Michael Sampson

Ambulatory electrocardiography: indications and devices

British Journal of Cardiac Nursing, March 2019, Vol 14, No 3, p. 114–121.

Abstract

Cardiac electrical abnormalities are common, and result in considerable morbidity and mortality. Although diagnosis can sometimes be made from the resting 12-lead electrocardiogram (ECG), a longer period of monitoring is often required to capture diagnostic information. Ambulatory ECG (AECG) devices allow cardiac rhythm to be monitored and recorded over days, weeks or years, and are used primarily in the outpatient setting. Multiple devices are available, with a variety of features. Recording may take place continuously or occur intermittently in response to patient activation or auto-sensing of rhythm disturbances. Devices may be fitted externally or implanted below the skin. Data may also be acquired from an existing pacemaker or implantable cardioverter defibrillator (ICD). In this article, commonly used methods of AECG monitoring are described and appraised. Newer developments in monitoring are also evaluated, including the role of patient-led, smart-phone-based devices.

Key words

Ambulatory ECG; Holter monitor; event recorder; loop recorder; patient-led monitoring

Key points

- Ambulatory ECG (AECG) monitoring is used to investigate palpitations, chest pain and syncope. It is also used to screen high risk individuals for arrhythmia, and to guide treatment in those with an established diagnosis.

- Recording of cardiac electrical activity can be continuous or intermittent. Continuous monitoring uses more memory, limiting the duration of monitoring that is possible. The most commonly employed continuous AECG device is the Holter monitor, which is fitted for a period of 24 hours to 7 days.

- Intermittent recording of cardiac electrical activity is possible using event or loop recorders. These allow a longer duration of monitoring, but some devices rely on patient activation, which means that important events may be missed. Newer devices have arrhythmia detection software, and record automatically if an arrhythmia is detected.

- The longest duration of monitoring is achieved using implantable loop recorders, which have a battery life of around 3 years. Pacemakers and implantable cardioverter defibrillators are also useful in long term monitoring as they continuously monitor heart rhythm and store key information.

- A variety of smart phone-based devices is now available, allowing patients to monitor their own heart rhythm. Although these devices are convenient and increase patient engagement, they are limited by basic arrhythmia detection software and single channel recording of lead I.

CPD activities

1. Find out which types of AECG monitor are available in your organisation, how they are requested, and the duration of monitoring that is available.

2. Consider a typical patient from your practice area who is likely to need AECG monitoring. Make a list of the issues that you would need to consider when choosing a monitor for them.

3. Patient are becoming more involved in monitoring their own health. Consider how this affects the relationship between patient and nurse, and what steps need to be taken to ensure that patient recorded data is handled and recorded appropriately.

Introduction

Disorders of cardiac electrical activity are common, and result in considerable morbidity and mortality (Bennett, 2013). Although diagnosis can sometimes be made from the resting 12-lead electrocardiogram (ECG), electrical abnormalities are frequently intermittent, and may be absent when the patient is assessed in the clinical setting (Zimetbaum and Goldman, 2010). Longer term monitoring of heart rhythm is necessary when this is the case, and is usually achieved using ambulatory ECG (AECG) monitors. These devices monitor and record electrical events while the individual goes about their usual activities, either during an inpatient stay, or more commonly in the outpatient setting.

Many different AECG devices are available, from short term external monitors such as Holters through to long term implanted devices. The choice of device is guided by multiple factors, including the indication for monitoring, the frequency of symptoms, and monitor availability within the healthcare setting. This article reviews AECG devices that are commonly used in the UK, and evaluates their role in contemporary healthcare practice.

Indications for ambulatory ECG

Common indications for AECG monitoring include the investigation of palpitations, chest pain and syncope; the evaluation of arrhythmia treatment; and the screening of patients with structural heart disease or cryptogenic stroke (one in which the cause is not known) (Steinberg et al, 2017). A list of common indications can be found in box 1. Depending on the indication, and assessment of the patient, a continuous or intermittent recording device may be selected.

Continuous recorders

Continuous recording devices capture every beat during the recording period and store it to memory (Kennedy, 2013). This provides a complete picture of electrical events, which is especially useful when assessing arrhythmia burden (for example the number of ectopic beats), heart rate profile, or rate control in atrial tachyarrhythmia (Steinberg et al, 2017). Because of the large amount of data captured, the duration of monitoring possible is relatively short. This makes these devices less suitable for symptoms that occur infrequently; their diagnostic yield is especially low in palpitations that occur less than weekly, syncope, and cryptogenic stroke (Zimetbaum and Goldman, 2010). The most commonly used continuous recorder is the Holter monitor, although the use of patch electrode monitors is becoming more widespread.

Holter monitors

Holter monitors were the first AECG recorders and remain the most commonly used (Kohno et al, 2017). The device was developed in the 1950s by Norman J Holter and Bill Glasscock, a pair of experimental physicists; the first commercially available devices appeared in the early 1960s. The Holter monitor uses wet gel skin electrodes to pick up cardiac electrical activity, which is transmitted to a recording device worn on a lanyard around the neck or clipped to the belt (see figure 1). Early devices were analogue and recorded a single channel onto magnetic tape, limiting the data that could be acquired (Kennedy, 2013). This limitation has been addressed to some extent in modern

devices, which use solid state components and record digital data onto memory cards. This allows the recording of multiple channels over a longer time period; Holter monitors used in the NHS are commonly capable of recording two or three channels for up to seven days, although recordings of 24 or 48 hours are more common (Steinberg et al, 2017). Some devices are capable of recording a full 12-lead ECG over a 24-hour period (Spacelabs Healthcare, 2018).

In the NHS, Holter monitors are typically fitted to a patient in the cardiology department or primary care clinic, and returned by the patient when recording is complete. The recording is played back and analysed using dedicated software which assesses rhythm as well as the timing and QRS morphology of each beat. A range of values are calculated including minimum, maximum and mean heart rate; number and type of normal and premature beats; and duration of any arrhythmia detected (Khalil et al, 2017) (see figure 2). Despite this automation, the recording must be evaluated by a cardiac technician or physiologist, a process which takes time and expertise. The final report will contain representative ECG strips chosen by the operator (see figure 3).

Holter monitoring is a powerful tool in patient assessment. Events that would be difficult or impossible to capture using 12-lead ECG or bedside monitoring can be recorded and analysed (Khalil et al, 2017). The use of multiple recording channels means that several ECG leads are available for comparison, which can be helpful in assessing waveforms and excluding artefacts (Bennett, 2013). Other advantages of the Holter include its wide availability, low cost and widespread acceptance by clinicians (Steinberg et al, 2017).

Despite its ubiquity, the device has several limitations. Diagnosis often depends on correlating symptoms with ECG findings. To achieve this, the patient must record relevant symptoms in a paper diary, and return it with the monitor. Compliance with this requirement is generally poor, making it difficult to interpret the significance of recorded ECG events (Bennett, 2013). Some people find the device obtrusive or suffer skin irritation from the electrodes. Devices are splash proof, but not waterproof, meaning the individual cannot bathe, shower or swim while wearing it. These issues reduce compliance with monitoring; accidental or deliberate disconnection is not uncommon (Steinberg et al, 2017). The short duration of monitoring means that diagnostic yield is low for infrequent events, so a negative result does not necessarily exclude significant disease (Zimetbaum & Goldman, 2010). Finally, analysis does not take place until the monitor has been returned, leading to a delay in the identification of important events (Steinberg et al, 2017). This delay often extends to several weeks because of the high volume of Holters that are analysed in NHS organisations.

Patch electrode monitors

Patch electrode monitors (PEM) are small, single-use AECG recorders that address many of the limitations of Holter monitoring (Lobodzinski and Laks, 2012). Typically, they monitor or record the ECG continuously over 7-14 days using two electrodes contained within a self-adhesive patch device, worn in the left pectoral region. In the UK, the most commonly used PEM is the Zio patch, produced by iRhythm (see figure 4).

The Zio patch provides 14 days of continuous ECG recording (Turakhia et al, 2013). The patient can highlight symptomatic events by pressing a button on the device and is encouraged to record the details using a paper diary or smart phone application (app). When monitoring is complete, the device is returned to iRhythm by mail. The company analyses the recording using dedicated software, and a report is produced in a similar way to a Holter. The device is self-contained, waterproof, and less obtrusive than a Holter monitor, resulting in increased patient compliance

(Steinberg et al, 2017). The longer monitoring period increases diagnostic yield; in a study of patients with suspected arrhythmia, almost twice as many arrhythmias were detected in patients fitted with a Zio patch compared to a 24-hour Holter (Barrett et al, 2014).

Despite these advantages, the device is not available in most NHS trusts, despite widespread adoption in the private sector. The principal reason for this is cost. The National Institute of Health and Care Excellence (NICE) estimates that the device, including analysis and report, costs £800 per single-use monitor (NICE, 2017). By comparison, a typical, reusable NHS Holter monitor costs just over £1600, with an estimated cost for fitting and analysis of £118.60 per patient (NICE, 2017).

Intermittent recorders

Intermittent recording devices are used for longer periods of monitoring, typically up to four weeks for external devices, and three to four years for implanted monitors (Kennedy, 2013). Unlike a Holter or Zio patch, they do not record every heartbeat, which generally makes them unsuitable for the assessment of rate control or ectopic frequency. They are, however, much more effective in establishing a diagnosis when symptoms or events are infrequent (Zimetbaum and Goldman, 2010). Intermittent recorders fall into several categories; those that are deployed only when the patient is aware of symptoms, commonly referred to as event recorders, and those that continuously monitor the heart rhythm. These latter devices are known as loop recorders and can be fitted externally or implanted inside the body. Recording of an event to memory occurs when the patient activates the monitor manually, or when the device auto-triggers in response to a rhythm abnormality identified by integral software (Steinberg et al, 2017).

Event recorders

Traditional event recorders are hand held devices that are capable of recording a single ECG lead for several minutes (Kohno et al, 2017). The recording is activated by the patient, who presses a button on the device whilst holding it against the chest (see figure 5). The recording can be downloaded to the monitoring centre by telephone, meaning that near real-time monitoring is possible if the patient downloads immediately. Unlike a Holter, an event recorder is unobtrusive as it can be carried in a pocket or bag when not in use; there are no wires stuck to the chest and no limitations to normal activities (Zimetbaum & Goldman, 2010).

Unfortunately, this lack of constant ECG monitoring is also its major limitation. Because the device must be placed against the chest, capturing brief symptomatic episodes can be difficult, and asymptomatic events will not be recorded at all (Kohno et al, 2017). Electrical events that are recorded will not show the onset of the episode, which can be an important diagnostic feature. Event recorders are of limited use in the evaluation of syncope, as the unconscious individual will be unable to activate the monitor, and bystanders may be unaware of it or lack the presence of mind to use it (Ruwald & Zareba, 2013).

External loop recorders

External loop recorders (ELR) overcome some of the limitations of event recorders. ELR are similar to Holter monitors in that wet gel electrodes are placed on the chest wall and attached to a monitor

that is carried around the neck or on the belt (Khalil et al, 2017). This constant interface with the skin allows the device to monitor the heart rhythm continuously, although recording to memory only occurs when the patient triggers the device, or it autodetects a rhythm abnormality. Older ELR were not equipped with arrhythmia detection software and relied on patient activation (Kennedy, 2013). With these devices, asymptomatic or disabling events are not recorded, resulting in a lower diagnostic yield than devices equipped with auto-triggering. In a study of arrhythmia detection by Reiffel et al (2005), the diagnostic yield from 24-hour Holter monitoring was 6.2% compared to 17% for patient-activated ELR and 36% for ELR with auto-triggering. All ELR store several minutes of ECG data in a short-term memory loop; this allows the device to save the ECG immediately prior to an event as well as after it, allowing evaluation of arrhythmia onset (Steinberg et al, 2017).

As with event recorders, ELR have limited memory so timely transmission to the monitoring centre is important. While this should ensure near real-time data acquisition, it also raises a potential problem. A certain degree of technological ability is required to operate an ELR or event recorder, and to download it via the telephone. In one study by Gula et al (2004), 84.5% of patients completed a satisfactory test transmission, but only 58.9% were successful in recording and transmitting a symptomatic event. This reliance on patient data transmission is a major limitation in the use of this type of monitor (Zimetbaum and Goldman, 2010). As with Holters, compliance with ELR can be problematic due to the use of skin electrodes.

Some newer devices combine features of the Holter monitor with those of an ELR. The best-known example in the UK is the Novacor R.Test (see figure 6). The latest version of this device, the R.Test evolution 4, analyses ECG in real time and automatically stores detected arrhythmias according to user defined criteria. It can be used for up to 32 days, and has a one-hour storage capacity for patient triggered events (Novacor UK Ltd, 2018). Heart rate and arrhythmia burden are calculated for the entire monitoring period, in a similar way to a Holter. The device is reusable, and is returned to the hospital or clinic at the end of the monitoring period for analysis using proprietary software. Patients are not required to transmit data trans-telephonically.

Implantable loop recorders

Although external monitors are effective when symptoms are frequent, the likelihood of achieving symptom-ECG correlation for events that occur less than once per month is low. In a study of recurrent, infrequent palpitations, Giada et al (2007) demonstrated a diagnostic yield of 21% using external monitors. The success rate for people with syncope or cryptogenic stroke is lower still (Steinberg et al, 2017).

For individuals needing an extended period of monitoring, the implantable loop recorder (ILR) offers an effective alternative to external monitors. Several devices are available, although the Medtronic Reveal device is the most widely known and studied. The latest iteration of this device, the Reveal LINQ, is similar in appearance to a USB memory stick, and weighs 2.5 grams (Medtronic, 2018) (see figure 7). The device is implanted subcutaneously over the fourth intercostal space to the left of the sternum, using a minimally invasive approach. It has a battery life of approximately three years. Recordings are prompted automatically by programmable arrhythmia detection software, and can also be initiated by the patient using a handheld activator (NICE, 2018). Results are downloaded in the pacing department using a programmer in a similar way to a pacemaker, or using a home monitoring device. This sits beside the patient's bed and downloads data wirelessly, before transmitting it to the local monitoring centre (Medtronic, 2018).

Diagnostic yields are much better with ILR because of the longer duration of monitoring. Steinberg et al (2017) estimate a yield of 80-90% for palpitations, 30-50% for syncope, and 15-20% for cryptogenic stroke. The device is a class one recommendation for undiagnosed syncope in current European guidelines (Brignole et al, 2018). Unlike external devices, an ILR cannot be disconnected or left at home, is unobtrusive, and does not limit daily activities. In a recent briefing, NICE (2018) evaluated the cost effectiveness of the Reveal LINQ in the detection of cryptogenic stroke. Without VAT, the device costs £1800 per person, plus an estimated £474 in follow-up costs over three years. While this is more expensive than external monitoring, there are potential cost savings in terms of stroke prevention. The main consideration for patients is the invasive nature of the device. In their meta-analysis of published studies, Solbiati et al (2017) found that device-related complications were rare although they acknowledge under-reporting in the literature. In the CRYSTAL-AF trial, 2.4% of patients had an ILR removed due to infection or pocket erosion (Sanna et al, 2014).

Pacemakers and implantable cardioverter defibrillators

Although pacemakers and implantable cardioverter defibrillators (ICD) are implanted primarily to deliver pacing therapies to the heart, monitoring of electrical activity is an intrinsic part of their function (Bennett, 2013). These devices have complex arrhythmia detection algorithms, and store detailed information concerning heart rate as well as arrhythmia frequency, duration, and burden. This makes them useful tools in the long-term monitoring of electrical activity. In patients who have a device in situ, it may be unnecessary to organise additional, external AECG monitoring (Steinberg et al, 2017). Interrogation of the pacemaker or ICD typically occurs in the pacing department during regular outpatient visits, but can be organised ad-hoc in both outpatient and inpatient settings. Accurate diagnosis of arrhythmias often requires comparison of data recorded by atrial and ventricular leads. Dual chamber systems therefore yield more useful information than single chamber devices.

Patient-led monitoring

Until recently, AECG monitoring was the sole preserve of healthcare providers. The rapid growth of personal computing and mobile technology has changed this, with patients now able to record an ECG using a small device communicating with a smartphone (Walker and Muhlestein, 2018). Although multiple technologies are available, the most relevant devices in the UK are probably the KardiaMobile and Apple watch.

KardiaMobile

The KardiaMobile is a handheld device the size of credit card (AliveCor Inc, 2018). It costs £99 and is used in conjunction with a smartphone or tablet running the KardiaMobile app, which can be downloaded for free. Using the app, the user initiates a recording and places two fingers on each of the electrodes housed in the device (see figure 8). Provided there is good contact, a rhythm strip of lead I is displayed on the smart phone or tablet. This can be saved as a PDF, and e-mailed to a clinician if necessary. The app has a basic arrhythmia recognition algorithm, and categorises each recording as normal sinus rhythm, probable atrial fibrillation, or unclassified.

In clinical trials, the device has proven efficacy in identifying atrial fibrillation, with a sensitivity of 96.6% and specificity of 94.1% (William et al, 2018). This was, however, after the exclusion of unclassified results, which are recordings that the device cannot interpret. Moreover, the device has several important limitations. Detection of atrial flutter has been problematic because this rhythm is often regular, and may be mistaken for sinus rhythm. Interpretation is difficult because P-wave amplitude is often low in lead I, making flutter waves hard to distinguish. A potential solution is to hold the device between bare legs, with the right hand holding the right electrode, and the left electrode against the left leg. This records lead II, which typically shows atrial activity more clearly (Rajakariar et al, 2018). Unfortunately, it can be quite hard to achieve good electrode contact with this technique, which also necessitates the removal of trousers or tights. The other limitation relates to data acquisition. Data is transmitted as a sound signal; if the device is too far from the smartphone, or there is ambient noise, recording may be unsuccessful. In the authors own practice, the device has proved impractical for routine use in the outpatient clinic, although several patients have used it successfully to document AF recurrence following catheter ablation.

Apple watch

The fourth iteration of the Apple watch was released on 6th December 2018, with a price in the UK of £400. The device has one ECG electrode built into the back of the watch, and another in the digital crown, a small control wheel on the side of the device (see figure 9). As with the KardiaMobile, a dedicated app is used to initiate recordings. The user places a finger on the digital crown to record a lead I rhythm strip, which is displayed on the watch face (Apple Inc, 2018). Arrhythmia analysis is similar to the KardiaMobile, with ECGs classified as normal, AF or unclassified. Recordings are stored as PDFs in the Health app on the user's i-phone. The watch also has an irregular rhythm notification feature. This assesses rhythm regularity intermittently, and alerts the user if repeated checks suggest an irregular rhythm.

Although the device is in its infancy, the popularity of Apple products and the convenience of the design suggest that it will become widely used in the future. This has led to concerns that an increase in false positive findings could increase unnecessary healthcare consultations (Wendling, 2018). Given the similarity of the recording method, it may also be subject to the same analytical limitations as the KardiaMobile. Nonetheless, empowering people to take control of their own health is an important aim in modern healthcare, and should reduce reliance on providers in the long term. Any clinician who has shared the frustration of a highly symptomatic patient, undiagnosed despite repeated hospital organised monitors, will welcome devices that enable people to monitor their own rhythm.

Conclusion

Ambulatory ECG has an important place in modern healthcare practice, and is used to diagnose symptoms, monitor the effects of treatment, and screen for possible disease. Multiple methods are available with key features including the duration of monitoring that is possible, continuous or intermittent recording, and patient activated versus auto-triggering of recordings. The limitations of traditional devices in terms of adherence and data transmission have largely been addressed by a new generation of smaller, smarter devices although these are not always available in the NHS due to cost. For infrequent events, implanted monitors offer a more effective alternative with a low rate of device-related complications. Patient-led monitoring is a rapidly expanding area of practice which

relies on smart phone technology. It has the advantage of greater patient involvement, but is limited by the design of currently available devices, which excel in detecting atrial fibrillation but lack discrimination in other types of rhythm disturbance.

References

AliveCor Inc (2018) *KardiaMobile*, available at https://www.alivecor.com/how-it-works/ Accessed 19/12/2018.

Apple Inc. (2018) ECG app and irregular heart rhythm notification available today on Apple Watch, available at https://www.apple.com/newsroom/2018/12/ecg-app-and-irregular-heart-rhythm-notification-available-today-on-apple-watch/ accessed 13/12/2018.

Barrett PM, Komatireddy R, Haaser S, Topol S, Sheard J, Encinas J, Fought AJ, Topol EJ. (2014) Comparison of 24-hour Holter monitoring with 14-day novel adhesive patch electrocardiographic monitoring. *American Journal of Medicine*, 127(1):95-e11.

Bennett DH (2013) *Bennett's Cardiac Arrhythmias: Practical notes on interpretation and treatment*, 8th edition, London: Hodder Arnold.

Brignole M, Moya A, de Lange FJ, Deharo JC, Elliott PM, Fanciulli A, Fedorowski A, Furlan R, Kenny RA, Martín A, Probst V. (2018) 2018 ESC Guidelines for the diagnosis and management of syncope, *European Heart Journal*, 39(21):1883-948.

Giada F, Gulizia M, Francese M, Croci F, Santangelo L, Santomauro M, Occhetta E, Menozzi C, Raviele A. (2007) Recurrent unexplained palpitations (RUP) study: comparison of implantable loop recorder versus conventional diagnostic strategy, *J Am Coll Cardiol,* 49:1951–1956.

Kennedy HL (2013) The evolution of ambulatory ECG monitoring, *Progress in Cardiovascular Diseases*, 56(2):127-32.

Khalil CA, Haddad F, Al Suwaidi J (2017) Investigating palpitations: the role of Holter monitoring and loop recorders. *BMJ: British Medical Journal (Online).* Jul 27;358.

Kohno R, Abe H, Benditt DG. (2017) Ambulatory electrocardiogram monitoring devices for evaluating transient loss of consciousness or other related symptoms, *Journal of Arrhythmia,* 33(6):583-9.

Lobodzinski SS, Laks MM (2012) New devices for very long-term ECG monitoring, *Cardiology Journal*, 19(2):210-4.

Medtronic (2018) *Reveal LINQ™ Insertable Cardiac Monitoring System*, available at https://www.medtronic.com/uk-en/healthcare-professionals/products/cardiac-rhythm/cardiac-monitors/reveal-linq-icm.html Accessed 18/12/2018

National Institute of Health and Care Excellence (2017) *Zio Service for detecting cardiac arrhythmias. Medtech innovation briefing [MIB101]*. Available at https://www.nice.org.uk/advice/mib101/chapter/The-technology Accessed 19/12/2018.

National Institute of Health and Care Excellence (2018) *Reveal LINQ insertable cardiac monitor to detect atrial fibrillation after cryptogenic stroke. Medtech innovation briefing [MIB141].* Available at https://www.nice.org.uk/advice/mib141 Accessed 18/12/2018

Novacor UK Ltd (2018) *R.Test evolution 4*, available at https://www.novacor.co.uk/item-rtest_4.html Accessed 19/12/2018

Rajakariar K, Koshy AN, Sajeev JK, Nair S, Roberts L, Teh AW (2018) Modified positioning of a smartphone based single-lead electrocardiogram device improves detection of atrial flutter, *Journal of Electrocardiology,* 51(5):884-8.

Reiffel JA, Schwarzberg R, Murry M (2005) Comparison of autotriggered memory loop recorders versus standard loop recorders versus 24-hour Holter monitors for arrhythmia detection*, Am J Cardiol*, 95:1055–9.

Ruwald MH, Zareba W (2013) ECG monitoring in syncope, *Progress in Cardiovascular Diseases*, 56(2):203-10.

Sanna T, Diener HC, Passman RS, Di Lazzaro V, Bernstein RA, Morillo CA, Rymer MM, Thijs V, Rogers T, Beckers F, Lindborg K. (2014) Cryptogenic stroke and underlying atrial fibrillation. *New England Journal of Medicine*, 370(26):2478-86.

Solbiati M, Casazza G, Dipaola F, Barbic F, Caldato M, Montano N, Furlan R, Sheldon RS, Costantino G. (2017) The diagnostic yield of implantable loop recorders in unexplained syncope: A systematic review and meta-analysis, *International Journal of Cardiology*, 231:170-6.

Spacelabs Healthcare (2018) *Lifecard CF*, available at https://www.spacelabshealthcare.com/diagnostic-cardiology/holter-analyzersrecorders/lifecard-cf#.XBjEjWj7SUk Accessed 18/12/2018

Steinberg JS, Varma N, Cygankiewicz I, Aziz P, Balsam P, Baranchuk A, Cantillon DJ, Dilaveris P, Dubner SJ, El-Sherif N, Krol J (2017) ISHNE-HRS expert consensus statement on ambulatory ECG and external cardiac monitoring/telemetry, *Heart Rhythm*, 14(7):e55-96.

Turakhia MP, Hoang DD, Zimetbaum P, Miller JD, Froelicher VF, Kumar UN, Xu X, Yang F, Heidenreich PA. (2013) Diagnostic utility of a novel leadless arrhythmia monitoring device, *American Journal of Cardiology*, 112(4):520-4.

Walker AL and Muhlestein JB (2018) Smartphone electrocardiogram monitoring: current perspectives, *Advanced Healthcare Technologies*, 4:15-24.

Wendling P (2018) *Apple Watch ECG App Rolls Out: The Healthcare Experiment Begins*, available at https://www.medscape.com/viewarticle/906206?nlid=126567_3865&src=WNL_mdplsfeat_181211_mscpedit_card&uac=124944BK&spon=2&impID=1827820&faf=1#vp_2 Accessed 19/12/2018

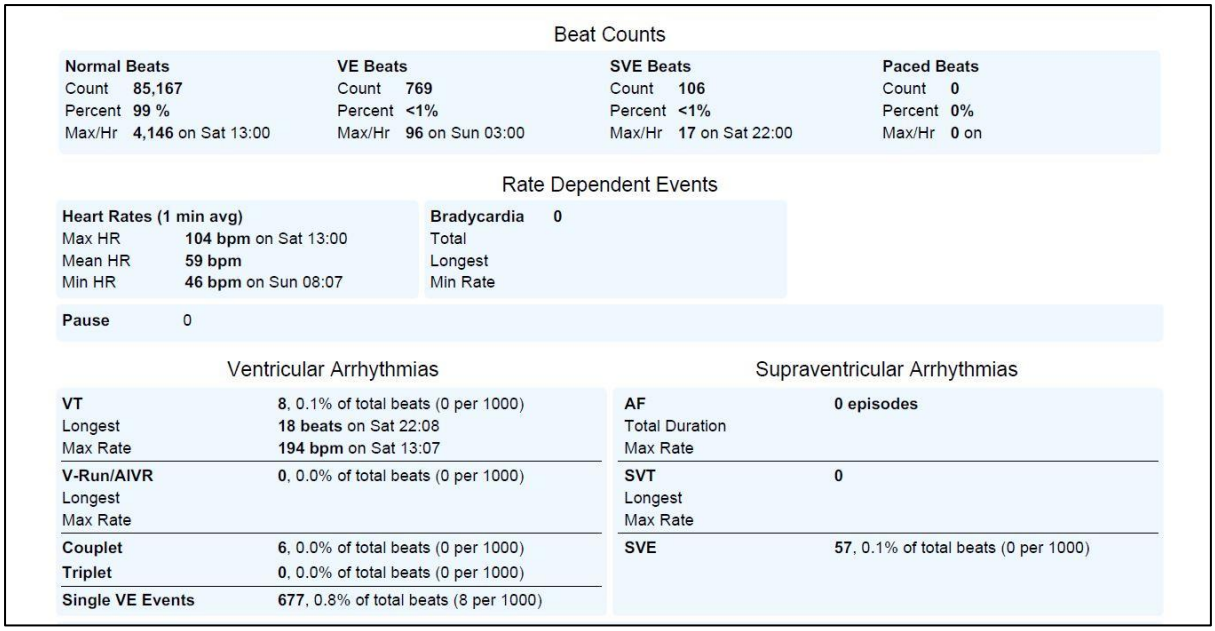
William AD, Kanbour M, Callahan T, Bhargava M, Varma N, Rickard J, Saliba W, Wolski K, Hussein A, Lindsay BD, Wazni OM. (2018) Assessing the accuracy of an automated atrial fibrillation detection algorithm using smartphone technology: The iREAD Study. *Heart rhythm*. 15(10):1561-5.

Zimetbaum P, Goldman A (2010) Ambulatory arrhythmia monitoring: choosing the right device. *Circulation,* 122:1629e1636.

Investigation of syncope, dizziness, chest pain, palpitations or shortness of breath
Screening for • atrial arrhythmia following cryptogenic stroke • arrhythmia recurrence following catheter ablation • arrhythmia in high risk individuals (e.g. post myocardial infarction)
Evaluation of • patient response to initiation or change in antiarrhythmic drug therapy • rate control in atrial tachyarrhythmia • arrhythmia burden, for example in paroxysmal AF or ventricular ectopy • pacemaker function • heart rate variability when chronotropic insufficiency is suspected • QT interval or ST-segment

Box 1. Common indications for ambulatory monitoring

Figure 1. A typical three-electrode Holter monitor



Beat Counts

Normal Beats	VE Beats	SVE Beats	Paced Beats
Count 85,167	Count 769	Count 106	Count 0
Percent 99 %	Percent <1%	Percent <1%	Percent 0%
Max/Hr 4,146 on Sat 13:00	Max/Hr 96 on Sun 03:00	Max/Hr 17 on Sat 22:00	Max/Hr 0 on

Rate Dependent Events

Heart Rates (1 min avg)		Bradycardia	0
Max HR	104 bpm on Sat 13:00	Total	
Mean HR	59 bpm	Longest	
Min HR	46 bpm on Sun 08:07	Min Rate	

Pause	0

Ventricular Arrhythmias

VT	8, 0.1% of total beats (0 per 1000)
Longest	18 beats on Sat 22:08
Max Rate	194 bpm on Sat 13:07
V-Run/AIVR	0, 0.0% of total beats (0 per 1000)
Longest	
Max Rate	
Couplet	6, 0.0% of total beats (0 per 1000)
Triplet	0, 0.0% of total beats (0 per 1000)
Single VE Events	677, 0.8% of total beats (8 per 1000)

Supraventricular Arrhythmias

AF	0 episodes
Total Duration	
Max Rate	
SVT	0
Longest	
Max Rate	
SVE	57, 0.1% of total beats (0 per 1000)

Figure 2. Extract from a Holter report showing numerical values

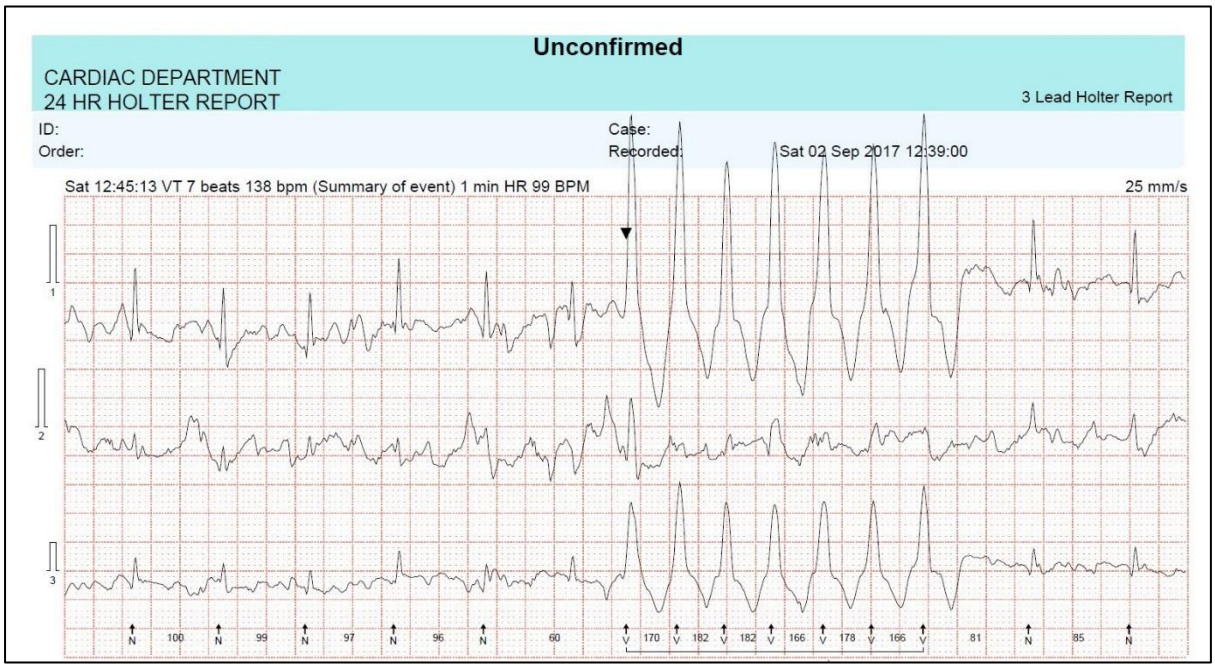


Figure 3. An episode of non-sustained ventricular tachycardia recorded during 24-hour Holter monitoring

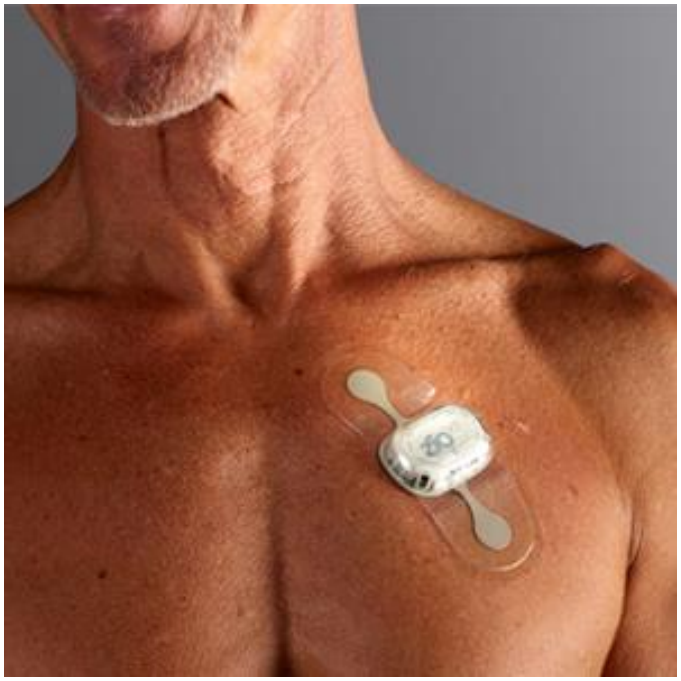


Figure 4. The Zio patch (used with kind permission from iRhythm)

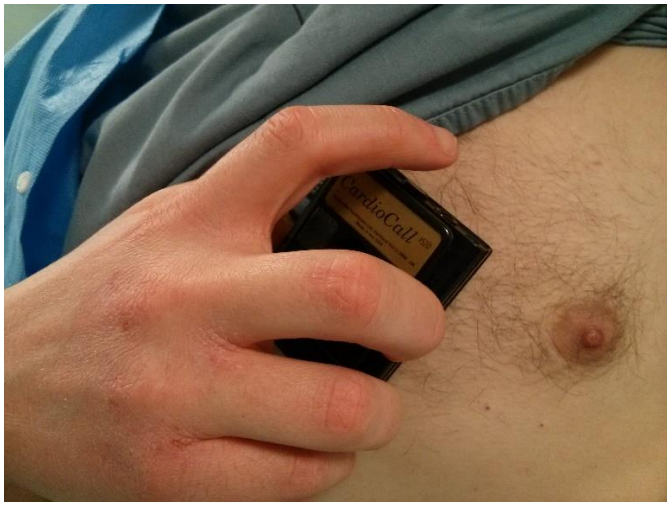


Figure 5. An event recorder is held against the chest when the patient experiences symptoms

Figure 6. The R.Test evolution 4 (used with kind permission from Novacor UK Ltd)

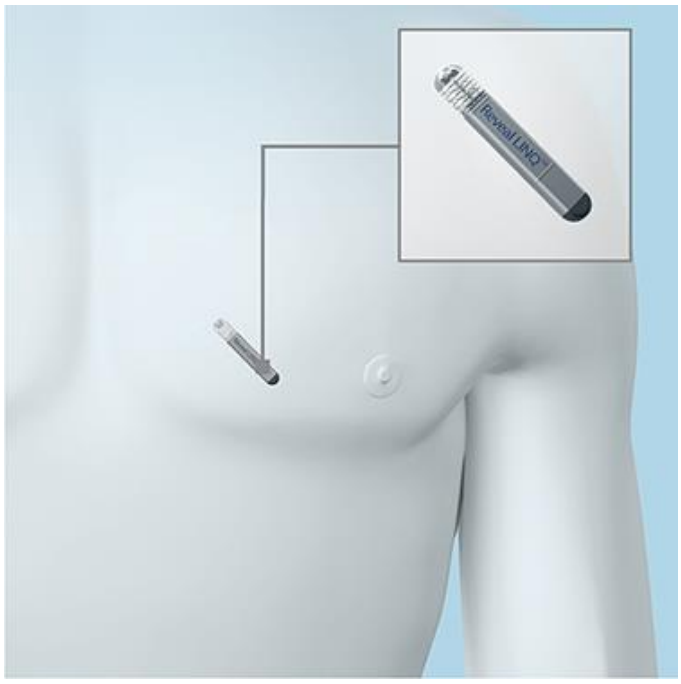


Figure 7. The Reveal LINQ (used with kind permission from Medtronic)

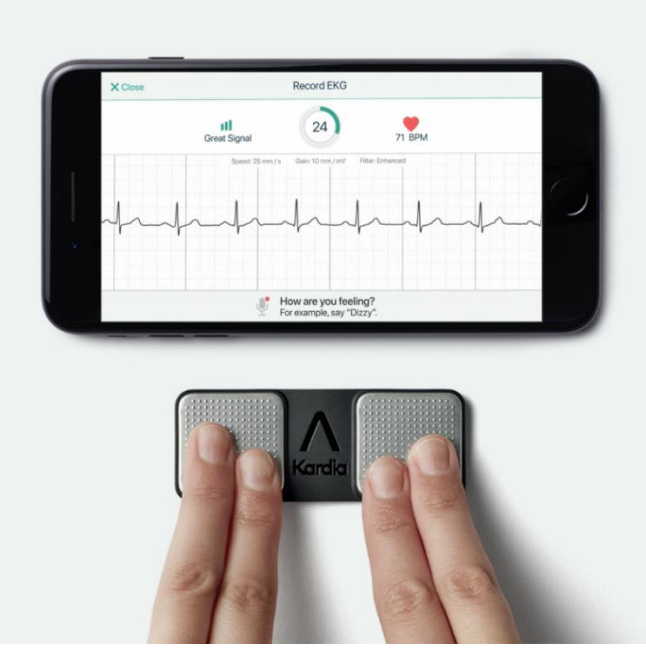


Figure 8. The KardiaMobile (used with kind permission from Alivecor Inc)

Figure 9. The Apple Watch (used with kind permission from Apple Inc)