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7. Basic Diagnostics in Cardiology

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The term basic cardiology diagnostics refers to the noninvasive measurement of the cardiac electrical action potential at rest and under stress, in order to assess heart function. Due to technical developments in ECG systems, the informative value of (basic) diagnostic assessments of the cardiovascular system has improved enormously with ever-increasing accuracy. This chapter introduces equipment-based diagnostic methods: Sect. 7.1 ECG, Sect. 7.9 Holter Monitoring and Sect. 7.19 Exercise ECG.

7.1 Electrocardiography

Electrocardiography (ECG) is a method of recording electrocardiograms – which record the temporal and spatial profiles of the electrical excitation processes in the myocardium in the form of waves, peaks and lines

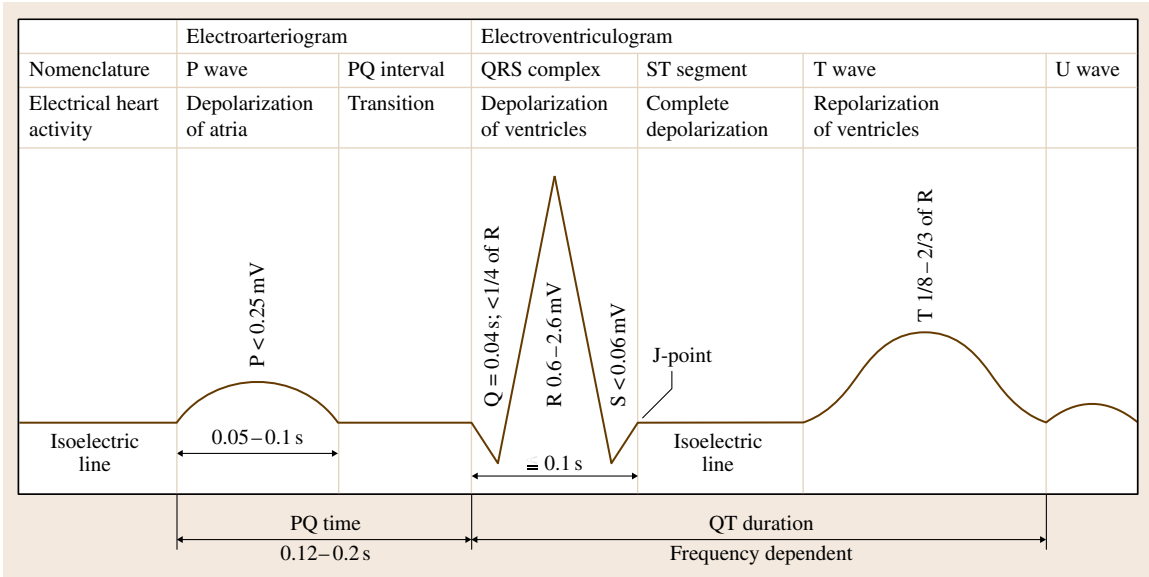

Fig. 7.1 Nomenclature of the electrocardiogram (ECG)

(Fig. 7.1) – and performing diagnostic analyses of these electrocardiograms.

Every instance of depolarization through cardiac fibres is the source of an electric potential. These noninvasive measurements generally measure potential differences that occur across an electric field on the surface of the body, which make up only a fraction of the potential generated by the heart. The heart is thus interpreted as a source of potential, so the ECG ultimately provides an image of the generation of electricity (potential shift) and reflects the excitation processes in the measurements selected.

7.2 Electrocardiograph Equipment Technology and PC ECG

Electrocardiographs (ECG devices for short) and PC ECG modules are diagnostic devices for recording, amplifying, storing, processing, analysing and documenting (registering) an electrocardiogram. Noninvasive electrocardiography has been a standard procedure for a number of decades, and ECG equipment is therefore as good as is mandatory in both hospitals and small private practices.

7.2.1 Physical and Technological Principles

ECG systems are low-noise differential amplifiers; in other words, they consist of a strongly coupled DC amplifier with a high amplification factor and inverting (reversed) and noninverting inputs. The output voltage is a multiple of the voltage present at the input terminals. It is the differential voltage of the two voltages present at the same pole. Particularly high requirements are set for an ECG preamplifier when compared to usual amplifier technology: interfering high-frequency AC voltages are attenuated by means of a high-frequency filter upstream of the preamplifier input, so that no overamplification or self-excitation can occur. Extreme interference voltages are likewise blocked by means of discharge sections and antiparallel diodes. A relatively high input resistance (generally 10 MΩ and above) keeps the input currents very low. Capacitively coupled mains-frequency AC voltages are eliminated through high common mode rejection. Following a 20- to 30-fold preamplification, the ECG signal is separated from the direct current via a high-pass filter. The time constant of this filter is 1.5 or 3.2 s. Whereas the processed ECG signal is fed to the respective channel amplifiers (1 . . . > 12) via an lead selector in analogue ECG equipment, this step is omitted in digital ECG equipment. The recorded signals are instead connected to 12

leads, amplified and fed to a processor system (control computer – CPU) via multiplexers and A/D converters. The system software processes all of the digitized input signals, interpolates the individual measurement readings to give continuous curves, controls equipment processes, and communicates with the operator via the keypad, display and printout; it prepares text outputs, displays the time, produces a QRS trigger signal, and evaluates the remote start ergometer input. Output occurs via a digital recording system, the thermal comb.

In analogue ECG equipment, following further amplification to ≈1–2 V using the respective channel amplifier, the ECG signal is output via a power amplifier stage (final amplifier) and finally through a mechanical recording system (e.g. lever recorder, inkjet recorder, etc.).

ECG measurement, the signal path and signal processing resemble a measurement chain, from the test object (patient) via transducers or sensors (electrodes) and the transfer of measurement readings (electrode leads and patient cables) to signal processing, signal evaluation and documentation (ECG equipment). The recording electrodes or the intracardiac electrode (signal source) on the surface of the body receive the ECG signal (useful signal) and transmit it via a cable to the input amplifier of the cardiograph. There is a galvanic potential between the skin and the metal section of the electrode, which is substantially influenced by the electrode material, the composition of the electrolytes, and by the condition of the electrode/electrolyte interface. This electrochemical contact potential can be up to 300 mV. The transmitted input signal from the amplifier consists of four different fractions:

1. The useful signal (ECG), with an amplitude of 50 µV to approximately 1 mV, and
2. A DC voltage component of up to 300 mV that is superimposed on the useful signal; however
3. Interfering signals of up to 100 mV (50 Hz *ripple voltage*) and
4. Extreme interference voltages (resulting from defibrillators and RF surgery equipment, among other sources) of up to 3000 V can also occur.

In order to ensure that the patient is galvanically isolated from the mains voltage, the power supply and the output signal are galvanically decoupled.

In order to promote reproducibility, the ECG signal processing, recording and measuring process is standardized:

- Frequency response:
  - Lower frequency limit $f_{limit} = 0.05$ Hz
  - Upper frequency limit $f_{limit} = >100$ Hz
- ECG amplitudes:
  2.5, 5, 10 and 20 mm/mV
- Times:
  10, 25, 50 and 100 mm/s

7.2.2 Equipment Classification

ECG recorders are mainly classified according to the number of channels of the device and the equipment technology used (Figs. 7.2, 7.3).

From analogue to digital ECG systems with integrated recording components, a new ECG generation has developed: the PC ECG. The recorded analogue signals are amplified, digitized and supplied to data transmission equipment in an external module. The data can be transmitted to a connected computer (PC or laptop) using either a USB microcontroller or wireless data transmission technology (bluetooth technology)

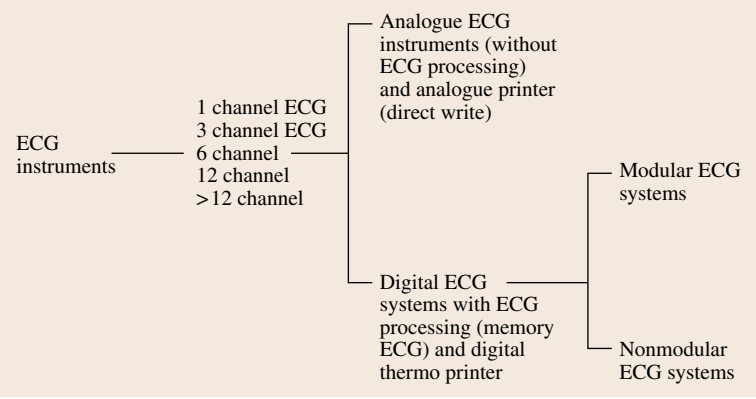

Fig. 7.2 Overview and differentiation of ECG recording equipment and PC ECG modules

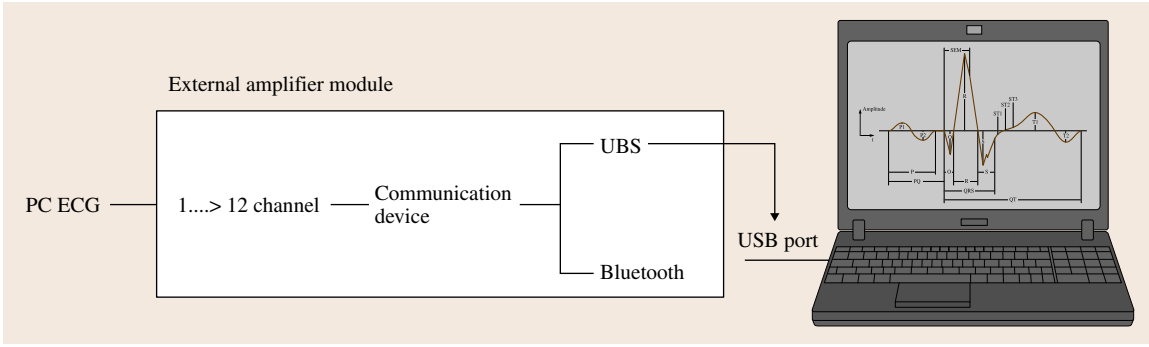

Fig. 7.3 PC ECG module

(Fig. 7.3). Whereas the USB port is also used to supply power to the module, the Bluetooth method makes mains-independent operation (10–12 h) possible with an accumulator battery. The transmitted data is processed and prepared on the computer using installed ECG application programs. In addition to the visual image on the computer display or external monitor, ECG graphs and interpretations can be printed out on a connected printer and plain paper for documentation purposes.

The PC ECG has practical advantages over conventional ECG equipment: the ability to save any desired ECG sequences at any time, the comprehensive availability of the data, the considerable reduction in the consumption of expensive ECG paper and therefore financial savings, the lack of mechanical equipment components, the ability to back up data on common storage media, the capacity for mobile use with mains-independent operation, as well as the possibility of interactive data exchange via the Internet. A particular disadvantage is the restricted data exchange possible via data carriers or over the Internet, as data can only be exchanged with an application program which is compatible with the PC ECG software. An artefact that is characteristic of PC ECG equipment, and is probably a result of computer electronics, leads to interference in the sensitive ECG analysis.

7.2.3 Recording Systems

Recording systems can be considered the various technical possibilities of the recording components (Fig. 7.3). The digital thermal array recording method is the current state of the art. Thermal comb recordings have high resolution and a low susceptibility to interference from the recording system, and allow optimum reproduction of the recorded and processed ECG signal.

7.2.4 Electrode Technology

The recording and transmission of the ECG signal from the surface of the body and the quality of this signal are fundamentally influenced by the electrodes. They repre-

Table 7.1 Overview of electrode types

Type of electrode	Electrode material	Recording region	Short application time	Long application time	Observation	Emergency application	Comments
Plate	V_2	Limbs	×				Without electrode gel
Suction	Silver/silver chloride	Chest	×				Low polarization voltage
Button	Silver/silver chloride	Limbs	×	×	×	×	Use foam plaster
Self-adhesive	Silver/silver chloride	Limbs					Comparatively low artefacts in restless patients
Single-use	Silver/silver chloride	Limbs, chest	×		×	×	Higher costs
Triple	Silver/silver chloride	Chest			×	×	Fast application possible

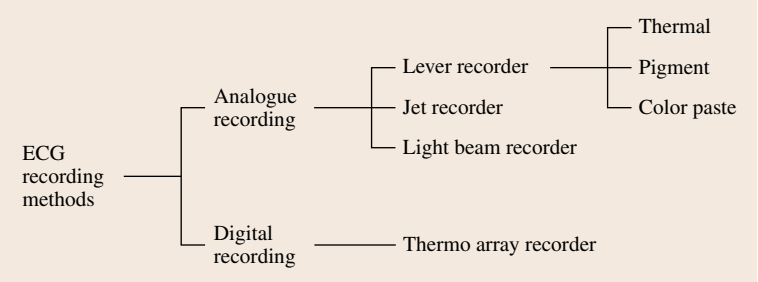

Fig. 7.4 ECG recording methods

sent a junction between the ionic conduction in the body and the metallic electronic conduction of the electrode surface and of the transmitting cable. There is therefore an electrical potential between the body and electrode, which is dependent on three factors in particular:

1. The electrode material
2. The composition of the electrolytes
3. The condition of the electrode–electrolyte interface.

Electrochemical contact potentials of up to 300 mV can occur at these interfaces. The electrode impedance (also known as electrode transfer impedance) – the sum of the electrode and skin impedances and also the resistance of the contact medium, which is dependent on the current density – is the result of the current state of the skin, body, contacting agent and electrode material. For this reason, electrode pastes or gels are used to reduce the transfer impedance.

Particularly in the case of polarizable electrode material (e.g. high-grade steel), unwanted polarization voltages may occur. These spontaneous voltage fluctuations are superimposed on the ECG signal and lead to signal instabilities in the recording (drifting leads). Nonpolarizable electrodes from Ag/AgCl (silver/silver chloride) have proven to be particularly advantageous (Table 7.1).

7.2.5 System Properties

The following properties represent the performance spectrum and at the same time the requirements for modern ECG systems:

- Simultaneous display of the 12 standard leads in a time frame of 15 s
- Various alphanumerical recording options
- High operational convenience and programmable
- Digital signal processing
- Automated control together with programs
- Interfaces for communication with other systems
- A high-resolution recording system without mechanical parts.

An upgradable system has the advantage of being able to perform more functions than just one ECG registration. The ECG device has these so-called multifunctional system properties when it is equipped with additional functions such as spirometry, long-term ECG monitoring, arrhythmia monitoring, Doppler ultrasound, pulse oximetry, capnography and late potentials, etc. Data communication with a PC and networking with other systems is also standard. The conditions for the use of medical EDP statistics, ECG data management and ECG software libraries are therefore satisfied.

7.2.6 Operating Modes

A fundamental distinction is drawn between manual and automatic operating modes. Automatic programs, such as standard ECGs with 12 leads, ergometry and arrhythmia, are typical of modern cardiographs which can be programmed by the user. The lead mode, formatting, baseline, calibration and sensitivity are for the most part automated. Alternatively, registration can be performed manually at any time.

7.3 ECG Methods

Figure 7.5 shows an overview of noninvasive and invasive ECG methods.

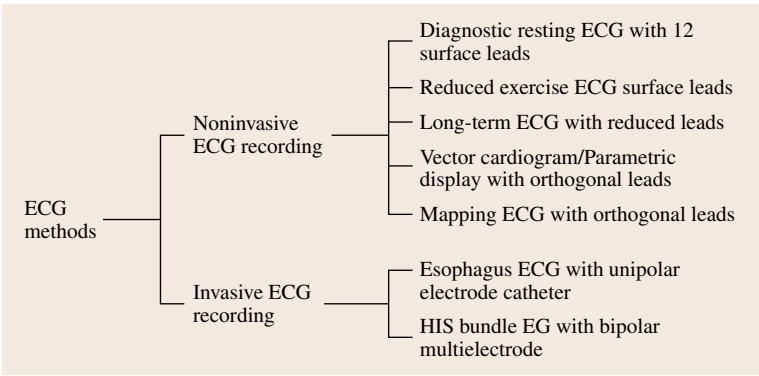

Fig. 7.5 Noninvasive and invasive ECG methods

7.4 Lead Systems

7.4.1 Measurements from the Surface of the Body

The action currents produced by biopotential differences that vary with time are measured as electrical potentials (the magnitude of the useful signal is around 1 mV) between two points on the surface of the body. Theoretically, any point on the surface of the body could be used for this purpose, but specific electrode sites have developed in practice, and the respective leads are defined according to these sites. The leads differ substantially in terms of recording technique and spatial arrangement.

Leads between two points are described as bipolar leads. In unipolar leads, in contrast, the different electrodes are connected to what is known as a zero electrode (collector electrode). This collector electrode is created by connecting together limb leads via high-impedance resistors. The limb leads provide a spatial view of the frontal plane, and the chest leads provide a spatial view of the horizontal plane.

7.4.2 Standard Leads

The standard leads are the three bipolar limb leads known as Einthoven's leads (I, II, III), the three unipo-

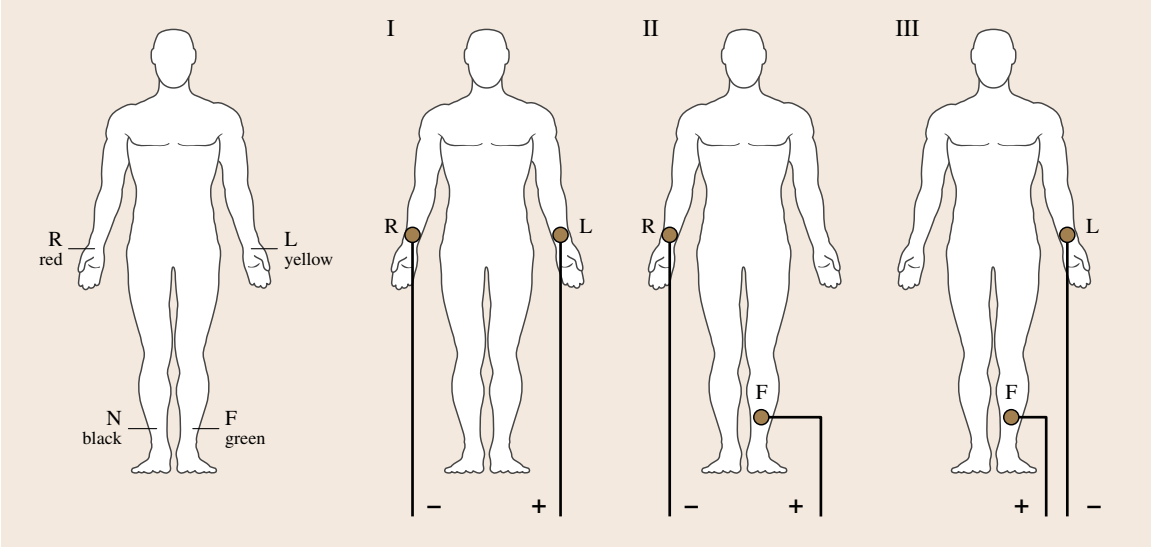

Fig. 7.6 Lead positions, connector colors and schematic diagram of the bipolar limb leads according to Einthoven

Table 7.2 Overview of the 12 standard leads of an ECG

	Limb leads		Chest leads
Description	According to Einthoven	According to Goldberger	According to Wilson
Electrodes	I, II, III	aVR, aVL, aVF	V_1, V_2, V_3, V_4, V_5, V_6
Measurement technique	Bipolar	Unipolar	Unipolar
Electrode sites	Upper and lower limbs	Constructed from I, II, III	Chest wall $C_1 \ldots C_6$
Projection	Distal potentials of the frontal plane		Proximal potentials of the horizontal plane

lar limb leads constructed from these three bipolar limb leads (known as Goldberger's leads: aVR, aVL, aVF), and six unipolar chest leads known as Wilson's chest leads (V1…V6) (Table 7.2).

Einthoven's Bipolar Limb Leads (Fig. 7.6)

For these, the potential difference is measured between two electrodes:

R: right arm = red connector
L: left arm = yellow connector
F: left foot = green connector
N: right foot = black connector (earth)

The three leads lie in the frontal plane and form what is known as Einthoven's triangle (Fig. 7.7).

Goldberger's Unipolar Limb Leads

For these, the potential difference is determined between each electrode on the limb and an *electrical zero* which lies at the central potential between the two other limbs (Fig. 7.8).

aVR: $R - L + F/2$
aVL: $L - F + R/2$
aVF: $F - L + R/2$

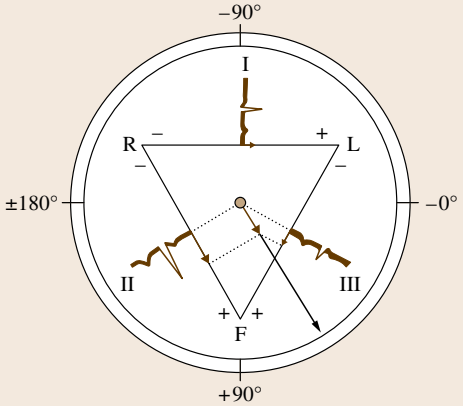

Fig. 7.7 Einthoven's triangle

Wilson's Unipolar Chest Leads

The chest electrodes ($V_1 \ldots V_6$, V = voltage) are placed at six defined points on the thorax ($C_1 \ldots C_6$, C = chest). The three limb leads are combined via

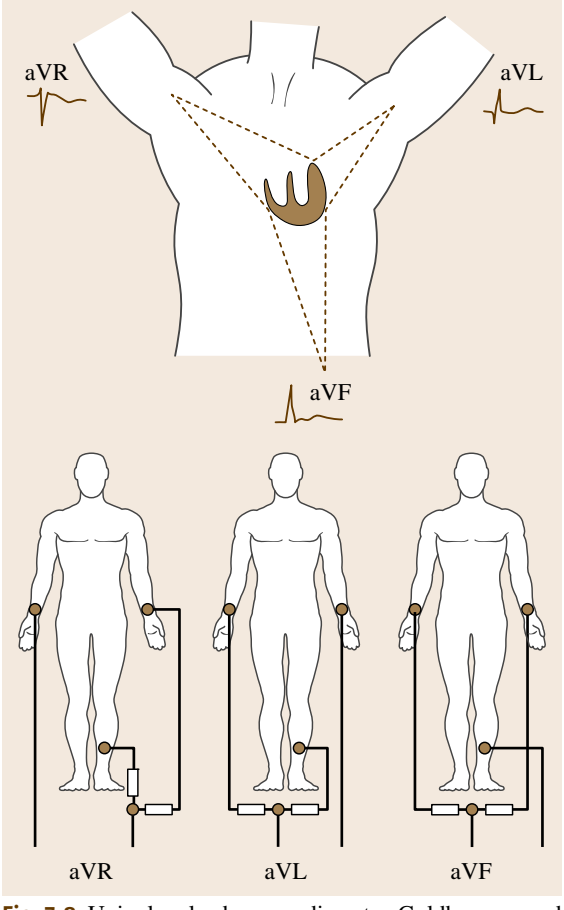

Fig. 7.8 Unipolar leads according to Goldberger, and schematic diagram

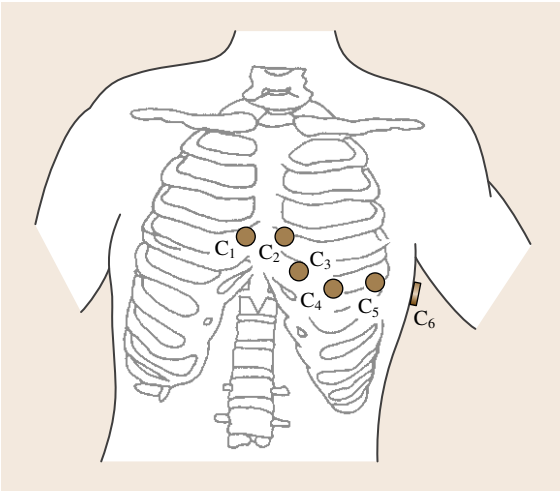

Fig. 7.9 Unipolar chest leads according to Wilson: C_1 – Fourth intercostal space at the right border of the sternum; C_2 – Fourth intercostal space at the left border of the sternum; C_3 – Fourth intercostal space at the fifth rib, midway between C_2 and C_4; C_4 – At the mid-clavicular line in the fifth intercostal space; C_5 – At the left anterior axillary line on the same horizontal level as C_4; C_6 – At the left mid-axillary line on the same horizontal level as C_4

a high-impedance resistor to form a collector electrode (indifferent electrode). Wilson's central terminal forms the electrical zero point. As a result of the proximity to the heart, the amplitudes of the chest leads are greater than those of the limb leads (Figs. 7.9, 7.10)

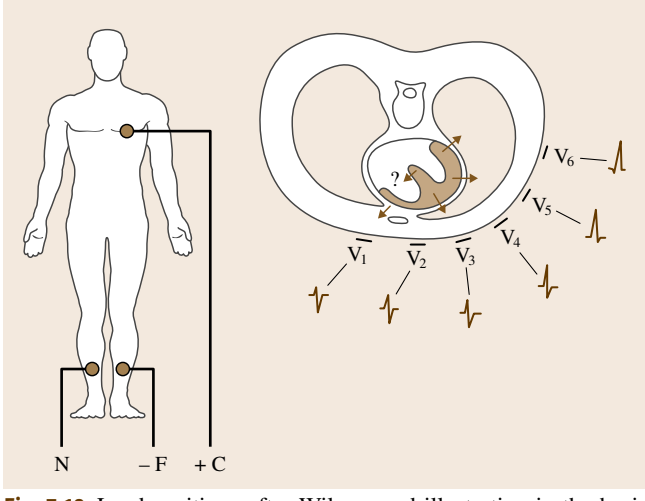

Fig. 7.10 Lead positions after Wilson, and illustration in the horizontal plane

Cabrera's Lead Sequence

Cabrera's circle is a hexaxial system that can be used, among other things, as an aid when determining the axis deviation. The circle includes leads of the frontal plane that are each rotated through 30° with respect to one another. The leads from Einthoven's triangle are shifted parallel such that lead I assumes an angle of zero, lead II +60° and lead III +120°. The Goldberger leads are also included in this system, and have angles of: aVR −150°, aVL −30° and aVF +90° (Fig. 7.11).

By flipping the aVR lead through 180°, we get −aVR at 30°. It is possible to determine the axis deviation simply by determining the highest R amplitude from the leads. The angular space allocated to the leads determines the deviation of the axis (for example, the highest R amplitude is found in lead II; i. e. the electrical axis of the heart falls at +60°. This corresponds to the normal position of the heart in a healthy adult).

7.4.3 Augmented and Reduced Leads from the Surface of the Body

Augmented Leads

Augmented leads include the corrected orthogonal leads of Frank and the additional unipolar chest leads of Wilson.

The Frank leads are based on a theoretical model in which the heart is at the centre of a square three-dimensional coordinate system consisting of a lateral axis x, a longitudinal axis y and a sagittal axis z. The excitation processes can therefore be registered in the form of vector loops (vectorcardiography).

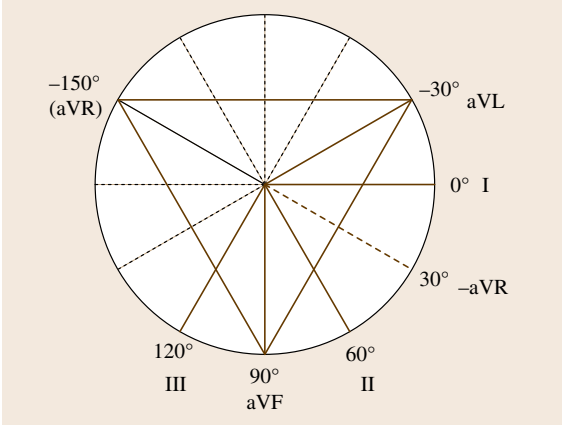

Fig. 7.11 Cabrera's circle

In addition to Wilson's standard leads on the chest, it is also possible to include other electrode sites. These can be extended precordially to the right (V_{r3}, V_{r4}, V_{r5}, V_{r6}) or to the left (V_7, V_8, V_9 or V_8 two ICS lower).

Reduced Leads

Reduced leads include leads for ECG monitoring, leads for long-term ECG and ergometry leads (see the individual chapter on this topic).

7.4.4 Invasive Leads

Unipolar Oesophageal Leads

When using oesophageal leads, an electrode catheter is inserted via the oesophagus to just above the cardia. The aim is to obtain a precise assessment of proximal potentials of the posterior myocardial wall and the left atrium.

HIS Bundle Electrocardiography

Here an intracardiac electrogram (EG) is obtained using a three-pole electrode catheter. This investigation is performed with radiological and electrocardiographic monitoring (this procedure is part of routine diagnostics in cardiac centres). The particular advantage of this lead is that it is possible to precisely investigate the proximal potentials of the right atrium, the right ventricle and the conductive system, and in this case the HIS-Purkinje system in particular (Fig. 7.12).

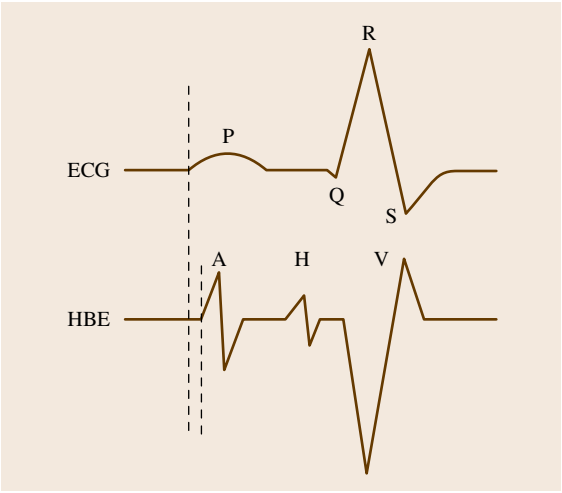

Fig. 7.12 Surface ECG compared with the intracardiac HIS bundle EG. *HBE* HIS bundle electrogram, *A* depolarization in the atria, *V* depolarization in the ventricles, *H* depolarization in the HIS bundle

7.5 Methodological Notes

Faults that occur during ECG registration can generally be differentiated into patient-, environment-, user- or equipment-related faults. Most faults (baseline shifts, irregular and regular superpositions of AC voltage) that occur during ECG registration can be traced back to external influences.

7.6 The Diagnostic Value of the ECG

As it illustrates the electrical excitation processes occurring in the heart, the ECG provides information about the origin and rhythm of excitation, the heart position and rate, pulse propagation, as well as repolarization and repolarization arrhythmias, which in turn can be caused by anatomical, mechanical, metabolic or circulatory problems. However, the ECG has no direct informative value regarding the contraction and pumping capacity of the heart (mechanical cardiac function). The medical significance of the ECG is undisputed, although its capabilities should not be overestimated. Within the field of cardiological investigation, the ECG is essential, and in routine internal investigations it is a valuable, possibly even crucial, investigation tool. Caution is advised regarding the informative power of the ECG in relation to the aetiology and pathogenesis of a cardiac disease, as well as in relation to the indications for and success of therapeutic measures. Anatomical damage and functional faults of the myocardium are not necessarily reflected in the ECG. It must be observed that the informative value of the ECG is dependent on the knowledge and experience of the individual providing the assessment. Whereas inexperienced users will be inclined to inter-

pret the ECG too broadly, the experienced user will give a more reserved assessment and where possible avoid schematization and generalizations. It must be noted that, particularly with computerized evaluation programs (e.g. diagnostic hints), an individual's own assessment is essential.

7.7 Complications

Whereas incidents during noninvasive ECG recording are a complete novelty, serious arrhythmias (e.g. flutter, fibrillation, etc.) can occur during intracardiac ECG registration.

7.8 Technical Safety Aspects of ECG Systems

Electrocardiographs are power-operated technical medical devices, with associated provisions, regulations and standards that are applied to protect patients and operating personnel.

ECG devices that measure intracardially, or are provided for that purpose, are subject to Annex 1 of the German Medical Devices Operator Ordinance (Medizinproduktebetreiberverordnung – MPBetreibV). The protection classes that apply to ECG equipment are primarily protection class 1 (with a protective earth) and protection class 2 (without a protective earth). VDE 0750 allows devices to be equipped with a protection class switch so that operation in either protection class is possible. In order to maintain functional and operational safety, the equipment must be subjected to technical safety checks and tests at regular intervals.

7.9 Long-Term ECG

Long-term electrocardiography – long-term ECG for short, and also known as Holter monitoring, *ambulant* ECG or ambulatory monitoring – is a noninvasive routine ECG procedure that is central to primary diagnosis and the therapeutic monitoring of cardiac arrhythmias. As its name suggests, in this procedure, the ECG is recorded and analysed over a relatively long period of time (generally 24 h), under everyday stress.

Whereas other electrocardiographic investigation procedures, such as resting or exercise ECGs, only allow a diagnostic statement to be made over a limited period of time under specific conditions (*laboratory conditions*), the long-term ECG follows the various physical and emotional stresses that occur over the course of at least one day/night period.

7.9.1 Leads

To date there is no uniform agreement on the best electrode positions for long-term electrocardiography. Efforts are being made towards standardization, however, in order to ensure better comparability of the results obtained. The electrode sites must be selected such that they satisfy the following criteria:

1. The electrodes must be placed on the thorax at sites where there is little muscle, since movements of the skeletal muscles during long-term monitoring can lead to undesirable fluctuations and tremors in the ECG (artefacts).
2. The patient's freedom of movement must not be restricted.
3. The amplitude of the R wave in relation to the P and T waves must be sufficient for computer-based ECG analysis of the recordings.

As a general rule, right and left precordial leads are chosen. Preference is given to the following bipolar chest leads:

MC5: This lead is applied parallel to the electrical axis of the heart; the different electrode level with the fifth ICS, and the indifferent electrode above the sternum (manubrium sterni). The position of the electrode is varied depending on the deviation of the axis.

MX: The indifferent electrode lies above the sternum, whereas the different electrode is applied above the xiphoid process (xiphoideus) of the sternum. This lead has the advantage of having the greatest freedom from interference from muscle tremors.

CC5: The electrodes are applied to both sides of the anterior axillary line, level with the fifth ICS, with the different electrode to the right and the indifferent electrode to the left.

In addition to the leads mentioned here, modified leads are recommended by various authors in order to optimize the sensitivity of detection.

7.10 Long-Term ECG Systems

The fundamental work of Norman J. Holter (physiologist) on the development of wireless telemetry – in 1947 he transmitted an ECG signal by radio, and then in 1949 he transmitted ECG signals from ambulant patients performing physical work – had a great influence on modern long-term ECG registration, and indeed made it possible in the first place.

Long-term ECG systems consist of a portable recording device (recorder) with 2–3 channels that registers and stores the ECG signals, a computerized playback device, and a high-performance analysis unit. By means of fast Fourier transformation, application programs enable frequency analysis for artefact recognition, automatic evaluation according to various criteria, accelerated analysis, or batch processing. If we consider the recording technology, a distinction can be drawn between continuously and discontinuously recording long-term electrocardiographic systems in which the data carrier of the recording device is either a tape cartridge or solid-state memory. The tape cassette, which records in analogue, has today been virtually completely superseded by digital solid-state memory. In continuous recording, the ECG potentials are stored in their entirety over a period of between 24 and 72 h. In addition to real-time analysis, high-quality devices also make it possible to evaluate a highly amplified ECG, long-term blood pressure, heart rate variability, and other functions on the unit in parallel.

Discontinuous system-based ECGs are plotted according to the limited storage capacity on the recording device. Following a continuous recording analysis, only time-limited ECG information and results are stored and documented. With these so-called event recorders, the patient has the option of activating the recording via an activator or remote control unit if symptoms occur. Loop recorders have memory on a loop; in this case, ECG information remains stored for a limited period of time. Only ECG sequences that have been marked by the patient using the activator remain stored. A further development of the event recorder is the subcutaneous implantable loop recorder (ILR), which is used particularly in the case of symptomatic cardiac arrhythmias that occur infrequently. The device, which generally has an operating time of up to two years, is implanted subcutaneously in the region of the left sternum using local anaesthetic. The continuously recording bipolar electrogram is evaluated in the implant. ECG episodes that deviate from programmed ECG criteria are recorded. Here, too, the patient has the option of marking and storing symptoms or events that occur using a remote control.

With so-called simple sampling recorders, ECG sections are recorded only in certain time segments, without the recording being triggered by cardiac arrhythmias and without being influenced by the patient. This intermittently recording system, which stores information only randomly and nonspecifically, leads to recordings with only very limited informative value regarding the complete day/night rhythm.

The transmission of stored ECGs and complete long-term ECG data records via telephone to a computer in the hospital or in a private practice is increasingly gaining in significance. Developments in telecommunications are enabling ECGs to be transmitted using mobile phones, thus permitting *online diagnosis*.

7.11 Computer-Based Assessment

The nature and number of events (e.g. SVES, VES, bigeminy, couplets, salvos, R-on-T phenomena, etc.) within a certain time interval provide insight into cardiac arrhythmia. At the beginning of the analysis, there is

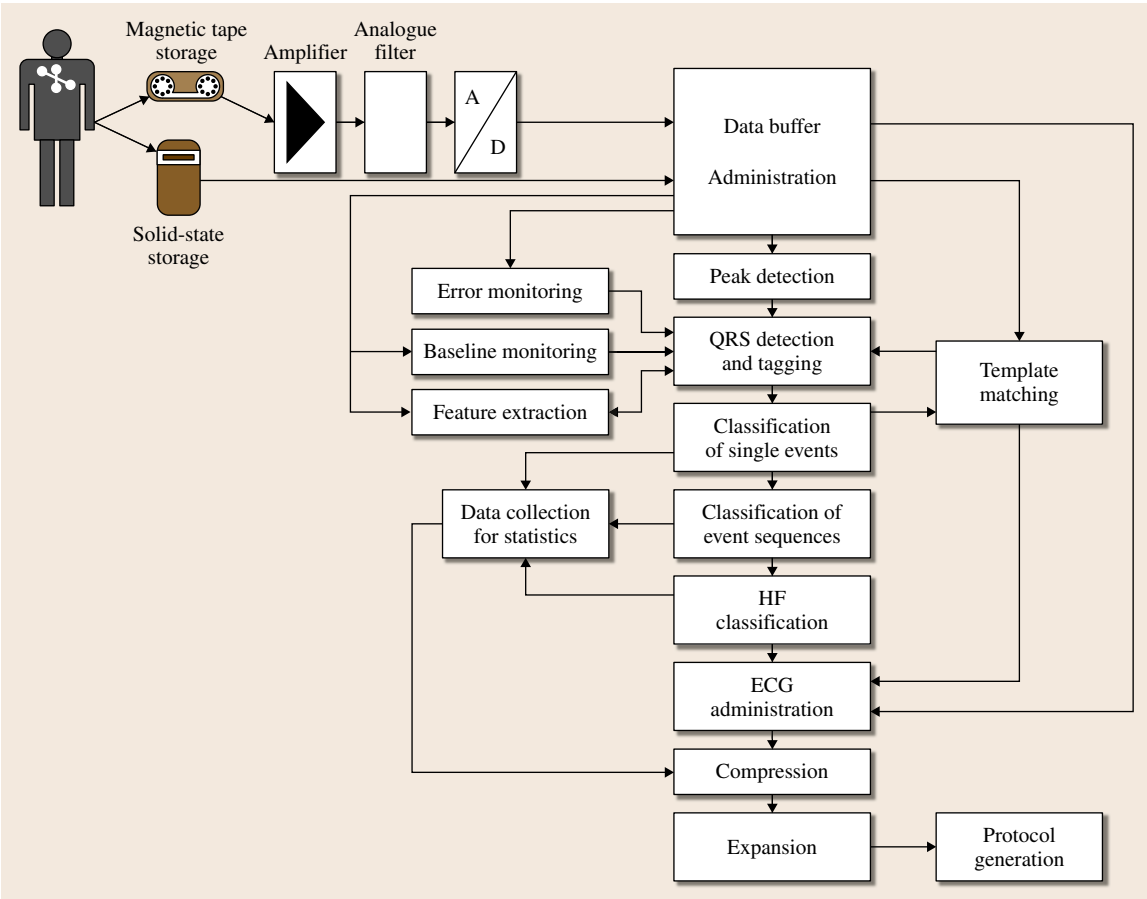

Fig. 7.13 Flow diagram of a computer-based assessment of the long-term ECG

a learning phase for the program: the QRS complex that is typical of this particular patient is calculated, and the QRS morphology is *learnt* and considered the normal curve shape, in order to be able to distinguish the QRS morphology from deviating QRS complexes and from artefacts. The arrhythmia program uses detection criteria (Fig. 7.13) for the QRS complex (a parameter comparison, also known as feature extraction or characteristics recognition) to draw a rhythmological distinction between physiological and pathological cardiac actions. The polarity of the R wave, the amplitude, the QRS area and position, the offset of the QRS from the baseline, and the slope of the R wave are calculated and determined as particular features for each QRS complex. The individual parameters are used at various points in the analysis for decision-making purposes. Thus, for example, the height of the complex provides an additional criterion when validating a QRS complex. A morphological (normal case or not) and rhythmological correlation (premature, delayed, later, etc.), as well as an individual complex assessment and ultimately a conclusion of arrhythmia, are possible using this feature determination. Continuous comparison between the current QRS complex and the learnt QRS is termed the cross-correlation method (or the template-matching method). The classification of each QRS complex forms the basis of the arrhythmia monitoring. The shape and time of occurrence of the complex are taken into account for this purpose. If the QRS shape that is typical of this particular patient is found after a learning phase, the next complex will be compared with the stored reference complex by *superimposing* the two complex shapes and checking point-for-point for a match. Where there is a low percentage of deviation, the complexes are defined as being identical in shape and are used as the reference complex for the next shape comparison. If there is no match (if the

complexes have different shapes), this is stored in what is known as a QRS class memory.

In order to qualitatively assess diagnostic effectiveness and analytical accuracy, it is necessary to test analytical programs that have equipment-specific algorithms against recognized and evaluated ECG databases, and to compare the results (validation). The quality of the analysis, and in particular the reliability of the system, can be described statistically by the sensitivity, positive correctness and specificity:

- True positive = an event is correctly recognized and evaluated
- True negative = a normal complex is correctly recognized and evaluated
- False positive = an event is incorrectly recognized and evaluated
- False negative = an event is overlooked
- True positive and true negative = number of complexes
- False positive and false negative = number of errors

$$\text{Sensitivity} = \frac{\text{true positive}}{\text{true positive} + \text{false negative}} \times 100(\%)\,,$$

$$\text{Positive correctness} = \frac{\text{true positive}}{\text{true positive} + \text{false positive}} \times 100(\%)\,,$$

$$\text{Specificity} = \frac{\text{true negative}}{\text{true negative} + \text{false positive}} \times 100(\%)\,.$$

7.12 Heart Rate Variability and Heart Rate Turbulence

Prognostic indicators such as heart rate variability (HRV) and heart rate turbulence can be calculated from the recording of a long-term ECG. Whereas heart rate variability provides information on the variations in heart rate over a relatively long period of time, heart rate turbulence refers to the variations in the interval between two heart beats (RR interval, where R denotes the peak in the QRS complex) following the occurrence of a ventricular extrasystole. In order to assess the heart rate variability, the standard deviation of the RR intervals recorded over a period of 24 h is ascertained (SDNN). A spectral analysis of heart rate variability can be performed by most analytical devices from approximately 300 recorded sinus beats. Various frequency ranges can be discerned by means of fast Fourier transformation:

- ULF (ultra low frequency power): <0.0034 Hz
- VLF (very low frequency power): 0.0034–0.04 Hz
- LF (low frequency power): 0.04–0.15 Hz
- HF (high frequency power): 0.15–0.4 Hz.

7.13 Indications for Long-Term Electrocardiography

The range of indications for performing a long-term ECG has changed over the years. The most important indication is an investigation where there is suspicion of underlying cardiac arrhythmias (Class I indication). Other indications are risk stratification achieved by recording ventricular arrhythmias, and the monitoring of an anti-arrhythmic therapy. The guidelines of the American College of Cardiology (ACC), the American Heart Association (AHA) and the European Society of Cardiology (ESC) provide further possible applications.

7.14 The Significance of the Long-Term ECG

The long-term ECG is of great significance for primary cardiological diagnosis and the monitoring of therapy for arrhythmias, as well as for the diagnosis of ischaemia. The resting and exercise ECG usually do not allow a reliable judgement to be made on the frequency and nature of cardiac arrhythmias, since they record only a small period of time. A significant advantage of the long-term ECG is the continuous recording of the

ECG over a relatively long period of time (at least 24 h). In addition, the results of the analysis can be quantitatively measured, documented, or passed on for further data processing.

7.15 The Exercise ECG

Ergometry, the most commonly used exercise tolerance test in clinical and outpatient cardiology, is a noninvasive routine procedure in cardiovascular diagnostics.

By providing additional information to the resting ECG, ergometry yields essential insights into current cardiopulmonary performance and into limitations on performance which may result from coronary heart conditions.

The Difference Between Ergometry and Exercise ECG

Ergometry (from the Greek *ergon*, meaning work or performance) refers to the generation of a defined and reproducible stress with an ergometer per unit time, and the subsequent monitoring of the ECG, heart rate, blood pressure and oxygen consumption. On the other hand, in an exercise ECG, the focus is less on the blood pressure, heart rate and oxygen consumption and more on recording electrocardiographic changes during and after the period of exertion. Conventional ergometry generally does not include measurements of the oxygen consumption and saturation, whereas such measurements are absolutely essential in ergospirometry (see more Chap. 8, Sect. 8.2.5).

7.16 Equipment Technology

7.16.1 Physical and Technological Principles

The work performed by the test subjects during the exercise period at various stress stages is the product of the force (in newtons, N) and the distance (in metres, m). Including the time component, the output generated can then be measured in newton metres per second = watts = joules per second (Nm/s = W = J/s).

If we now consider a bicycle ergometer, when the bicycle peddle is rotated, a force must be expended over a distance. The speed at which the bicycle peddle is rotated is equal to the time in which this output is generated. As the bicycle pedal rotates, the output is thus calculated from $2\pi\times$ rotational speed × torque. The torque is calculated from the force with which the pedals are rotated multiplied by the length of the pedal cranks. In the process, it becomes clear that the performance changes depending on the force or rotational speed applied.

7.16.2 Ergometry Measuring Station

In order to avoid standalone systems and restrictions on the range of equipment that can be used, complete systems known as fully automatic ergometry measuring stations are currently available. These measuring stations consist of a 3-, 6- or 12-channel ECG device, an ergometer or treadmill, a 1-, 3-, 6- or 12-channel cardioscope, a defibrillator, a noninvasive blood pressure meter, an electrode application system and a portable equipment trolley that carries this equipment and thus enables flexible transportation of it (Fig. 7.14). When new equipment is acquired, conventional ECG devices are usually replaced with PC ECGs. The advantage of these systems is that they allow data storage and data transfer.

7.16.3 Types of Ergometers

In terms of technology and apparatus, there are three main types of ergometer: bicycle ergometers that are used in the sitting position, recumbent bicycle ergometers, and *treadmill ergometers* (*primarily in Anglo-Saxon countries*).

Essential requirements for an ergometer – primarily bicycle ergometers – are:

- Ability to adjust the stress accuracy (max. ±5%)
- Accurate monitoring as a result of standardization and comparability
- 5 W should be the smallest stress that can be set
- Ability to display the stress and rotational speed
- Optimized adjustment options for different body sizes

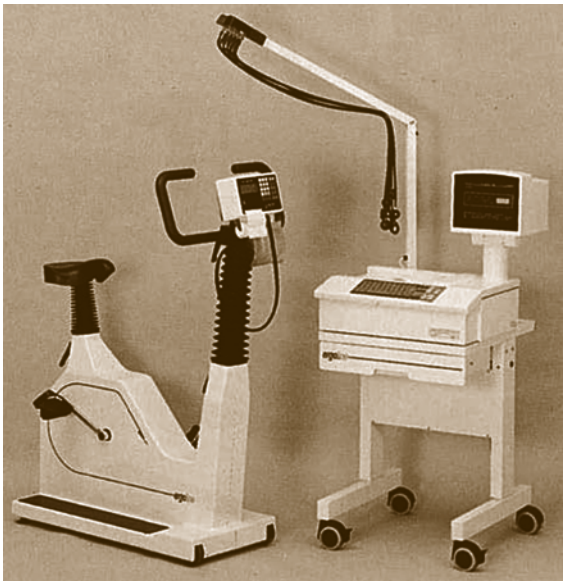

Fig. 7.14 Ergometry measuring station with bicycle ergometer (courtesy of ergoline Inc., Germany)

- Low requirements in terms of space, and high stability at the same time.

Rotational Speed Dependence of Bicycle Ergometers

In bicycle ergometers that are dependent on rotational speed, the output can be increased by both increasing the braking resistance and increasing the pedalling frequency. If a particular braking action (belts, brake shoes, weights or an electromechanical eddy-current brake) that predefines the force is set, a specific rotational speed must be maintained in order to be able to precisely determine the output. In practice, this situation is rather difficult to implement. It is for this reason (as well as the inaccuracies in the coefficients of friction for different braking systems) that bicycle ergometers which depend on rotational speed are unsuitable for ergometry. The use of these devices for medical investigations has therefore been banned. Bicycle ergometers that do not depend on rotational speed are predominantly used today. These are usually equipped with a computer-controlled eddy-current brake, and only the output to be attained is predefined; if the pedalling frequency is increased, the resistance decreases proportionally. The braking action is constantly compared with the rotational speed, the force expended and the predefined stress. Deviations are corrected electronically by increasing or decreasing the braking force. The accuracy is specific to the measuring system, and dependent on the consistency and the control rate. In good systems, deviations of between 1 and 3% in the stress set are observed; the standard allows deviations of up to 5%.

Characteristics and Criteria for Bicycle and Recumbent Ergometers

The following characteristics are important when assessing a bicycle or recumbent ergometer:

1. *Braking principle.* Computer-controlled eddy-current brake, independent of rotational speed, torque measurement.
2. *Stress range.* Dependent on the test subject clientele:
   a) Standard ergometer 20–450 W
   b) High-performance ergometer 20–1000 W
3. *Rotational speed range*:
   a) 30–100 /min
   b) 30–130 /min
4. *Stress accuracy*. No less than ±3 W or 3% (standard 5%).
5. *Stress stages*. Smallest stress which can be manually set of 5 W.
6. *Time interval*. Smallest time interval of 1 min.
7. *Exercise tolerance testing programs*. Can be programmed freely.
8. *Seat height adjustment*. Infinitely variable.
9. *Handlebar adjustment*. Infinitely variable.

7.17 Reduced Exercise ECG Leads

As with the other ECG leads, there are currently a vast number of ergometry lead programs. The are two main requirements for the reduced ECG leads during the exercise ECG:

- Minimal susceptibility to faults due to superposition of muscle potentials and movement artefacts
- Qualitative and quantitative registration of ST segment deviations.

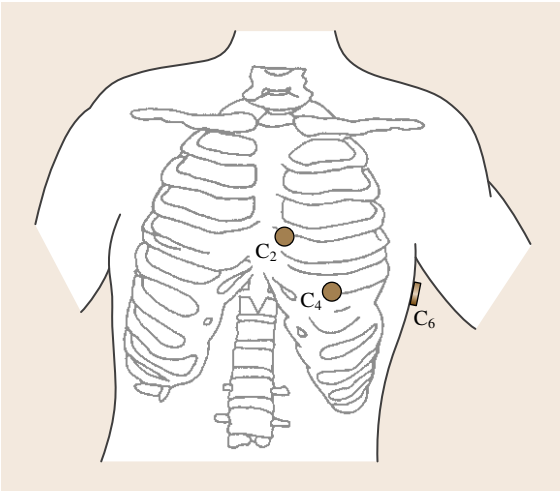

Fig. 7.15 Exercise ECG with reduced chest leads (C_2, C_4 and C_6) ◀

Six leads are generally sufficient. The measurements can be taken using multiple-use electrodes on tensioning straps and electrode belts. Appropriate use of single-use adhesive electrodes or electrode suction units is more hygienic, simpler and faster. The limb leads can be applied respectively to the right and left sides of the shoulder blade (head of the humerus) and in the lateral regions of the right and left iliac wings. These show the least superposition from muscle potentials. The chest leads are of particular interest, because ischaemic ST depressions and repolarization arrhythmias of the anterior wall appear to be most pronounced and occur most frequently in these leads. The most popular electrode sites for chest leads are C_2, C_4 and C_5 or C_6 (Fig. 7.15).

7.18 Automatic ST Measuring Programs

Elevation or depression of the ST segment in the ECG under stress allows diagnostic conclusions to be drawn regarding coronary heart conditions, so this is a major focus of measurements. Modern electrocardiographs, which usually provide an ergometry program, automatically measure and document the ST segment and amplitude. A distinction must be drawn between continuous and discontinuous ST measurement programs: in the case of continuous measurement, each QRS complex recorded is measured and analysed directly. An average beat is generated continuously for each channel from a number of beats that exhibit good correlation (usually 16). In contrast, in the case of discontinuous ST measurement, the average beat is generated from either values taken at timed intervals (e.g. per minute) or just from a start and end complex.

To obtain the average beat, the start and end point of the QRS complex are first determined. The ST amplitude and slope are measured at point $J + x$ (J point = junction point, which marks the end of the QRS complex and the transition to the full excitation phase: the ST segment). The $J + x$ interval is determined as a function of the heart rate. The isoelectric line is established between the P wave and the start of the QRS complex. The amplitude at point x is the interval from the calculated and displayed baseline. The slope at point x is given by the angle α, and is obtained by passing a regression line through the ST segment and point x.

7.19 Exercise Test

Since the diagnostic issues and the composition of the patient clientéle are assessed in very different ways, a uniform, standardized exercise tolerance test is not always possible. The guidelines compiled by the International Commission for the Standardization of Ergometry Application (ICSPE) have led to a largely standardized procedure in routine investigation and in sports medicine.

7.19.1 Stress Intensity

In ergometry, there are two different types of stress intensity in principle: maximal stress and submaximal stress. In the case of maximal stress, the exertion increases until the physical output limit of the test subject is reached (e.g. in sports medicine investigations, performance diagnosis, etc.). In the case of submaximal

stress, exertion is continued until medically relevant problems occur or their correlation with the exertion can be ascertained (e.g. arrhythmias, ST elevation or depression, etc.). The level of submaximal stress is dependent on the medical problem, and may be arrived at long before maximal stress is reached.

Stress Steps

The Standardization Commission for Ergometry (ICSPE) has stipulated the following stress steps:

- 5 W for 1 min
- 10 W for 1 min
- 25 W for 2 min
- 50 W for 3 min.

Ergometry – according to standardized regulations – consists of a warm-up phase with a basic stress and at least three of these predefined stress steps as well as a recovery phase. The warm-up phase should stimulate circulation and prepare for the stress to come. It is generally of the same duration as the subsequent stress step. The wattage and the duration of the stress step are selected according to the physical capability of the test subject. A further criterion is that a so-called *steady state* is reached at the end of the stress stage. *Steady state* in this case means that at the end of the stress stage both the pulse and the blood pressure no longer deviate upwards – these values remain constant (equilibrium). (For more on the selection of the stress stage, see the section on PWC later.)

Stress Limits

The following is a rule of thumb for maximal stress with bicycle ergometry: a maximum heart rate of 220/min minus the age of the test subject. To ensure the safety of the test subject, the following so-called submaximal stress limit is recommended as a guide for routine investigations: a maximum heart rate 200/min minus the age of the test subject.

Assessment of Performance

To make sure that the ergometry procedure is suitable for diagnosis, it is very important to roughly estimate the performance of the test subject prior to the beginning of ergometry. The following rule applies to this:

The maximum nominal output for a man is 3 W/kg of body weight minus 10% for every decade over the age of 30. The maximum nominal output for a woman is 2.5 W/kg of body weight minus 8% for every decade over the age of 30.

As an example, let us consider the output settings for a 65 year old woman weighing 55 kg.
Nominal output: $(2.5\,\text{W} \times 55\,\text{kg}) - (8\% \times 3.5\,\text{decades}) = 137.5\,\text{W} - 28\% = 99\,\text{W}$; the maximum stress for this woman is therefore approximately 90 W. A basic stress and a stress interval must now be selected that will definitely enable the test subject to cope with three stress stages. In this case, the recommended approach would be to begin with a basic stress of 50 W and then carry out ergometer exercise with stress stages of 10 W and a stress duration of 1 min up to the maximum stress, which is expected to lie between 80 and 90 W. Another advantage of this method is that the output limit can be defined more precisely for test subjects that have comparatively low outputs with relatively low stress increase segments.

Pulse Working Capacity (PWC)

Derived from the rules for assessing performance and the rules for stress limits, the PWC method allows the comparison of outputs standardized to the pulse rate. The PWC value assesses the performance (i. e. the output achieved at specific pulse rates) in the submaximal range when the maximum rate has not been reached. The selected rate is added as an index (e.g. PWC_{150}). The nominal values for the PWC are not dependent on age; they are calculated based on weight and gender (for example, the nominal PWC_{150} value for men is 2.1 W/kg and for women 1.8 W/kg). These values can be found in PWC tables, which generally list PWC_{130}, PWC_{150} and PWC_{170} values.

Exercise Tolerance Test Procedure

A room temperature of 18–23 °C with a relative atmospheric humidity of 40–60% is recommended when performing an ergometry test. Aberrations should be logged. A resting ECG is recorded prior to the actual exercise tolerance test. It serves as a starting point when summarising the exercise tolerance test later. Following the application of the reduced ECG leads and the blood pressure cuff, the exercise tolerance test is initiated using a calibrated ergometer according to the exercise tolerance test method described. In modern ergometry measuring stations, the customary stress programs are stored in either the ergometer or the ECG device. In a timed ergometry investigation, one of these two devices serves as the command unit for the course of the investigation. In order to provide complete documentation, an intermediate ECG printout giving details of the heart rate, the blood pressure as well as the ST segment and the amplitude is automatically printed after

each stress stage. However, it is also possible to initiate a manual ECG recording at any desired stage or to record an ECG trend over the entire duration of the test. The following actions must be performed during the exercise tolerance test:

- Constant observations of the test subject and the ECG graphs on the monitor
- The ECG strip as well as the blood pressure, the heart rate and the ST properties after each stress stage must be monitored.

Following the completion of the exercise tolerance test and a recovery phase, a resting ECG is recorded once more (and if necessary more than once), and the blood pressure is repeatedly monitored.

Types of Exercise Tolerance Testing

The general requirements for an evaluable exercise tolerance test can be summarised as follows: it should be capable of precise metering, physically measurable, and reproducible at any time. There are many types of exercise that do not satisfy these requirements, but they are mentioned below for the sake of completeness:

- *Forward bends and squats*. Insufficient for the exercise ECG because even the general requirements (*capable of metering and physically measurable*) cannot be satisfied.
- *Climbing stairs*. Unsuitable for the exercise ECG since the *reproducibility* must be questioned, there is no possibility of ECG monitoring, and the test subject cannot be subjected to maximum stress.
- *Hand crank ergometer*. Interference with the ECG recording as a result of the arm and thorax movements of the test subject and the lack of maximum stress (small muscle mass) are disadvantages of this method. However, this type of exercise tolerance test is often the only option for patients with impaired walking abilities.
- *Isometric stress (hand-grip)*. Similar disadvantages to those for the hand crank ergometer.
- *Master's step test*. The one-step or two-step test offers the following advantages: it is a relatively physiological form of exercise tolerance testing, involves a simple sequence of movements, is standardized and therefore reproducible, is simple to carry out, stresses a relatively large proportion of the total musculature, and requires a comparatively low financial outlay. Disadvantages: the timescale for maximum stress, it is virtually impossible to record the ECG and blood pressure during the exercise intolerance test, and its diagnostic informative value is very low when compared to those of bicycle and treadmill ergometry.
- *Kaltenbach and Klepzig's step-climbing test*. This test is a modification of Master's test, and the advantages and disadvantages are therefore similar.
- *Treadmill ergometer*. The treadmill is predominantly used for exercise tolerance testing of competitive athletes. The fundamental advantages of the treadmill ergometer are that it physiologically stresses the entire musculature (and this can be reproduced at any time), and it allows the stress intensity to be changed (by varying the speed at which the belt runs). Disadvantages are its relatively high investment costs, its structural requirements (in particular soundproofing), and a limited clientéle for exercise tolerance testing.
- *Bicycle ergometer*. The most popular and widely used type of exercise tolerance test is bicycle ergometry, which can be performed in a sitting position or in a recumbent position. Fundamental advantages of bicycle ergometry in the sitting position are the physiological stress and the use of the body weight; the procedure is also usually found to be pleasant by the test subject. Disadvantages are the recording of ECG and blood pressure during the exercise tolerance test and orthostatic complaints following the exercise intolerance test. The fundamental advantages of the recumbent ergometer are the unimpeded recording of the ECG and blood pressure and the quality of these recordings, the relatively high level of safety (predominantly for elderly or frail people), and the absence of orthostatic complaints following the exercise tolerance test.

Standardized Investigation Programmes

A number of individual and standardized exercise tolerance testing programmes from the early days of ergometry investigation are still employed. These are listed below, along with some examples:

- Hollman's standard test method (begins with 30 W and is increased every 3 min by 40 W up to the stress limit)
- The WHO's standard programme (begins with 25 W and is increased every 2 min by 25 W up to the stress limit)
- Knipping's vita maxima (begins with 10 W and is increased every minute by 10 W up to the stress limit)

- Kirchhoff's square wave test (stress duration of 10 min with 100 W in a sitting or recumbent position; blood pressure, heart rate and ECG are monitored every 2 min).

However, ergometry has increasingly evolved into a standardized method based on the internationally recognized regulations of the ICSPE. This has the advantage that results of investigations from different institutes and those obtained by different testing personnel can be compared and assessed according to the same standards. It is therefore the duty of all testing personnel to adhere to these regulations.

7.20 Methodological Notes

Most faults that occur during ergometry can be attributed to the patient. A large proportion of these faults are compensated for by modern equipment technology. Nevertheless, the test subject can be made aware of the fact that the necessary pedalling work can be carried out without excessive movements of the upper body. Incidents are extremely rare in the case of ergometry when performed correctly, and routine investigations are today therefore predominantly carried out by well-briefed medical assistants. The only ergometric investigations that must be supervised by the doctor over the entire duration of the exercise tolerance test are those in which – due to the general condition of the test subject – complications cannot be ruled out. A nurse or medical assistant must be present at the same time in order to assist or to provide immediate assistance if necessary.

An emergency supply of equipment and medication as well as a functioning defibrillator must be available to hand at all times.

7.21 The Diagnostic Value of Ergometry

ST segment variation during the exercise ECG is of the utmost importance for the detection of temporary myocardial ischaemias. In addition, coronary heart conditions can be established unambiguously. Coronary angiography has made an essential contribution to improving the interpretation of the exercise ECG, although there is a fundamental difference between the two: coronary angiography detects the morphological changes in the coronary arteries, whereas the exercise ECG detects the functional effects.

7.22 Indications

An indication for an exercise ECG can be given for diagnostic, therapeutic or prognostic reasons:

- Investigation of a coronary heart condition (e.g. chest pain during physical exertion)
- Investigation of the blood pressure where there is suspicion of exercise-induced hypertension
- Investigation of the stress tolerance (e.g. following a myocardial infarction, etc.)
- Assessment of cardiac arrhythmias
- Assessment of the progress and therapeutic success of medication and exercise therapy and following heart surgery
- Assessment and classification of the degree of severity of stress-induced coronary insufficiency.

7.23 Abort Criteria and Safety Measures

Exercise tolerance tests cannot be performed without risks (e.g. myocardial infarction, life-threatening arrhythmias, etc.). In order to minimize the risks, safety measures should be taken before and after the exercise tolerance test. Before the exercise tolerance test, information from the resting ECG should be analysed,

including anamnesis, and the patient should be examined and informed. It is important to tell the patient to report any subjective complaints during the exercise tolerance test, and to continue to monitor the test subject following the exercise tolerance test (generally for 5–10 min); a monitoring ECG should be recorded again and the blood pressure should be measured.

Criteria for aborting ergometry are:

- Increasing retrosternal severe pain (angina pectoris)
- Horizontal or descending ST depression of >0.2 mV
- Cumulative monomorphic or polytopic ventricular extrasystoles
- Ventricular salvos
- Isolated extrasystoles that fall in the T wave of the previous cardiac action (R-on-T phenomenon)
- Atrial fibrillation or flutter
- Serious conduction defects (e.g. total AV block)
- Depolarization defects (e.g. bundle branch block)
- Systolic blood pressure >250 mmHg, diastolic blood pressure >130 mmHg, and drop in blood pressure
- Noticeable breathing difficulty (dyspnea)
- Signs of the beginning of left ventricular insufficiency
- ECG signs of a fresh myocardial infarction.

7.24 Technical Safety Aspects

Bicycle ergometers are subject to the provisions of the German Medical Devices Act (IIa) and DIN VDE 0750-238. They must be serviced regularly, as must the noninvasive blood pressure meters that may be installed on them.

7.25 Notes on Planning

A room temperature of 18–23 °C with a relative atmospheric humidity of 40–60% is recommended. As a guide, a floor space of area 16 m^2 would be suitable. There should be the option to get changed (changing cubicle ≈3 m^2), and bathroom facilities with WC/shower (approx. ≈5 m^2) should also be provided.

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