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REVIEW ARTICLE

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Heart rate monitors used by athletes — from gadget to medical equipment. A decade of own observations

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ABSTRACT

Introduction: For many years, many athletes have reported to the Centre for Sports Cardiology in Pułtusk that during endurance training, mainly running and cycling, they found unexpected increases in heart rate (HR) values observed on sports heart rate monitors (HRMs), in the vast majority of cases without the accompanying clinical symptoms. The authors have attempted to answer the question of whether the "arrhythmia" observed on HRMs is a rhythm disturbance or a mere technical artefact. This article aimed to summarize the authors' observations in the field of the usefulness of HRMs for the assessment of cardiac arrhythmias in the situation of introducing new technological solutions in the modernized and enriched ones with new functions HRMs.

Material and methods: Over ten years, numerous studies have been carried out and the world literature has been also analysed many times, finally describing the authors' study results and observations in numerous types of English-language articles published between 2017 and 2021.

In this review article, the authors focused only on their publications from the Centre for Sports Cardiology in Pultusk on the issues of heart rhythm disturbances observed on HRMs by endurance athletes, and on publications in which researchers from CKS participated and the articles themselves were related with the use of HRMs. Only a few references have been cited from other sources.

Conclusions: The HRMs used in the past years were not significant for the treatment of asymptomatic exercise-stimulated arrhythmias. These HRMs, however, in a symptomatic arrhythmia situation, became an effective diagnostic tool confirming its occurrence. The analysis of cases and literature shows that modern sports heart rate monitors used by athletes of endurance disciplines (especially with the possibility of ECG recording) are becoming a useful, important and more and more effective diagnostic tool in the detection and final diagnosis of cardiac arrhythmias stimulated by exercise, both symptomatic and asymptomatic athletes and can significantly contribute to the increase of safety during training. It can be assumed that future HRMs will have comparable diagnostic value in detecting cardiac arrhythmias as the Holter ECG, surpassing them with the possibility of constant data transmission, ease of use and affordable price.

Key words: arrhythmia, supraventricular tachycardia, ventricular tachycardia, atrial fibrillation, endurance athletes, atrioventricular nodal re-entrant tachycardia (AVNRT), commotio cordis, heart rate monitors, exertion rhythm disorders

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Material and methods

This review article uses manuscripts created almost exclusively (mostly) based on own experience related to the use of HRMs and published by researchers co-operating with the Sports Cardiology Centre in Pułtusk. The articles used in this manuscript mainly concerned the published results of own research, observations and analyses of the literature on the use of HRMs to control heart rhythm and the identification of potential post-exercise arrhythmia mainly among endurance athletes. The article also includes its own observations (published articles) on rehabilitated and treated patients with cardiovascular diseases using HRMs to control heart rhythm.

Inclusion criteria for literature selection, apart from those already mentioned (own observations), were the following keywords: arrhythmia, supraventricular tachycardia, ventricular tachycardia, atrial fibrillation, endurance athletes, Atrioventricular Nodal Re-entrant Tachycardia (AVNRT), Commotio Cordis, heart rate monitors (HRMs), exertion rhythm disorders.

Exclusion criteria for literature selection: listed keywords (for own articles) but articles not relevant for article review.

Results and discussion

The usefulness of sports heart rate monitors in diagnosing arrhythmia in asymptomatic and symptomatic athletes

Millions of physically active individuals worldwide use heart rate monitors (HRMs) to monitor their exercise intensity. In many cases, HRMs may indicate an unusually high heart rate (HR) or even arrhythmias during training. Unfortunately, few studies existed that assessed the reliability of these devices in monitoring HR disturbances during exercise.

The observation was started in 2011. After preparing methods 142 regularly training endurance runners and cyclists were examined, aged 18–51 years, with unexplained HR abnormalities indicated by various HRMs to assess the utility of HRMs in diagnosing exertion-induced arrhythmias. Each athlete simultaneously wore a Holter electrocardiogram (ECG) recorder and an HRM during typical endurance training in which they had previously detected “arrhythmias”, to verify the diagnosis. Average HRs during exercise were precisely recorded by all types of HRMs. No signs of arrhythmia were detected during exercise in approximately 39% of the athletes, and concordant HRs were recorded by the HRMs and Holter ECG. Surprisingly, high short-term HRs were detected by HRMs in 45% of the athletes, but not by the Holter ECG and were considered artefacts. In 15% of the athletes, single ventricular/supraventricular beats were detected by the Holter ECG but not by the HRM. In one athlete was detected a serious tachyarrhythmia via both the HRM and Holter ECG with concomitant clinical symptoms; this athlete was forced to cease exercising (Holter ECG examination revealed atrioventricular nodal reentrant tachycardia [AVNRT]). It was concluded that the HRM is not a suitable tool for monitoring heart arrhythmias in athletes and proposed an algorithm to exclude the suspicion of exercise-induced arrhythmia detected by HRMs in asymptomatic, physically active individuals [1, 2].

Having information about the usefulness of HRMs in the diagnosis of asymptomatic arrhythmias, another research was started (actually continued the previous one) completed after 6 years of observation, on their usefulness in the situation of symptomatic athletes (triathlete) with suspicion of arrhythmia. This case study described triathlete in whom HRM showed high HR values during exercise and clinical symptoms forced him to stop training (AVNRT in Holter ECG and the same HR on HRMS at this moment) during the first study.

This case study completed finally in 2020, described a triathlete with effort-provoked AVNRT diagnosed 6 years prior, who ineffectively controlled his training load via HRMs to avoid tachyarrhythmia. Of the 1800 workouts recorded over 6 years via the HRMs, 45 tachyarrhythmias were found, which forced the athlete to stop exercising. In three of them, AVNRT was simultaneously confirmed by a Holter ECG. Tachyarrhythmias occurred at different phases (after the 2nd–131st minutes, median: 29th minute) and frequencies (3–8, average: 6.5 times/year), characterized by different HRs (150–227 beats per minute (bpm), median: 187 bpm) and durations (10–186, median: 40 s). Tachyarrhythmia appeared unexpectedly in the initial stages of training, as well as quite predictably, during prolonged submaximal exercise but without rigid rules. Tachyarrhythmias during cycling were more intensive (200 *vs.* 162 bpm, $p = 0.0004$) and occurred later (41 *vs.* 10 min, $p = 0.0007$) than those during running (the only one noticed but not recorded during swimming). A tendency was noticed ($p = 0.1748$) towards the decreasing duration time of tachycardias (2014–2015: 60 s; 2016–2017: 50 s; 2018–later: 37 s). The amateur athlete tolerated the tachycardic episodes quite well, and the ECG test and echocardiography were normal. In this studied case, the HRM was a useful diagnostic tool for detecting symptomatic arrhythmia; however, no change in the amount, phase of training, speed, or duration of exercise-stimulated tachyarrhythmia was observed [3].

The above studies showed that the HRMs used in the past years were not useful in detecting asymptomatic exercise-stimulated arrhythmias. However, in the event of symptomatic arrhythmia, these HR monitors became an effective diagnostic tool for confirming its occurrence. None of the HRMs used in these studies had an ECG recording function, a feature that is slowly emerging in modern HRMs.

Sports HRMs — how do they work and why are they indispensable for athletes, especially in endurance sports?

The key to effective training of endurance athletes in disciplines such as the triathlon, cycling, and long-distance running is to perform the training within a specific range of HR values. For this reason, HRMs have become an indispensable tool for athletes in achieving their training objectives [4]. HR is a useful indicator of physiologic adaptation and effort intensity. Therefore, HR monitoring is an important component of cardiovascular fitness assessments and training programs [5]. Similar to conventional ECG devices, the HRMs used by athletes determine their HRs by receiving the main electrical field produced by the heart muscle through electrodes placed on a transmitter belt attached to the chest; the signal is then transmitted by a probe to a digital recorder, most commonly a special wristwatch, via telemetry. Thus, an HRM may also function as a Global Positioning System. In recent years, the extensive use of sports HRMs by cardiac patients performing physical activities was observed, particularly running and cycling, as primary and secondary methods for preventing cardiovascular diseases, including coronary heart disease and hypertension [6]. HRMs have been designed for use by healthy athletes with a baseline sinus rhythm, but they also capture exercise-induced arrhythmia [7]. However, information about the morphology of the QRS complex has not been reported, and atrial signals have not been detected [8]. During medical consultations at the Centre for Sports Cardiology in Pułtusk, doubts repeatedly arose regarding the reliability of results generated by HRMs during running or cycling training that suggested an "arrhythmia," particularly in situations where clinical symptoms were not observed and when only unspecified symptoms typical of an anxiety disorder were observed [1].

With the increasing popularity of the use of HRMs by athletes and cardiac patients using running or cycling as primary and secondary methods for preventing cardiovascular diseases and because of the many reports of suspected arrhythmia based on HRM indications, several systematic investigations among Centre for Sports Cardiology study participants were initiated, testing "old" and "modern" HRMs [3].

History of HRMs — from "fingers on the radial artery" to advanced ECG recording technologies

The first reports of commercial medical devices for measuring HR were published at the beginning of the 18th century [9]. Partially reliable HR control during training appeared with the widespread introduction of sweep hand watches more than 200 hundred years ago. The athlete had to stop and count their pulse on the radial artery for 10 seconds and then multiply this number by 6 to determine their HR. In this way, they obtained their HR value at the peak of exercise, allowing them to determine the load in the last phase. There was no opportunity to determine the average HR during training; thus, exercise intensity could not be evaluated as a whole.

All HRMs today record HR; however, this is not enough to establish a complete diagnosis of the origin of the rhythm and potential threats to the life and health of the athlete when pathological. There is no facility to determine whether an arrhythmia at a given time is caused by numerous harmless supraventricular beats – or atrial fibrillation – or whether it is a life-threatening ventricular tachycardia [10, 11]. The ability to measure HR in water was another important step, enabling swimmers and triathletes to monitor their training, although without the possibility of recognizing the source of the "beat" in HRMs (sinus rhythm, supraventricular or ventricular beats, etc.) [12, 13].

Commonly used strap HRMs (SHRMs), which have been commercially available for many years, indicate the correct HR value; however, in the event of an arrhythmia, they are still not a reliable source of information about its type. The introduction of the Heart Rate Variability assessment function to HRMs has allowed rhythm "regularity" to be determined; however, it is unable to determine whether a regular or complete arrhythmia is the result of supraventricular/ventricular beats or ordinary artefacts [10]. SHRMs assess the main electric field produced during ventricle contraction. Therefore, they estimate the distance of the R-R points without identifying either P-wave morphology or the QRS complex [14]. This function is completely inadequate in the case of commotio cordis, the mortality rate of which—regardless of the type of HRM or the device controlling the workings of the heart (except for the cardioverter-defibrillator)—is very high. However, healthy athletes do not have access to cardioverter-defibrillators [15].

Optical HRMs (OHRMs) have been on the market for about 10 years. The principle of their operation is common, and the accuracy of their measurements is similar to that of the chest SHRM. Optical pulse monitors operate under a completely different principle than SHRMs. While SHRMs work similarly to ECGs, OHRMs use a phenomenon called photoplethysmography, which constitutes transmission of light through the skin and measurement of the amount of light that is scattered by blood flow. Photoplethysmography sensors are based on the fact that light entering the body will scatter predictably as the blood flow dynamics change, such as with changes in the blood pulse rate or with changes in blood volume (cardiac output). In practice, the optical HR sensor located on the underside of the watch illuminates the blood vessels in the wrist tissue using LEDs, measuring the amount of light dispersed by the blood flow. The advantage of a wrist pulse measurement is convenience, i.e., the ability to measure HR without having to wear a separate strap or other sensors to measure the pulse. Such a watch must be placed directly on the skin with no material in between; occasionally, the watch must be worn higher on the wrist than a normal wristwatch. The sensor detects blood flow through the blood vessels; therefore, the tissue thickness determines the measurement accuracy [16].

OHRMs can only determine rhythm regularity and, thus, can indirectly be used to make diagnoses e.g., complete arrhythmia—suspicion of atrial fibrillation [17].

The use of smartphones for arrhythmia monitoring is another advancement for ECG utilization and arrhythmia detection, effectively making the technology available to any smartphone user. Smart wearable technology, while very common, is mostly limited to activity tracking and exercise motivation. Rhythm-strip-generating smartphone products, such as Kardia Mobile by AliveCor and ECG Check by Cardiac Designs, can more accurately detect arrhythmias than wearable monitors. These products, which have been studied in a variety of situations, rely on the use of an external device with metal sensors to create a rhythm strip, which is usually Lead I. A different subset of smartphone products utilizes photoplethysmography through a phone camera and light to detect atrial fibrillation. Together, these products have created a paradigm shift in rhythm detection and monitoring [18].

New electrodes built into the back crystal and digital crown on the Apple Watch Series 4 work together with the ECG app to enable customers to produce an ECG recording similar to a single-lead reading. To take an ECG recording at any time, or following an irregular rhythm notification, users launch the new ECG app on Apple Watch Series 4 and hold their finger on the digital crown. As the user touches the digital crown, the circuit is complete and electrical signals across the heart are measured. After 30 seconds, the heart rhythm is classified as either AFib, sinus rhythm, or inconclusive. All recordings, their associated classifications, and any noted symptoms are stored securely in the Health application of the iPhone. Users can share a PDF of their results with physicians. Although similar to the Apple Watch, it is only a record of one limb lead, and it can clearly recognize both the P-wave and the QRS complex. This fully corresponds to the classic single Lead 1 ECG recording. The biggest disadvantage of this function is that activity must be paused for the recording, contradicting the idea of measurement during training [19].

However, technological advancements brought new solutions including HRMs with applications enabling constant ECG recording during training to the market. The QardioMD system (namely, QardioCore ECG with QardioMD remote monitoring cloud-based portal) can be described as a typical strap HRM with the difference that the information from the transmitter (strap) is transferred to the Qardio mobile app on the iPhone, i.e., the receiver. After a delay of about 3 minutes, information from the iPhone is transmitted to the "cloud." The downloading of information to the Monitoring Centre (Hospital, Clinic with QardioMD remote monitoring cloud-based portal) allows ECG control, which is continuously recorded, and automatic recognition of life-threatening heart rhythm disorders. The inconvenience of carrying a phone during training is minor considering the enormous amount of information obtained and stored. The Monitoring Centre offers an ECG recording with three limb leads (modified leads I, II, III) with automated arrhythmia detection, QRS morphology analysis, P-wave detection (for enhanced automated AF detection), and the possibility of manually assessing PQ, QT, and ST segments. It is a matter of time until an automatic diagnosis of stress ischaemia with the QardioMD system will become available. Preliminary studies have shown that it is a system with comparable diagnostic value to the standard 3 Lead Holter ECG monitor [20].

Strap HRMs or optical HRM?

The surveyed athletes, coaches, and physicians answered this question unequivocally [18]. OHRMs, provided that their indications are reliable, are preferred. Wearing a chest strap is troublesome for athletes for numerous reasons, ranging from battery depletion artefacts, interference in the transmission between the strap and the receiver, to the most important for ultramarathon runners: chafing of the skin during long hours of running by a moving strap [21]. It is also common to simply forget to put it on during training, which significantly changes the subsequent evaluation of training. Therefore, OHRMs are preferred on the condition that the accuracy of their indications, which remains a problem, is improved [21]. In the past, the inability to measure HR by HRMs in the water was an issue, which was a significant limitation for triathletes and swimmers; however, this problem has now been resolved [12]. OHRMs usually also have a longer battery life which, in 24- or 48-hour ultramarathons, is of great importance [22]. It is important to note that there are still outstanding endurance runners who, for mental reasons, do not use an HRM during competition [23, 24].

Will HRMs replace the Holter ECG?

Sports HRMs were introduced to monitor HR values in healthy athletes and were not meant to be or compete with medical devices [25]; however, it is impossible to run daily with an ECG Holter to verify periodic indications of incorrect values while training with an HRM. An algorithm has been developed to deal with such cases [16]. Nevertheless, HRMs should be considered as devices with useful and reliable medical functions, such as reliable ECG recording, intended for use by athletes. Today's ECGs recorded by HRMs are single limb lead recordings (Apple Watch) or, as in the case of the QardioMD system, a 3-limb lead recording. However, this is an evolutionary advancement, introducing devices "for measuring HR for healthy athletes" as advanced medical diagnostic tools for use in sports cardiology [26].

The trouble-free use of HRMs in everyday life makes them a candidate for use as professional equipment that requires special handling skills and professional knowledge for result interpretation (e.g., Holter ECG). It seems that it will only be a matter of time before HRMs will be able to record a 12-lead ECG with the possibility of assessing all ECG features, including the ST segment, which will be extremely important for the diagnosis of exercise ischaemia in a classic exercise test [27]. Other data, such as measuring the QT interval or identifying the origin of ventricular beats, will become automatic information related to these recordings.

Anyone, including potentially healthy top athletes, may experience life-threatening exercise arrhythmias [28]. The registration and early interpretation by the HRMs used today by millions of active people may save lives in the future.

It seems that, in the future, the increasingly perfect ECG data recorded on a typical sports HRM will lead to these devices being treated as medical devices necessary for safe, highly professional, and recreational training. The usefulness of these devices in cardiac rehabilitation is undisputed [29].

Currently, a long-term observational study of patients with long QT syndrome type VII is performed, employing modern HRMs (with long "battery life") for use in ultramarathoners [30, 31].

Bradycardia and bradyarrhythmia in athletes ,,caught" on HRMs?

Tachyarrhythmias are mentioned constantly, regarding the usefulness of HRMs in the assessment of cardiac arrhythmias; however, wearing HRMs – as in the case of OHRMs – may contribute to the registration of not only fast rhythms during training but also night bradyarrhythmias, which are common rhythm disturbances in athletes of endurance disciplines [32]. Undoubtedly, this is a space where HRMs, which are used by many athletes, can contribute both to the diagnosis of arrhythmias – if data are "recorded continuously" – and data collection. All existing HRM models register a decrease in HR, but they do not all recognize the mechanism by which this decrease occurs (either a conduction block or ordinary bradycardia). In asymptomatic and apparently healthy athletes, either at rest or during sleep, even 15-second pauses in the Holter ECG examination are common. Northcote et al. examined 20 male veteran endurance runners who underwent resting, exercise, and ambulatory electrocardiography testing; six athletes had a first-degree heart block, four had a Mobitz II second-degree block, and three had a complete heart block [33].

The "athlete's heart" and its accompanying bradycardia, or the second-degree A-V block, are physiological adaptations to exercise; however, a break of a few seconds is certainly a pathology that has the potential to be increasingly recognized by athletes using HRMs both in training and at rest and/or sleep. Comfort is also the reason why OHRMs seem to be a more common direction of development [34].

Perspectives — directions of HRMs development

The future of HRMs includes improvement in the accuracy of already-existing indications, in addition to the development of new technology that will allow the widespread use of OHRMs with the function of 24-hour ECG recording. Moreover, athletes, coaches, and doctors are interested in other functions that are not yet available today, such as the expected oxygen threshold indicator. Certainly, new solutions will be presented, other than the ones currently available, allowing not only trouble-free ECG recording during training, but also the ability to inform the athlete, coach, or doctor via online means regarding any potential threats in the form of heart rhythm disturbances, as well as the emerging features of stress ischaemia.

This is important to increase the awareness of athletes regarding the need to protect their health during training by controlling heart rhythm and not just HR (i.e., ECG recording). Furthermore, to protect the lives and health of athletes who sometimes experience tragic cardiac arrhythmias triggered by exercise, the widespread use of HRMs with continuous ECG recording should be encouraged in the future.

Conclusions and practical applications

The HRMs used over the past years were not shown to be useful in the detection of asymptomatic exercise-stimulated arrhythmias. However, these

HRMs were effective diagnostic tools in confirming the occurrence of symptomatic arrhythmia. The analyses of cases and review of the literature show that modern sports HRMs used by endurance sport athletes are becoming a useful, important, and more effective diagnostic tool in the detection and final diagnosis of exercise-stimulated cardiac arrhythmias, which may contribute to the increase in safety of both symptomatic and asymptomatic athletes during training. It can be assumed that future HRMs will have comparable diagnostic value in detecting cardiac arrhythmias as the Holter ECG, surpassing them with the possibility of constant data transmission, ease of use and affordable price.

List of abbreviations: HR — heart rate; HRMs — heart rate monitors; ECG — electrocardiogram; AVNRT — atrioventricular nodal reentrant tachycardia; SHRM — strap heart rate monitor.

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