Module 5. Use of new technologies in the management of athletes with arrhythmias

Today, millions of consumers worldwide have access to wearable devices, such as smartphones and smartwatches, among others, capable of measuring biological signals that were previously only possible in medical settings. In 2019, the global market for these devices was 181.5 million units and is expected to reach 520 million units by 2025 (Research and Markets, 2020).

Currently, through various smart devices, it is possible to record heart rate (HR), electrocardiograms (ECG), and other physiological variables comfortably, continuously, and in real time. This is of great interest when it comes to monitoring the progress of training, physical activity, and the cardiovascular health of athletes, facilitating the diagnosis, treatment, and prevention of arrhythmias. These technologies offer endless opportunities to collect functional information at a very low cost in the general population, and particularly in athletes. However, it should be noted that the clinical benefits of these devices have not been validated in randomized studies and their use could potentially be associated with side effects due to misinterpretation of the data generated.

In this chapter, we describe the different new wearable technologies available, explore their potential uses in the management of athletes with arrhythmias, discuss the results of relevant studies, and analyze their potential limitations and knowledge gaps that may influence their implementation in real life. These digital devices can also provide measurements such as HR variability, acceleration, body position, temperature, oxygen saturation, and sleep quality, all of which are useful for monitoring athletes, but they will not be covered in this chapter.

1. Types of new wearable technologies for athlete monitoring

Digital devices for heart rate monitoring can be divided into two major groups according to the technology used to assess heart rate (Figure 1):

1. Devices not based on ECG recording, including photoplethysmography (PPG).
2. Devices based on ECG recording.

Figure 1. Examples of wrist devices for rhythm monitoring. A., based on photoplethysmography; B., based on ECG recording

Source: own source based on a screenshot from Huawei (https://consumer.huawei.com/es/mobileservices/health/) and Apple, 2021, https://apple.co/44qxThF

The choice of digital heart rate monitoring device should be tailored to the athlete, taking into account the presence or absence of symptoms and their frequency, the duration of monitoring, local infrastructure, and user preferences (Svennberg et al., 2021). When precise monitoring is needed, chest straps are usually preferred for their greater accuracy, even in high-intensity sports (Cosoli et al., 2022; Ruiz-Alias et al., 2022; Schaffarczyk et al., 2022). In other cases, wristbands (and smartwatches) may be preferred for their multifunctionality and comfort. Other wearable textiles with sensors have also been developed to obtain high-quality signals without limiting movement in certain sports.

Recently, the possibility of remote monitoring of wearable technologies in the management of athletes with arrhythmias has been introduced. These systems allow healthcare providers to remotely monitor the athlete's HR, ECG, and other vital signs using a smartphone or other mobile device. This could be particularly useful for athletes who travel frequently or live in remote areas, as it allows them to receive medical attention quickly if needed.

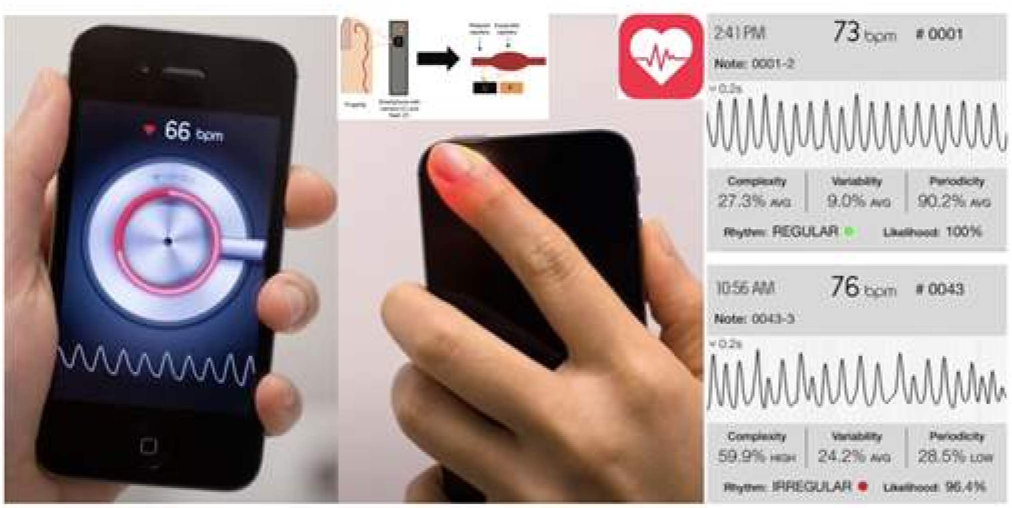
It is important to emphasize that, regardless of the digital device used, a physician must review the recordings to confirm the clinical diagnosis.

1.1 Digital devices based on photoplethysmography

Photoplethysmography can monitor HR and detect arrhythmias through an optical technique that analyzes the peripheral pulse wave. A light source (such as a smartphone's LED flashlight) and a detector (the camera) are used to measure changes in blood volume within the skin's surface by detecting changes in the intensity of reflected light (Figure 2). Currently, PPG is routinely used to measure oxygen saturation and pulse rate (Friberg et al., 2013). The simplicity of the technology has allowed its incorporation into multiple wearable devices to analyze HR and rhythm (Dörr et al., 2019), such as chest straps, wristbands, armbands, rings, and earbuds (Navalta,

2020) (Table 1). There are automatic algorithms for detecting atrial fibrillation (AF) that have shown high accuracy, as long as the measurements are taken in a comfortable seated position (Dörr et al., 2019). However, in active individuals, the accuracy is considerably lower due to the presence of artifacts (Tison et al., 2018). These devices may miss rapid or brief HR transitions and fail to detect up to 60% of short duration arrhythmias (Fanous & Dorian, 2021; Sequeira et al., 2020).

Figure 2. Example of an application based on photoplethysmography



Source: adapted from Chan et al., 2016.

Table 1. Heart rate monitoring devices based on photoplethysmography

Device	Type	Detection mode	Number of sensors	Area of application	EC vis
Cardio Rhythm	Mobile application	PPG	Smartphone camera	Fingertip or face detection via video	No
Fibricheck	Mobile application	PPG	Smartphone camera	Fingertip	No anc det alg
Preventicus Heartbeats	Mobile application	PPG	Smartphone camera	Fingertip	No anc det alg
Huawei	Wristband	PPG	2 electrodes	Wrist	On- dev
Apple Watch	Smartwatch	ECG and PPG	2 electrodes;	Wrist - finger	Int anc

			1 lead		de
Fitbit	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	On- de
Samsung	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	On- de
Withings	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	On- de

Source: own source based on Svennberg et al., 2021.

1.2 Digital devices based on ECG

There are various devices for heart rate monitoring via ECG, which differ in aspects such as application site, placement method, number of leads available, amount of user feedback, battery type, data storage and transmission, etc. Additionally, not all of them have been validated in clinical trials or received approval from regulatory agencies (European Commission/Food and Drug Administration).

The ECG recording devices available on the market require the athlete to activate the device by placing their hands on an electrode (either on the main device or on an accessory), with a contact time of approximately 30 seconds, before an ECG is recorded. This limits the usefulness of these technologies to arrhythmias lasting → 1 minute. Some of these devices may require the athlete to remain still to capture a diagnostic-quality ECG trace, which may not be possible or could further delay the time from the onset of symptoms to obtaining the ECG trace. In addition, not all sports are appropriate for the use of these devices. A cyclist, swimmer or rower could not easily use these devices to "control" their underlying rhythm.

1.3 Hand-held ECG devices

Generally, these are single lead devices that usually provide records from lead I (Table 2). Some models can be applied to the chest to record chest and right arm leads, which can produce higher amplitude QRS complexes and clearer P waves than in lead I (Desteghe et al., 2017; Brito et al., 2018). Leads II and III can be recorded by applying the bipolar device to the left leg (the device can be placed over dampened pants to simplify the process) while holding the device with the right and left hands, respectively. A model with three electrodes allows for simultaneous recording of all limb leads by holding the device with both hands and applying the posterior electrode against the left leg (Figure 3).

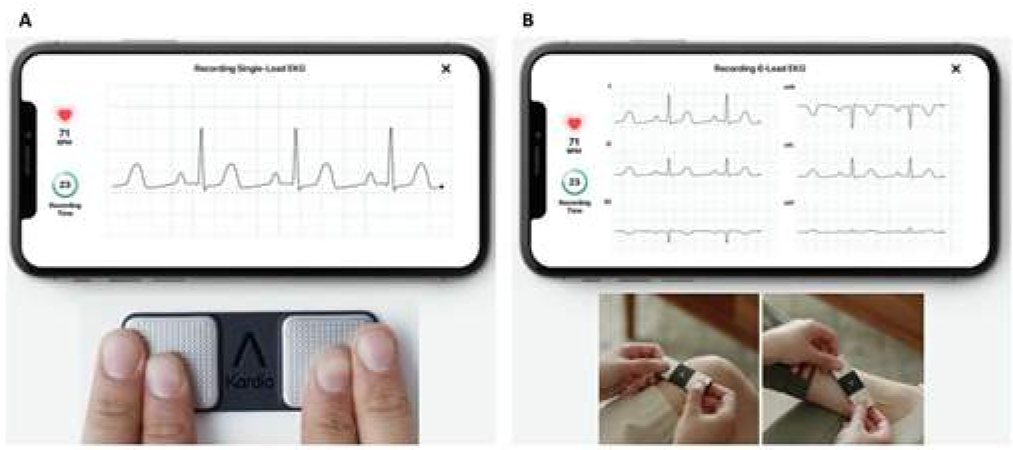
Table 2. Heart rate monitoring devices based on hand-held ECG

Device	Type	Detection mode	Number of sensors	Area of application
Alivecor Kardia	Hand-held	ECG	2 or 3 electrodes; 1 or 6 leads	Fingertips ± leg or chest
Beurer ME 90	Hand-held	ECG	2 electrodes; 1 lead	Chest-to-fingertip or fingertip-to-fingertip
Coala Heart Monitor	Hand-held	ECG	2 electrodes; 1 lead	Thumb-chest
ECGCheck	Hand-held	ECG	2 electrodes; 1 lead	Fingertips ± leg or chest
Eko Duo	Hand-held	ECG	2 electrodes; 1 lead	Chest

HeartCheck CardiBeat, ECG Pen, Palm	Hand-held	ECG	2 electrodes; 1 lead	Fingertip, palm/chest/hip
MyDiagnostick	Hand-held	ECG	2 electrodes; 1 lead	Hands
Omron HCG-801	Hand-held	ECG	2 electrodes; 1 lead	Fingers/chest
SnapECG E-H19	Hand-held	ECG	2 electrodes; 1 lead	Fingertips
Zenicor-ECG	Hand-held	ECG	2 electrodes; 1 lead	Thumbs

Source: own source based on Svennberg et al., 2021.

Figure 3. Example of heart rate monitoring devices based on handheld ECG. A., single lead recording (2 electrode recording between both hands); B., 6 lead recording (simultaneous recording of 3 electrodes between both hands and applying the posterior electrode against the left leg at the knee or heel)



Source: own adaptation based on screenshot from Alivecor (https://www.alivecor.es)

1.4 Patch-based ECG devices

Patch-based ECG monitors are self adhesive, wireless devices that are well-tolerated, water resistant, and easy to use (Turakhia et al., 2013). A variety of ambulatory ECG patches are available, offering continuous recording of a single channel for 5 to 30 days, and some provide live monitoring using mobile devices or cloud based technology (Table 3). Some of them also offer the ability to monitor vital signs and track movement through accelerometers.

Table 3. Heart rate monitoring devices based on patch-based ECGs

Device	Type	Detection mode	Number of sensors	Area of application	ECG visuali
Bardy Dx Carnation Patch Ambulatory Monitor (CAM)	Patch	ECG	2 electrodes; 1 lead	Chest, self-adhesive	Web-ba platforr
Bio Tel Mobile Patient Telemetry (MCOT)	Patch	ECG	3 electrodes; 2 leads	Chest, self-adhesive	Web-ba platforr
BodyGuardian Mini patches (Preventice)	Patch	ECG	2 electrodes; 1 lead	Chest, self-adhesive	Web-ba platforr
Life Signal Biosensor Patch	Patch	ECG	4 electrodes; 2 leads	Chest, self-adhesive	On-pair device web-ba platforr

MyPatch-SL (CardioScan)	Patch	ECG	3 electrodes; 2/3 leads	Chest, self-adhesive	Web-ba platforr
S-Patch Cardio (Samsung SDS Wellsis)	Patch	ECG	2 electrodes; 1 lead	Chest, self-adhesive	Web-ba platforr
VitalPatch (VitalConnect)	Patch	ECG	2 electrodes; 1 lead	Chest, self-adhesive	Web-ba platforr
VivaLink		ECG	2 electrodes; 1 lead	Chest, self-adhesive	Mobile applicat web-ba platforr

Source: own source based on Svennberg et al., 2021.

Patches have high accuracy and superior diagnostic performance compared to 24-hour Holter monitoring (Barrett et al., 2014). Patch monitoring is cost-effective, with many symptomatic and clinically significant arrhythmias detected within the first week of monitoring (Turakhia et al., 2013; Patel et al., 2021). Their main limitation has been the relatively short battery life and the durability of the adhesive.

1.5 Smartwatches with ECG recording

Smartwatches are becoming a popular wearable technology for monitoring HR and rhythm in athletes. Additionally, they offer other features such as GPS tracking and physical activity monitoring, making them useful for athlete training and competition (Seshadri et al., 2019).

Several models can record a 30 second, single lead ECG using electrodes built into the back of the watch and in the crown or case of the watch (Table 4). The ECG tracings can be viewed in real time on the watch's screen and stored in a mobile app on a smart device. Additionally, PDF files can be generated and shared with the healthcare team, and notifications/alerts based on HR can be programmed to notify the athlete of significant alterations. These smartwatches include built-in AF detection algorithms, but the generated ECG tracings still require medical supervision and analysis to confirm the rhythm.

Table 4. Heart rate monitoring devices based on ECGs via smartwatch

Device	Type	Detection mode	Number of sensors	Area of application	ECG visual
Apple Watch	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	Integra and on device
Fitbit	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	On-pai device
Samsung Galaxy	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	On-pai device
Withings	Smartwatch	ECG and PPG	2 electrodes; 1 lead	Wrist - finger	On-pai device

Source: own source based on Svennberg et al., 2021.

1.6 Other digital devices and smart textiles

Traditionally, blood pressure measurement devices provide HR information and have an AF predictive ability >85% (Kane et al., 2016). With a more active population in mind, garments with built-in electrodes have been designed to monitor HR and rhythm without the need for wires. There are different types of “compression” garments, such as shirts and sports bras, vests, and HR chest straps that are isolated or combined with wristbands (Fouassier et al., 2020; Navalta et al., 2020; Pagola et al., 2018) (Table 5). Chest strap HR devices consist of two parts: an integrated chest strap with an ECG sensor that directly measures cardiac electrical activity, and a wrist receiver that displays HR readings. HR is measured by counting RR intervals without electrocardiographic recordings. These devices have high R wave detection accuracy compared to the ECG Holter (Nunan et al., 2009; Pasadyn et al., 2019; Gillinov et al., 2017). The main limitations include artifacts due to transmission interference between the strap and the receiver, often caused by inadequate contact, the interaction of bras in women with the strap, and general discomfort when wearing them (Gajda et al., 2018; Gajda, 2020).

Table 5. Heart rate monitoring devices based on ECGs via smartwatch

Device	Type	Detection	Number of	Area of	ECG

		mode	sensors	application	visualiza
Movesense Medical (Suunto)	Chest strap	ECG	2 electrodes; 1 lead	Chest	On-paired device
Zephyr BioHarness 3.0 (Medtronic)	Chest strap	ECG	2 electrodes; 1 lead	Chest	On-paired device
Polar H10	Chest strap	ECG and PPG	2 electrodes; 1 lead	Chest	On-paired device
Garmin HRM-PRO	Chest strap	PPG		Chest	On-paired device
NUUBO	Chest strap	ECG	2 electrodes; 1 lead	Chest	On-paired device

Source: own source based on Svennberg et al., 2021.

1.7 User preference considerations

The choice of device should not only consider the indication (presence or absence of symptoms, duration of monitoring, etc.) and the sensitivity/specificity of the device, but should also be tailored to the athlete's preferences (Svennberg et al., 2021). These preferences seem to depend on the type of activity performed. In particular, chest straps generally provide greater accuracy, even during high intensity training, and are more affordable (Cosoli et al., 2022; Ruiz-Alias et al., 2022; Schaffarczyk et al., 2022; Muggeridge et a., 2021). On the other hand, wrist devices provide multifunctionality and comfort. Equipment with built in sensors and smart textiles can also provide high quality signals without hindering movement (Navalta et al., 2020; Yong and Tan, 2017; Breen et al., 2022). Sensor location preference will depend on the sport, type of movement/exercise, or external factors such as the possibility of contusion/contact (Aroganam et al., 2019).

1.8 Uses of new technologies in athletes

Both the athlete and their healthcare provider must be aware of the nuances involved in evaluating the suitability and usefulness of these devices in clinical practice. The term "wearable technology" is a generic phrase that can misleadingly suggest ubiquitous applicability. Several aspects must be considered when selecting the appropriate device or interpreting its findings, as its functionality and limitations are largely context-specific (Fanous & Dorian, 2021):

1. Whether the device is used for optimizing athletic performance or is intended as a clinical tool (including the detection, diagnosis, and monitoring of arrhythmias).

2. If used as a diagnostic tool, it is important to:

    - assess whether it is being applied to a symptomatic or asymptomatic athlete; and
    - evaluate the pre-test probability of having a relevant pathology.

3. If used as a medical tool, it is important to:

- differentiate whether it is employed to diagnose diseases or to monitor known pathologies; and
- determine if the device is being used to measure HR or to record an ECG trace.

4 Are the parameters recorded intermittently or continuously?

5 For devices with ECG capability, does the device generate single- or multi-lead tracings?

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2. Symptomatic athletes

The 12-lead ECG represents the gold standard for the diagnosis of arrhythmias. However, it has limited availability and cannot diagnose paroxysmal arrhythmias unless the recording coincides with the presence of symptoms. Therefore, new technologies present themselves as an interesting alternative in symptomatic athletes despite the fact that most provide a 1 3 lead ECG (Frederix et al., 2019).

The considerations when using digital devices are as follows (Svennberg et al., 2022):

- Many digital devices do not record heart rate continuously. In such cases, recordings must be initiated by the user, and in the event of hemodynamic compromise, this may not be possible.
- Starting a recording requires several seconds followed by a recording of at least 30 seconds. This delay makes existing digital technologies less suitable for diagnosing short arrhythmias.

- Before making therapeutic decisions based on digital device recordings (e.g., initiating anticoagulation for suspected AF or considering an implantable cardioverter defibrillator for presumed ventricular tachycardia), it is imperative to confirm the arrhythmia, carefully ruling out artifacts or noise. To minimize the risk of false positives, recording quality is key, and steps to minimize baseline deviation and artifacts are essential.

PPG recordings can be helpful in confirming normal rhythm and HR in symptomatic patients with very low probability that symptoms are caused by arrhythmias. Any arrhythmia detected using PPG recordings should be confirmed, if possible, using a 12 lead ECG or an ECG based device when 12 lead ECG is not available or the duration of the arrhythmia does not permit an ECG based recording. However, even a regular rhythm with HR within normal limits does not completely rule out the possibility of regular arrhythmias (such as flutter or atrial tachycardia with controlled HR); therefore, in case of doubt, it should always be confirmed by ECG.

CONTINUE

3. Asymptomatic athletes

Athletes have been among the first to adopt new digital technologies to guide their training. However, it is important to note that the use of these devices to identify or monitor events in healthy, asymptomatic athletes, even for screening purposes, may be associated with more damage than benefits.

It is important to bear in mind that the vast majority of arrhythmias detected in healthy asymptomatic athletes are benign in nature and that investigating them excessively can lead to unwanted and unwarranted complications. The risk of sudden cardiac death in athletes is ~1 in 100,000 per person year (Landry et al., 2017), while abnormal ECGs are identified at a rate of 2 10%, yielding a very small positive predictive value (0.001-0.05%) (Fuller et al., 2016). There are no data on the incidence of abnormal findings suggestive of potential risk of sudden death in relation to the use of portable devices. The detection of AF is often considered a relevant diagnosis. However, discovering asymptomatic AF in a person at low risk of stroke has no proven utility (most athletes are younger than 65 years old) (Frederix et al., 2019). ECG-based devices can also generate false positives, and the rate appears to be higher with the use of portable ECG devices with few leads and PPG technology. An athlete who is identified with some abnormality through HR measurement or ECG recording may, as a result, undergo tests or therapies with limited or no benefit or, in the worst case scenario, experience adverse effects. On the other hand, psychological damage ranging from anxiety to depression may occur in disqualified athletes. Even among athletes identified as "true positives", diagnosed disorders may not be associated with an increased risk of sudden cardiac death or the risks may not be modifiable by intervention.

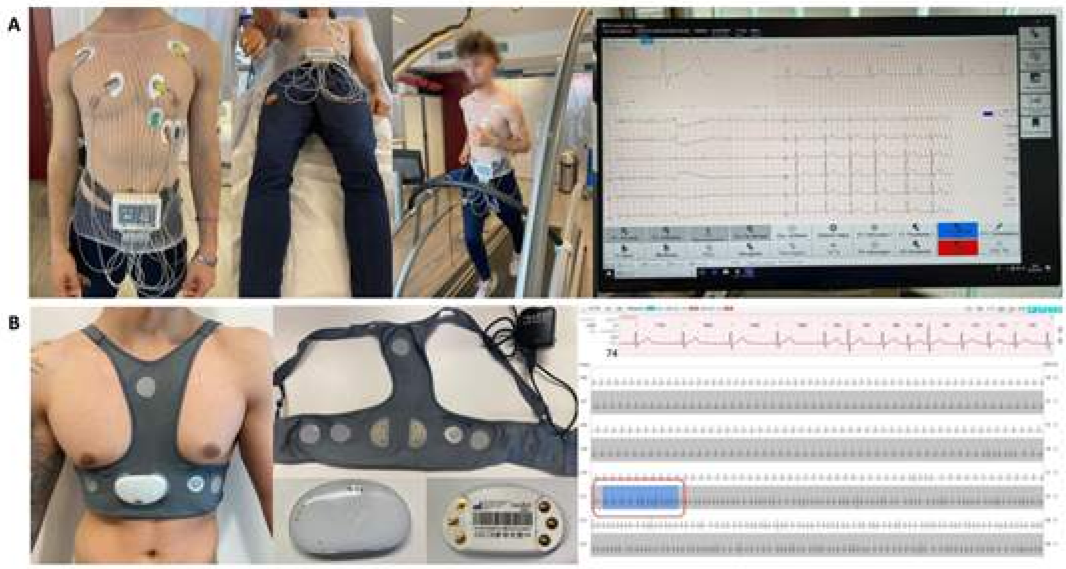
In asymptomatic athletes who are considered to be at high risk of sudden death according to personal or family history and physical examination, 12 lead ECG is the tool of choice. The usefulness of portable ECG devices in this context is limited, as they typically provide only a single lead and face difficulties in continuous ECG monitoring during exercise.

CONTINUE

4. Monitoring of athletes with rhythm disorders

Sports practice produces a series of morphological and functional cardiac adaptations that can give rise to rhythm disorders, some of which are benign and others not. In individuals with detected arrhythmias, beyond a targeted study, it may be interesting to evaluate their behavior during exercise. In these cases, the stress test may not be enough to reproduce the conditions of normal sports practice (Figure 4). Smart devices are a useful tool for rhythm monitoring in patients with known arrhythmias (for example, in patients with ventricular extrasystoles, assessing the burden and complexity in relation to physical activity, or in recurrences of atrial fibrillation or other arrhythmias in individuals who have undergone ablation).

Figure 4. Monitoring of athletes with rhythm disorders using a stress test (A) and smart textile with electrocardiographic recording capability (B)



Source: own source.

On the other hand, rhythm monitoring “in the field” using this technology can be useful for adjusting the programming in patients with implantable cardiac devices (pacemakers or defibrillators).

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5. Monitoring for the prevention of sudden cardiac death

Wearable devices could potentially play a role in the “real-time” monitoring of potentially life threatening arrhythmias during sports competitions to allow for the rapid and targeted deployment of resuscitation efforts. A proof-of-concept test has shown that this is feasible (Spethmann et al., 2014). Given the extreme rarity of such events (1 in 100-200,000 marathon participants, for example), the economic sustainability and the practicality of such an approach (i.e., equipping all athletes with the device) versus preemptive placement of automatic external defibrillators (AEDs) and personnel in sports facilities have yet to be established and will likely continue to change as the price and availability of these devices change (Reagan et al., 2019).

5.1 Results and technology comparison

Although many of the portable devices with HR and ECG detection have been validated in independent studies, we have few data comparing them with each other, and even fewer in the field of sports practice. Overall, validation studies suggest that high end chest band devices have superior performance (accuracy of >0.90) compared to PPG based wrist devices (highly variable accuracy range, 0.36-0.99) (Pasadyn et al., 2019; Gillinov et al., 2017; Boudreaux et al., 2018; Hettiarachchi et al., 2019; Bunn et al., 2019). Furthermore, accuracy varies depending on the type and intensity of exercise (Boudreaux et al., 2019; Bunn et al., 2019).

It should be noted that, in most of the validation studies for each device, inconclusive tracings were excluded for calculating sensitivity and specificity. In an “intention to treat” analysis, which provides a more realistic picture of the diagnostic potential of these tests, there is a drastic reduction in sensitivity and specificity, with values that can be less than 50% in some cases (Mannhart et al., 2023). This is particularly relevant considering that the rate of inconclusive recordings ranges around 20 30% (Mannhart et al., 2023; William et al., 2018; Seshadri et al., 2020; Ford et al., 2022; Bumgarner et al., 2018), mainly due to the presence of bradycardia, tachycardia, or artifacts (noise), such as baseline movement during physical activity. This suggests that automated diagnosis is not sufficient for clinical decision making and that verification of recordings by an experienced professional is essential.

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6. Conclusion

Wearable devices encompass a variety of technologies with different potential applications within the athletic population. When choosing a type, it is necessary to consider its availability, accuracy, and reliability depending on the intended use. An athlete-centered approach is needed when considering the individual benefits and risks associated with the use of wearable devices for cardiac monitoring. On the other hand, it is important to keep in mind that the underlying technology will continue to progress, and therefore, the utility of these devices will remain dynamic.

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