entry. Laczay B. and Faulx M.D. It is emphasized that the recognition of these patterns requires synchronous registration of ECG and respiratory parameters, since isolated cardiac monitoring may not reveal the true etiology of rhythm disturbances [17].

The analysis of heart rate variability provides a unique opportunity to quantify the autonomic modulation of cardiac activity. Patients with OSA are characterized by a decrease in overall HRV indices, in particular SDNN, which reflects the depletion of adaptive reserves of the autonomic nervous system. He H. and co-authors. It is noted that the degree of reduced variability correlates with the severity of hypoxemia and can serve as an independent predictor of arrhythmic complications, especially in combination with other markers of electrical instability [13].

The spectral analysis of HRV makes it possible to differentiate the contribution of sympathetic and parasympathetic regulatory links. In OSA, there is a characteristic decrease in the high-frequency component (HF), reflecting vagal activity, and a relative dominance of the low-frequency spectrum (LF), which indicates a shift in balance towards sympathicotonia. Horvath C.M. and colleagues indicate that these changes are most pronounced at night and are partially reversible against the background of effective CPAP therapy, which confirms their association with respiratory obstruction rather than with primary cardiac pathology [15]. The LF/HF ratio, often used as an integral index of sympathovagus balance, demonstrates significant lability in severe OSA, which can be considered as an additional marker of instability of autonomic regulation and increased arrhythmic risk.

Traditionally, the severity of obstructive sleep apnea syndrome has been assessed primarily by the apnea-hypopnea index (AHI), however, current evidence suggests that the frequency of respiratory events does not always accurately reflect the arrhythmic risk. The parameters of nocturnal hypoxemia, such as the time spent with oxygen saturation below 90% (T90) and the minimum SpO2 level, are attracting increasing attention from researchers. Major epidemiological studies confirm that it is sleep characteristics reflecting the depth of desaturation and fragmentation that are independent predictors of the development of rhythm disturbances, often having greater prognostic significance than classical AHI [18].

The importance of taking into account dynamic changes in the severity of respiratory disorders is emphasized in studies analyzing the variability of OSA parameters from night to night. It has been shown that instability in the severity of apnea is associated with an increased risk of arrhythmias, which indicates the need for repeated

assessment of the patient's condition for accurate risk stratification [19]. The review data systematize information about the association of obstructive sleep apnea with various types of rhythm disorders, confirming that the presence of respiratory obstruction significantly increases the likelihood of electrical instability, and this relationship can be traced even after adjusting for traditional cardiological risk factors [20]. Thus, modern clinical practice is shifting the focus from a simple statement of the fact of apnea to a quantitative assessment of hypoxic load as a key driver of arrhythmogenesis.

Verification of the relationship between respiratory events and rhythm disturbances requires highly accurate recording methods that synchronize polysomnography and electrocardiography data. Isolated Holter monitoring often does not reveal the true etiology of nocturnal bradyarrhythmias or ventricular ectopia, since without recording respiratory flow, it is impossible to correlate rhythm pauses with phases of apnea. Comprehensive reviews of the effects of OSAS on heart health indicate that activation of the sympathetic nervous system, recorded in such studies, plays a central role in the modulation of heart rhythm during sleep [21].

A comparison of the night and day arrhythmia profiles in patients with OSA reveals a characteristic pattern: the maximum density of ventricular arrhythmias occurs during periods of respiratory recovery after obstruction, when peaks of sympathetic activity and blood pressure are observed. Synchronization of PSG and ECG data makes it possible to identify these critical risk windows that remain unnoticed during a standard daytime examination. A review of the associations between apnea and atrial fibrillation, extrapolated to the general mechanisms of arrhythmogenesis, emphasizes that the effectiveness of detecting rhythm disturbances directly depends on the quality and duration of monitoring, as well as on taking into account concomitant therapy such as CPAP, which can modify the daily profile of arrhythmias [20]. The integration of these diagnostic methods is becoming the standard for patients with unexplained nocturnal arrhythmias and suspected respiratory disorders during sleep.

Patients with implanted cardioverter defibrillators (ICDs) represent a unique cohort for studying the relationship between sleep-related breathing disorders and life-threatening arrhythmias, as the devices provide continuous recording of heart rhythm with high temporal accuracy. The analysis of ICD telemetry data makes it possible to identify specific patterns of arrhythmogenesis associated with nocturnal episodes of desaturation. Marinheiro R. and co-authors. In their review, they emphasize that defibrillator discharges are significantly more often recorded in patients with OSA and implanted devices at night, and these events are often synchronized with the phases of respiratory recovery after apnea, when peaks of sympathetic activity are observed [22]. This temporal association of arrhythmic events with the respiratory cycle indirectly confirms the role of hypoxemia and autonomic dysregulation as direct triggers of ventricular tachyarrhythmias.

An important aspect is the fact that a significant proportion of patients with ICD may have undiagnosed OSAS, which potentially reduces the effectiveness of the antiarrhythmic strategy. Martí-Almor J. and colleagues point out that the presence of untreated sleep apnea is associated with an increased frequency of both adequate and inadequate defibrillator discharges, which dictates the need for active screening of respiratory disorders in this high-risk group [23]. Modern devices equipped with algorithms for detecting respiratory disorders open up new opportunities for early detection of OSAS, but their sensitivity and specificity require further validation in prospective studies.

The effect of obstructive sleep apnea syndrome on the electrical stability of the myocardium is significantly modified by the presence of concomitant cardiac pathology. In patients with heart failure, OSAS acts as an independent predictor of worsening prognosis, exacerbating neurohumoral activation and contributing to the progression of ventricular remodeling. Marinheiro R. and co-authors. It is noted that the combination of heart failure and nocturnal hypoxemia creates a particularly favorable substrate for the occurrence of polymorphic ventricular tachycardia, since the ischemic myocardium demonstrates increased sensitivity to fluctuations in autonomic tone [22].

In patients with coronary artery disease (CAD), intermittent hypoxia potentiates the risk of arrhythmias through mechanisms of endothelial dysfunction and instability of atherosclerotic plaques. Martí-Almor J. and colleagues emphasize that episodes of desaturation can induce transient myocardial ischemia even in the absence of critical coronary artery stenosis, creating conditions for the occurrence of ischemia-dependent ventricular arrhythmias [23]. Patients with myocardial infarction are particularly vulnerable, in whom the scar area serves as an anatomical substrate for re-entry mechanisms activated by sympathetic bursts during apnea.

A systematic analysis of data on the association of sleep apnea and sudden death in a noncardiological population conducted by Martinez AB R. et al., demonstrates that the severity of nocturnal hypoxemia is a universal risk factor for fatal arrhythmias, regardless of the initial cardiological status [24]. This observation highlights the importance of considering OSAS not just as a comorbid condition, but as an independent modifiable arrhythmic risk factor that requires targeted correction as part of the comprehensive prevention of sudden cardiac death.

DISCUSSION

Timely detection of obstructive sleep apnea syndrome in patients with cardiac arrhythmias is a critically important step in preventive cardiology, since untreated OSAS significantly modifies the prognosis and reduces the effectiveness of antiarrhythmic therapy. In clinical practice, it is advisable to conduct primary screening using validated questionnaires such as the STOP-Bang or the Berlin Questionnaire, which demonstrate acceptable sensitivity to identify high-risk patients. However, it should be borne in mind that these tools, being focused on subjective symptoms, may underestimate the severity of the condition in patients with a predominance of

nocturnal hypoxemia with minimal daytime sleepiness. In this regard, the scientific statement of the American Heart Association emphasizes the need to expand the indications for instrumental diagnosis: polysomnography or respiratory monitoring is recommended for all patients with resistant ventricular arrhythmias, unexplained rhythm pauses or atrial fibrillation, especially in the presence of concomitant hypertension or heart failure [26].

Verification of the causal relationship between respiratory events and episodes of electrical instability requires synchronous registration of cardiac and respiratory parameters. Isolated Holter monitoring, although it allows you to record the fact of an arrhythmia, often does not answer the question of its trigger, whereas standard polysomnography may not cover the full range of possible rhythm disturbances. Modern approaches involve the use of implantable devices with the function of detecting respiratory disorders, which opens up new opportunities for long-term monitoring. Mazza A. and co-authors. It has been demonstrated that data obtained from cardioverter defibrillators are able to detect hidden forms of respiratory disorders associated with an increased frequency of device discharges, which confirms the diagnostic value of integrating methods [25]. Simultaneous recording of the ECG and respiratory flow allows precise synchronization of desaturation episodes with changes in repolarization intervals or the occurrence of ectopia, providing a personalized approach to the choice of treatment tactics.

The development of prognostic models for stratification of the risk of sudden cardiac death in patients with OSA requires consideration of the complex interaction of cardiological and somnological variables. Traditional risk scales that focus solely on left ventricular parameters or the presence of coronary artery disease may underestimate the contribution of nocturnal hypoxemia to arrhythmogenesis. Menon T. and colleagues in their review indicate that the inclusion of parameters such as the saturation time index <90% (T90) and the minimum SpO2 level significantly improves the predictive ability of models in relation to life-threatening ventricular arrhythmias [27]. Experimental data confirm that it is chronic intermittent hypoxia, and not just the frequency of apnea, that contributes to the development of myocardial ischemia and fibrosis, creating a stable substrate for sudden death [28]. Moreover, recent electrophysiological studies have revealed specific features of arrhythmogenesis in OSAS, including increased excitability of the right ventricular outlet tract, which requires taking into account the localization of arrhythmias when constructing prognostic algorithms [29]. Thus, a modern prevention strategy should be based on a multiparametric assessment combining heart imaging data, rhythm variability, and nighttime oxygenation characteristics.

A pathogenetically based approach to correcting myocardial electrical instability in obstructive sleep apnea is the use of constant positive airway pressure (CPAP therapy). The mechanism of antiarrhythmic action of this method is realized through the elimination of upper respiratory tract obstruction, normalization of blood oxygenation and stabilization of vegetative balance. Clinical evidence suggests that effective CPAP therapy can reduce the frequency of ventricular extrasystoles and episodes of unstable tachycardia, especially in patients with high initial arrhythmic load. Peker Y. and co-authors. In their review, they emphasize that a positive effect on electrical stability is observed mainly with sufficient duration of use of the device (more than 4 hours per night), which correlates with a decrease in the time of night desaturation [30].

The effect of CPAP therapy on repolarization parameters is also attracting the attention of researchers. A number of studies demonstrate a decrease in the variance of the QT interval and normalization of heart rate variability during treatment, which reflects the restoration of balance between the sympathetic and parasympathetic regulatory links. However, these changes are not always linear in nature and may depend on the initial cardiological status of the patient. Ramphul K. And colleagues note that in patients who have suffered acute coronary syndrome or stroke, the presence of untreated OSAS is associated with an increased risk of fatal arrhythmias, whereas timely initiation of CPAP therapy may modify this risk, although data on the effect on hard endpoints remain contradictory [31].

The key problem limiting the realization of the potential of CPAP therapy in the prevention of arrhythmias remains low adherence to treatment. A significant proportion of patients experience difficulties adapting to the mask, discomfort from the airflow or side effects, which leads to irregular use of the device. Rana D. and co-authors. It is pointed out that insufficient compliance not only negates the therapeutic effect, but can also create a false impression of the ineffectiveness of the method as a whole, requiring clinicians to take an active approach to patient motivation and individualization of therapy parameters [32].

An alternative to CPAP therapy in certain categories of patients may be surgery on the upper respiratory tract or the use of intraoral applicators (mouthguards) that move the lower jaw forward. The effectiveness of these methods in correcting hypoxemia varies widely and depends on the anatomical features of the patient, the degree of pharyngeal collapse and the severity of OSAS alternative to CPAP therapy in certain categories of patients may be surgery on the upper respiratory tract or the use of intraoral applicators (mouthguards) that move the lower jaw forward. The effectiveness of these methods in correcting hypoxemia varies widely and depends on the anatomical features of the patient, the degree of pharyngeal collapse and the severity of OSAS. In the context of the effect on the electrical stability of the myocardium, data are limited, but it is logical to assume that successful elimination of obstruction and a decrease in the apnIn the context of the effect on the electrical stability of the myocardium, data are limited, but it is logical to assume that successful elimination of obstruction and a decrease in the apnea-hypopnea index should be accompanied by a decrease in arrhythmic load. Reshetnik A. And colleagues in the CESAAR study draw attention to the fact that any interventions aimed at correcting respiratory disorders require

careful assessment of not only respiratory, but also cardiac outcomes, since incomplete treatment effectiveness may retain a residual arrhythmogenic risk [33].
Special care should be taken when considering surgical methods in patients with severe cardiovascular pathology, where perioperative stress and anesthesia alone can provoke rhythm disturbances. An individualized approach based on multidisciplinary assessment seems to be the optimal strategy for choosing between conservative and invasive OSAS correction methods.
Pharmacological correction of rhythm disturbances in patients with OSAS requires special attention due to the potential interaction of antiarrhythmic drugs with pathogenetic mechanisms of respiratory disorders. Some cPharmacological correction of rhythm disturbances in patients with OSA requires special attention due to the potential interaction of antiarrhythmic drugs with pathogenetic mechanisms of respiratory disorders. Some classes of antiarrhythmics that have sedative or muscle relaxant effects can worsen upper respiratory tract collapse and increase hypoxemia, creating a vicious circle. In this regard, the appointment of such drugs should be accompanied by careful monitoring of respiratory function and, if possible, combined with pathogenetic therapy of OSA. Schweitzer P.K. et al. The MARIPOSA study demonstrates the promise of combined pharmacotherapy (hydroxybutynin and atomoxetine) to improve the tone of the upper respiratory tract, which opens up new horizons for drug treatment of the very cause of arrhythmogenesis in OSAS, although data on the direct effect on ventricular arrhythmias still require further study [34].
Beta-blockers occupy a special place in the treatment of patients with combined pathology, since they not only have antiarrhythmic potential, but can also modulate sympathetic hyperactivation characteristic of OSAS. However, their use also requires caution: non-selective beta-blockers can provoke bronchospasm and worsen breathing parameters during sleep. The optimal choice of the drug, its dosage and time of administration should be determined taking into account the daily profile of blood pressure, vegetative status and characteristics of nocturnal respiratory disorders, which emphasizes the need for a personalized approach to the management of this category of patients.
Despite significant progress in understanding the pathophysiological relationships between obstructive sleep apnea and electrical instability of the myocardium, a number of fundamental issues remain open and require further scientific understanding. The central point of discussion is the inconsistency of data on the effect of OSAS pathogenetic therapy on "hard" endpoints, in particular on overall and cardiovascular mortality in the context of the prevention of ventricular arrhythmias. On the one hand, randomized trials such as the work of Traaen G.M. et al., demonstrate the beneficial effect of CPAP therapy on the frequency of atrial fibrillation episodes and some repolarization parameters, however, the authors rightly point out that these changes do not always translate into a reduction in the risk of life-threatening events [35]. On the other hand, a meta-analysis by Yang D. and colleagues, who combined data from patients with coronary heart disease, point to the potential benefit of CPAP therapy in relation to cardiac outcomes, but emphasize the heterogeneity of the included studies and the need for longer follow-up [38]. The scientific statement of the American Heart Association, prepared by Yeghiazarians Y. et al., summarizes that, although correction of respiratory disorders certainly improves the quality of life and some surrogate risk markers, there is still insufficient convincing evidence of a reduction in mortality from arrhythmias during treatment, which dictates caution in formulating clinical recommendations [39].
The second important aspect of the discussion concerns the need for a personalized approach to the management of patients with combined cardiorespiratory pathology. It is obvious that universal algorithms based solely on the apnea-hypopnea index do not take into account the individual variability of the response to hypoxia, differences in the phenotypes of autonomic dysregulation and the specifics of concomitant myocardial remodeling. Xu W. and colleagues, analyzing the data from the multicenter registry of patients with atrial fibrillation, show that the clinical characteristics and thrombotic risk vary significantly depending on the presence and severity of OSAS, which justifies the stratification of patients not only by cardiological, but also by somnological parameters [37]. A similar position is taken by Menon T. et al., who emphasize that the choice of treatment tactics – be it CPAP, surgical correction or pharmacotherapy – should be based on a comprehensive assessment of the dominant pathogenetic mechanism in a particular patient [27]. However, the implementation of this approach faces methodological difficulties: the lack of validated algorithms for integrating polysomnography, Holter monitoring and cardiac imaging data, as well as insufficient knowledge of predictors of response to therapy.
A promising area that can overcome these limitations is the widespread introduction of artificial intelligence and machine learning methods for analyzing multimodal data. Synchronous processing of long-term ECG recordings and respiratory parameters generates arrays of information inaccessible to traditional visual analysis. Wong C.X. et al. The I-STOP-AFIB study demonstrates that even short-term fluctuations in sleep quality, detected using digital tools, can predict episodes of arrhythmia, which opens up opportunities for precision prediction [36]. Di Caro M.V. and colleagues in their review indicate that deep learning algorithms are able to identify hidden patterns in the variability of repolarization intervals associated with episodes of desaturation, which can become the basis for creating early warning systems for arrhythmic events [12]. Nevertheless, the introduction of such technologies requires solving a number of problems: ensuring interpretability of models ("black box"), validation on diverse populations, and integration into clinical workflows without undue burden on medical personnel.
An additional layer of discussion is related to the definition of optimal markers for evaluating the effectiveness of therapy. Dose-response meta-analysis by Zhang D. et al. confirms the linear relationship between the severity of OSAS and the risk of atrial fibrillation, however, the authors note that the threshold values of the indices at which

intervention becomes clinically justified in relation to the prevention of arrhythmias remain the subject of debate [40]. Laczay B. and Faulx M.D. Attention is drawn to the fact that traditional electrocardiographic parameters, such as the QT interval, may not accurately reflect the dynamics of arrhythmic risk in OSAS, and it is proposed to consider complex indices that include data on rhythm variability and T wave morphology [17]. Marinheiro R. and co-authors. They emphasize the importance of taking into account not only the frequency, but also the gradation of ventricular extrasystoles, since it is the complex forms of ectopia that are more often associated with an unfavorable prognosis [22].

Finally, the question of to what extent the observed antiarrhythmic effects of therapy are due to specific effects on the respiratory tract, and to what extent to non–specific factors, such as improving compliance with treatment in general or lifestyle modification, cannot be ignored. Mehra R. and co-authors. The AHA's scientific statement focuses on the need to conduct studies with active control groups and a long follow-up period in order to separate the true pathophysiological effects from concomitant changes [26]. Only such a methodologically rigorous approach will allow us to form an evidence base for personalized strategies for the prevention of sudden cardiac death in patients with obstructive sleep apnea.

CONCLUSIONS

The analysis suggests that obstructive sleep apnea syndrome is not just a concomitant pathology, but an independent modifiable risk factor for sudden cardiac death. The arrhythmogenic potential of the disease is based on a complex cascade of reactions triggered by intermittent hypoxia. We are talking not only about mechanical obstruction of the upper respiratory tract, but also about deep biochemical shifts, including oxidative stress, systemic inflammation and impaired function of ion channels, which together create a stable substrate for electrical instability of the myocardium. Cyclical fluctuations in sympathetic tone and sudden drops in intrathoracic pressure complement this picture, creating conditions for the occurrence of life-threatening rhythm disturbances mainly at night.

Clinical data strongly suggest that it is the parameters of nocturnal desaturation, such as the time spent with saturation below the critical level and the minimum blood oxygen index, that have greater prognostic significance than the traditional apnea-hypopnea index. This observation shifts the focus of attention from the frequency of respiratory events to their severity and duration of hypoxic effects. The revealed correlation between the depth of oxygen drop and the frequency of ventricular arrhythmias underscores the need to reconsider approaches to risk stratification in cardiac patients, since standard scales may underestimate the contribution of the respiratory factor to the overall prognosis.

From a practical point of view, the integration of somnological screening into the routine practice of managing patients with ventricular arrhythmias is becoming not just desirable, but a mandatory measure. Active detection and timely correction of respiratory disorders during sleep should be considered as an integral part of the comprehensive prevention of sudden cardiac death. The effectiveness of therapy, in particular methods of positive airway pressure, directly depends on treatment adherence, which requires clinicians to pay special attention to patient motivation, individual selection of equipment parameters and long-term monitoring of compliance with the regime. Thus, risk management in this category of patients is impossible without taking into account the respiratory status, which opens up new prospects for reducing mortality in the cardiological population and requires interdisciplinary interaction between cardiologists and somnologists.

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