



Technologies for non-invasive physiological sensing: Status, challenges, and future horizons

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ARTICLE INFO

Keywords:

Non-invasive diagnostic technique
Photoplethysmography (PPG)
Electroencephalography (EEG)
Electromyography (EMG)
Electrocardiography (ECG)
Computed tomography (CT)
Magnetic resonance imaging (MRI)
Ultrasound (US)
Electrical impedance tomography (EIT)

ABSTRACT

Non-invasive techniques have become increasingly vital in modern medicine, providing valuable diagnostic information without invasive procedures. These techniques encompass a diverse range of procedures, including imaging scans, blood tests, urine tests, and genetic testing, enabling the investigation of various conditions without device insertion. In contrast to conventional invasive methods, non-invasive diagnostics have numerous advantages, including reduced complications, shorter recovery times, improved patient comfort, and lower costs. As a result, the exploration of alternative diagnostic approaches has become imperative. This article provides a comprehensive overview of advances, challenges, and opportunities in the realm of non-invasive diagnostic techniques. It delves into a detailed exploration of non-invasive techniques, including photoplethysmography (PPG), electroencephalography (EEG), electromyography (EMG), electrocardiography (ECG), computed tomography (CT), magnetic resonance imaging (MRI), ultrasound (US), and electrical impedance tomography (EIT) discussing their origin, underlying principles, instrumentation, and applications in various medical fields. Furthermore, the advantages and limitations of various Surface Measurement and Imaging Modalities techniques are thoroughly compared and analysed. The article also addresses these challenges and highlights emerging technologies and methodologies that offer solutions. More importantly, we propose several promising directions for future research and development of non-invasive diagnostic techniques.

1. Introduction

Health status across the globe has been significantly impacted in recent years, resulting in high morbidity and mortality. According to the World Health Organization (WHO), as of 2021, there have been over 231 million confirmed cases of coronavirus disease (COVID-19) and over 4.75 million deaths worldwide since the pandemic began (“Weekly epidemiological update on COVID-19–September 14, 2021,” 2021). The Global Burden of Disease Study indicates that the leading causes of death worldwide are ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lower respiratory infections, and Alzheimer’s disease (“The top 10 causes of death,” 2023). Noncommunicable diseases (NCDs), also known as chronic diseases, are characterized by their long-lasting nature and arise from a combination of genetic, physiological, environmental, and behavioural factors. They include

cardiovascular diseases, cancers, chronic respiratory diseases, and diabetes (Hunter and Reddy, 2013). NCDs disproportionately affect low- and middle-income countries, with over three-quarters of global NCD deaths occurring in these regions (Alwan and MacLean, 2009; Devi et al., 2020). Managing NCDs requires early detection, screening, treatment, and access to palliative care. These diagnostic techniques are key to achieving the Sustainable Development Goal related to NCDs and reducing their impact on individuals and society (Srinath Reddy, 2015; Varghese et al., 2019). Therefore, it has become increasingly important to monitor our health and well-being. Human physiological monitoring can include measuring our vital signs, cardiovascular health, brain function, body composition, hemodynamic, organ function, and much more. The evolution of sensing technologies has made it convenient to measure biopotentials from our body, monitor our cardiovascular health, keep track of our body composition, and even measure our

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psychological stress levels (see Fig. 1). Over the last few decades, the healthcare landscape is undergoing a profound transformation, marked by a significant shift from traditional hospital-centric care to increasingly prevalent online doctor consultations (Mold et al., 2019) and the integration of Artificial Intelligence (AI)-driven auto diagnostic tools (Amjad et al., 2023; Bohr and Memarzadeh, 2020). These changes reflect a broader evolution towards patient-centred, digitally enabled healthcare solutions, enhancing accessibility and efficiency while redefining the patient-provider relationship (Verily et al., 2022).

This article defines non-invasive physiological monitoring techniques that capture data from the skin surface as “surface measurements”, encompassing methods such as photoplethysmography (PPG), electroencephalography (EEG), electromyography (EMG), and electrocardiography (ECG), among others. These surface measurements find widespread applications in clinical practice and home settings, serving as invaluable tools for healthcare professionals and enabling patients to monitor their well-being with ease.

For instance, in clinical practice, PPG serves as a non-invasive optical method for monitoring blood volume changes in peripheral tissues, yielding crucial information on cardiovascular function and arterial stiffness (Alian and Shelley, 2022). Simultaneously, PPG sensors have been seamlessly integrated into wearable bands and watches, facilitating continuous and user-friendly vital sign monitoring (Charlton and Marozas, 2022). This enables early detection of cardiovascular irregularities and extends the reach of preventive healthcare interventions beyond conventional clinical contexts. EEG serves as a vital diagnostic tool to assess brain function, diagnose neurological disorders, and monitor changes in a controlled medical environment in clinical practice (Henry, 2006). Beyond clinical settings, EEG has found applications in home-based neurofeedback and sleep studies, providing valuable insights into the dynamics of brain activity during everyday life and sleep patterns, fostering research and personalized interventions for cognitive enhancement and sleep quality improvement (Carr et al., 2020; Hirsch et al., 2020; Santangeli et al., 2017; Zhang et al., 2020). EMG is a sophisticated diagnostic and research tool used to assess and analyse electrical muscle activity by detecting and quantifying the electrical signals generated by muscle contractions. EMG offers valuable insights into neuromuscular function, enabling comprehensive investigations into muscle physiology, movement disorders, and the evaluation of

therapeutic interventions (Jarque-Bou et al., 2021; Jiang, 2020; Kama-vuako, 2022). ECG is the pivotal diagnostic tool to monitor and analyse the cardiac health. Besides the comprehensive standard 12-lead ECG measurement used in clinical condition, ECG signals can be easily measured by embedding electrodes into wearable products (Arquilla et al., 2020; Boehm et al., 2016; Kamga et al., 2022; Piuzzi et al., 2020). Portable ECG monitors empower patients to engage in continuous self-monitoring, enabling early detection of irregularities and facilitating a more proactive approach to cardiac care.

On the other end of this spectrum, imaging modalities, such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasound (US), and electrical impedance tomography (EIT), offer detailed anatomical images and facilitate precise localization of abnormalities and comprehensive structural evaluation. CT scanning has emerged as a highly accurate non-invasive technique for the detection of various cancers. The procedure involves acquiring multiple X-ray images of an individual’s chest to construct a 3D representation of the lungs. These images enable physicians to thoroughly examine the lungs and identify any abnormalities that may require intervention or treatment (Taylor et al., 2020). In recent years, CT scans have emerged as a widely utilized method for detecting novel Coronavirus strains, including COVID-19. This imaging technique has proven particularly effective in the later stages of infection when the virus is more active in the lungs. Recent studies have shown that CT scans can detect COVID-19 in the lungs with a sensitivity ranging from 86% to 98%, demonstrating its high diagnostic accuracy in identifying the presence of the disease. (Udugama et al., 2020). The use of US during preoperative diagnosis, prediction of surgical results, and cost-effectiveness has proved to be a feasible, practical, and cost-effective technique. In the past few years, it has been widely used in low- and middle-income countries, particularly for surgical applications (Jiang, 2020). The use of diaphragm US can be useful for diagnosing diaphragmatic dysfunction, assessing the dysfunction’s severity, and monitoring the disease’s progress (Patel et al., 2022). The integration of automated deep learning-based systems with point-of-care ultrasound (POCUS) holds significant potential to introduce new applications and advancements in various areas of POCUS imaging. By incorporating deep learning algorithms into POCUS imaging, there is a promising opportunity to enhance the accuracy and effectiveness of image interpretation. This can be achieved through

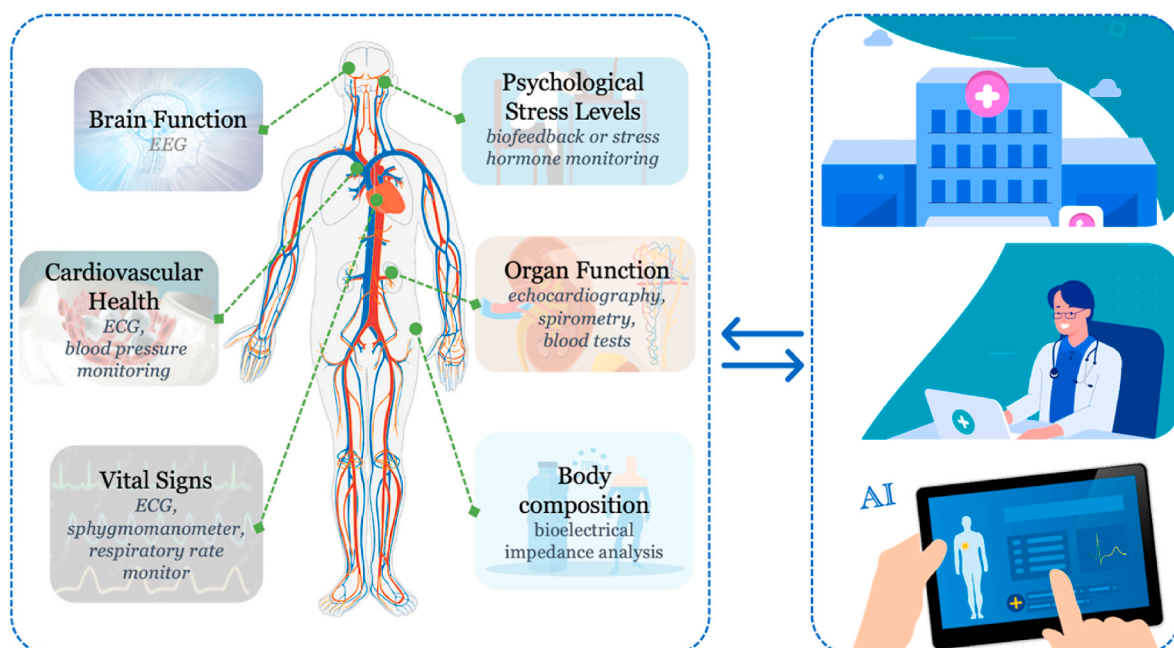


Fig. 1. Human physiological monitoring.

automation of the interpretation process, allowing for more efficient and reliable analysis of ultrasound images. Additionally, by tailoring different algorithms based on the specific clinical context, the integration of deep learning can further optimize the performance of POCUS imaging, ensuring its suitability and effectiveness in diverse clinical scenarios (Shokoohi et al., 2019).

MRI has emerged as a prominent medical imaging modality within the contemporary healthcare landscape. Its versatility has enabled the development of various techniques that facilitate the characterization of gross anatomical structures, tissue microstructure, alterations in blood oxygenation levels, bulk blood flow, and tissue perfusion throughout the body (Yousaf et al., 2018). In the context of neuroimaging, MRI has proven invaluable in providing valuable insights into the brain for diagnostic purposes. Through the utilization of MRI, clinicians can obtain crucial information that aids in the accurate diagnosis and understanding of various medical conditions (Liu, 2020; Yun et al., 2018). EIT is a non-invasive imaging technique that measures electrical impedance on an object's surface to create detailed cross-sectional images of its internal conductivity distribution. EIT has wide-ranging applications in fields like medical imaging, materials science, and environmental monitoring due to its portability, cost-effectiveness, and versatility (Bera, 2018).

Numerous reviews have explored the benefits and potentials of different techniques, while some have focused on the materials, techniques, and algorithms involved. However, this study aims to offer a more extensive examination of the historical background, emerging trends, and advancements in both surface measurement and imaging modalities. The main aim of this research is to conduct a thorough literature review on surface measurement and imaging modalities techniques utilized for non-invasive disease diagnosis. To our knowledge, there is a lack of comprehensive literature reviews that encompass both surface measurement and imaging modalities, while also addressing the limitations associated with current diagnostic technologies. Moreover, this paper aims to shed light on potential future directions that can guide further advancements in this field of research. This paper aims to accomplish the following objectives:

1. Explore various surface sensing techniques employed for the non-invasive early detection of cardiovascular, neurological, and muscular diseases.
2. Examine different imaging techniques utilized for the early diagnosis of diseases with minimal infrastructure requirements.
3. Evaluate existing technologies based on their accuracy, efficiency, credibility, accessibility, cost, and user-friendliness.
4. Outline future directions and advancements expected in the field of non-invasive diagnostics in the near future.

The structure of the remaining paper is as follows: In section 2, we describe the research methodology employed in this study. Section 3 presents a comprehensive discussion on both surface measurement and imaging modalities techniques utilized in various domains. Furthermore, section 4 examines the relative advantages and limitations associated with non-invasive monitoring. Finally, in section 5, we outline potential directions for future research in this field.

2. Material and methods

This review paper follows a systematic literature review approach, synthesizing a wide range of research conducted by different authors in the field of non-invasive diagnosis. Given the diverse landscape of non-invasive diagnostic techniques, it is crucial to comprehensively evaluate the various methods employed by researchers and medical professionals to enhance early disease detection and improve patient well-being. Prior to initiating this systematic literature review, we establish clear research goals and objectives, which serve as the guiding framework for organizing the paper. A thorough search across multiple databases is

conducted to compile relevant articles and papers from various sources. The selection process is rigorous, with precise criteria for inclusion and exclusion based on the research objectives and pertinent keywords, including healthcare monitoring, non-invasive diagnosis, ECG, EEG, EMG, and more. From the extensive pool of articles and online databases, more than 170 references are thoughtfully selected for review. These references primarily originate from well-regarded sources such as IEEE Xplore, Springer, Elsevier, Multidisciplinary Digital Publishing Institute (MDPI), PubMed, Science Direct, and respected journals and conferences, all published up to the year 2023.

3. Surface measurement

3.1. Photoplethysmography

PPG is a non-invasive optical technology to track arterial blood volume change based on the principle of pulse oximetry, which has gained significant attention in recent years due to its applications in various fields, including healthcare (Almarshad et al., 2022), fitness tracking (Chow and Yang, 2020), and biometric authentication (Donida Labati et al., 2022). An optical sensor emits light to the skin and measures the intensity of light which is reflected or transmitted through the skin (Kamal et al., 1989; Weinman et al., 1977). The amplitude of PPG signals depends on the amount of blood rushing into the peripheral vascular bed, the optical absorption of blood, skin pigmentation, ambient light, and the wavelength (e.g., infrared and green) used to illuminate the blood (Allen, 2007). The main principles of PPG sensor has been illustrated in Fig. 2. The early application of PPG was to record the change in blood content of the nasal septum, fingers, and toes (Hertzman, 1937), dating to 1937, and to the cutaneous blood pulse in 1946 (Hertzman et al., 1946). Nowadays, PPG sensors are widely applied in wrist-worn smart devices to detect users' heart rates during daily physical activities (Van, 2019) and blood oxygen saturation (SpO₂) to provide insights into stress levels and sleep quality (Tamura, 2019). Additionally, there has been much interest in extracting more valuable health-related information from the PPG signal in addition to heart rate estimation and pulse oximetry readings. It was reported that the second derivative wave of the PPG signal could help researchers and clinicians evaluate various cardiovascular-related diseases, such as atherosclerosis and arterial stiffness (Castaneda et al., 2018). Recently, the advancements in signal processing techniques have opened new horizons for cuffless continuous BPM using multi-features from PPG signals with machine learning (ML) and AI (Chao et al., 2021; El-Hajj and Kyriacou, 2020; Hosanee et al., 2020).

According to a recent market analysis report ("PPG Biosensors Market Size & Share [2023 Global Report]," 2023), the global PPG biosensors market size was valued at USD 416.80 million in 2022 and is expected to grow at a compound annual growth rate of 11.6% from 2023 to 2030. PPG has evolved from a simple cardiovascular research tool to a widely adopted technology for non-invasive monitoring of various physiological parameters. Its continuous development and integration into wearable devices hold great promise for personalized healthcare and preventive medicine.

3.2. Electroencephalography

Among the various techniques available for the acquisition of bio-potentials, EEG stands out as the predominant method employed for monitoring cerebral activity. In 1929, Hans Berger marked the discovery of the human EEG and provided the first description of recording electrical brain activity using electrodes placed on the scalp (İnce et al., 2021). After nearly a century, EEG product development has witnessed the integration of wearable devices with mobile technology, enabling continuous monitoring, AI-assisted analysis, and wireless connectivity for remote monitoring and personalized care. (Gu et al., 2022; He et al., 2023; Sen et al., 2023).

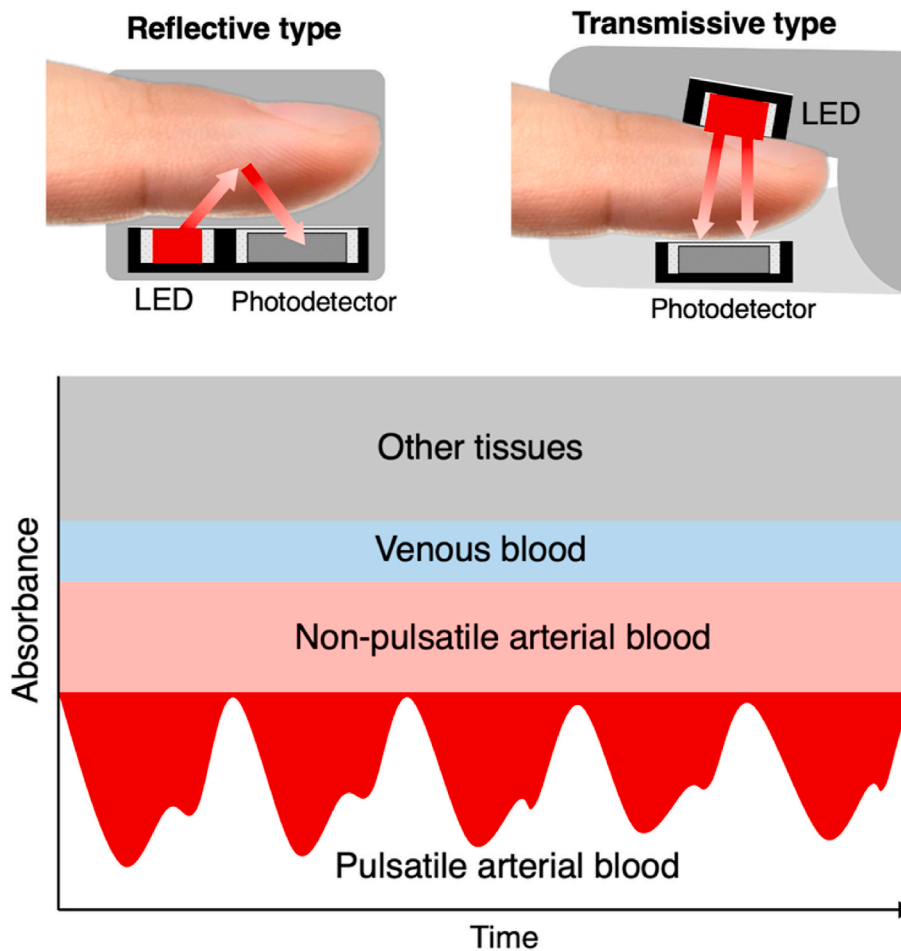


Fig. 2. Configuration for photoplethysmography measurement and the main principle of photoplethysmogram generation.

Neuronal excitations cause brainwaves to contain several frequencies – somewhat between 1 and 90 Hz. Brainwaves can be divided into five general categories: Gamma, Beta, Alpha, Theta and Delta (or Zeta) (Kalra et al., 2020), with properties illustrated in Fig. 3. (Kalra et al., 2020).

Due to its extensive applicability, EEG finds utility in numerous domains encompassing the detection of brain tumours, diagnosis of brain death, and assessment of diverse neurological disorders (Kirschstein and Köhling, 2009). Depression, a severe neurological disorder characterized by diminished motivation and an increased propensity for suicide, can be diagnosed using various biomarkers in EEG (Sander et al., 2018),

such as a high tendency of sleep disturbances (Santangeli et al., 2017), stronger pupillary reactions to emotional faces (Burkhouse et al., 2017), frontal alpha asymmetry variation (Zhao et al., 2021), and gamma and high gamma oscillations (Fitzgerald and Watson, 2018).

In a study conducted by (Gnezditskiy et al., 2017), EEG signals were employed to examine the brain activity of 99 individuals who had experienced a stroke or had neurological impairments. The recorded EEGs revealed a diverse range of epileptiform signs, each with varying occurrence rates. These signs included rhythmic delta activity in the form of Periodic Lateralized Epileptiform Discharges (PLED), frontal intermittent rhythmic delta activity (FIRDA), temporal intermittent

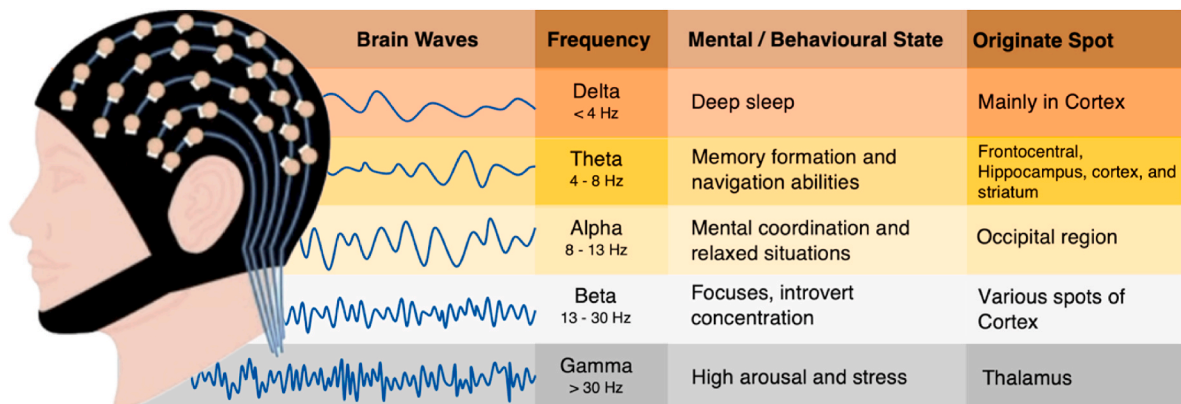


Fig. 3. The Frequency band of EEG signals.

rhythmic delta activity (TIRDA), as well as spikes and complexes, which could occur either in the left or right hemisphere. In another study conducted by (Cho et al., 2020), an analysis of non-invasive EEG signals was performed on patients undergoing extracorporeal membrane oxygenation (ECMO), which is a technique utilized to provide respiratory and cardiac support to individuals whose heart and lungs were not functioning properly. This study focused on patients who had undergone ECMO and aimed to investigate the prevalence of neurological disorders among them, as well as the impact of these disorders on their quality of life. The results revealed that a significant proportion, specifically 85% of the total patients, exhibited neurological disorders that had a notable effect on their overall quality of life.

Additionally, it was found that employing verbal suggestions during hyperventilation and photic stimulation aided in diagnosing psychogenic non-epileptic seizures (PNES) using EEG (Whitehead et al., 2017). The diagnosis of PNES is challenging. In the epilepsy monitoring unit (EMU) setting, non-invasive techniques such as verbal suggestion during hyperventilation and photic stimulation have been used to induce events and aid in the diagnosis of PNES. Among 189 patients diagnosed with PNES, 47% had their diagnosis confirmed through induction techniques, allowing for the cessation of antiepileptic drugs in 53% of induced PNES cases (Gogia et al., 2019). Their findings highlight the importance of induction techniques in diagnosing PNES and identifying a significant proportion of previously undiagnosed patients. Furthermore, Camp et al. proposed an electrode made from PEDOT polymer for the monitoring of EEG signals. As an alternative to standard EEG electrodes that lose conductivity when they are dried, the proposed electrodes are self-adhesive and do not lose conductivity after drying (de Camp et al., 2018). A new system for non-invasive, portable, and functional near-infrared spectroscopy (fNIRS) has been proposed by Saikia et al. to measure the hemodynamic response of the prefrontal cortex using fNIRS. The use of fNIRS to augment psychological sensing may eventually lead to the development of medical rehabilitation techniques through integration with fNIRS (Saikia et al., 2021).

Extended EEG recordings can be obtained through clinical diagnostic procedures or by employing portable wearable devices. The outcomes derived from these recordings serve as a foundation for a wide array of applications, such as brain-computer interfaces, image recognition, dream engineering, and virtual reality. Nonetheless, it is crucial to acknowledge that substantial potential for advancements remains in this field. There are several EEG devices available in the market that are commonly used for various applications (i.e., medical diagnosis, neurofeedback, and cognitive research), as shown in Table 1.

It also presents channel numbers and resolution, as they are important factors in EEG data acquisition, as they influence the level of detail and information captured from the brain's electrical activity. Increasing

the number of channels allows for more precise localization of brain activity and the detection of subtle spatial patterns, providing a higher spatial resolution and thereby enabling researchers or clinicians to examine specific brain regions or networks more comprehensively. Higher resolution enables the device to capture smaller voltage differences accurately, resulting in a more precise representation of the EEG waveform, which is particularly important for detecting subtle changes or low-amplitude signals in the EEG.

3.3. Electromyography

EMG has a rich history of technological advancements, beginning with the introduction of the first commercially available system in 1950 (Ladegaard, 2002). Over the years, EMG technology has undergone significant transformations, transitioning from analog to digital systems and embracing the power of microprocessors and personal computers. EMG has found successful application in various clinical contexts, proving to be a valuable tool in fields such as sports medicine, urology, posture and falls prevention, orofacial functions, and other diverse clinical areas (Grabherr et al., 2015). Surface electromyography (sEMG) has diverse applications beyond monitoring neuromuscular pathologies. The simplified sEMG signal acquisition process has been illustrated in Fig. 4. It finds utility in the prevention of work-related disorders, occupational therapy, and monitoring neuromuscular changes in acute patients to track their progress. By capturing and analysing muscle electrical activity, sEMG yields quantitative information about wave shape, amplitude, power spectral density, and other parameters (Campanini et al., 2020). This enables a deeper understanding of muscle function and aids in assessing treatment efficacy and rehabilitation progress in various clinical contexts. For instance, transcutaneous electrical nerve stimulation (TENS), a non-invasive technology based on EMG, has proven effective in analyzing fatigue levels during both short and long durations (Mohana, 2020), which can provide valuable insights into the physiological state of individuals, enabling better assessment and management of fatigue in various applications, such as sports performance, occupational health, and rehabilitation settings.

Moreover, EMG is utilized for the diagnosis of various neuromuscular diseases, including neuropathy and myopathy. Neuropathy refers to a disorder that affects the peripheral nervous system, resulting in the loss of motor function and subsequent muscle weakness. On the other hand, myopathy is characterized by the impairment of muscle fibres, leading to reduced muscle functionality and resulting in muscular weakness. By examining the electrical activity of muscles through EMG, healthcare professionals can aid in the accurate diagnosis and assessment of these conditions, facilitating appropriate treatment strategies (Chowdhury and Cheung, 2019). A disruption in the anatomy of the

Table 1

Commercially available EEG devices in the market with their features, and performance parameters.

Device Name	Brand & Country	Main Features	Channel Numbers	Resolution	Official Website
Emotiv Insight	Emotiv® USA	Portable and wireless EEG headset, suitable for various applications such as gaming, research, and education	5	14-bit	https://www.emotiv.com/insight/
Muse	Interaxon™ Canada	Portable and wireless EEG headset designed for meditation and mindfulness training, but can also be used for general brain monitoring	4	24-bit	https://choosemuse.com/
NeuroSky MindWave	NeuroSky® USA	Cost-effective and easy-to-use EEG headset, suitable for basic brain monitoring and educational purposes	1	10-bit	https://store.neurosky.com/
OpenBCI	OpenBCI USA	Open-source EEG platform that provides a range of customizable and modular EEG devices for research and development	Varies by device	Varies by device	https://openbci.com/
BrainVision Recorder	Brain Products™ Germany	Professional EEG system that offers high-quality EEG recordings and advanced analysis features for clinical and research applications	Varies by system	Varies by system	https://www.brainproducts.com/productdetails.php?id=21
Biosemi ActiveTwo	Biosemi™	High-end EEG system that provides high-quality recordings and advanced signal processing capabilities for research and clinical applications	32, 64, or 128	24-bit	https://www.biosemi.com/products.htm
g.Tec g.USBamp	g.Tec™	Portable and high-performance EEG amplifier that can be used with a variety of EEG electrodes and sensors for research and clinical purposes	Varies by device	Varies by device	https://www.gtec.at/products/bio-medical/gusbamp/

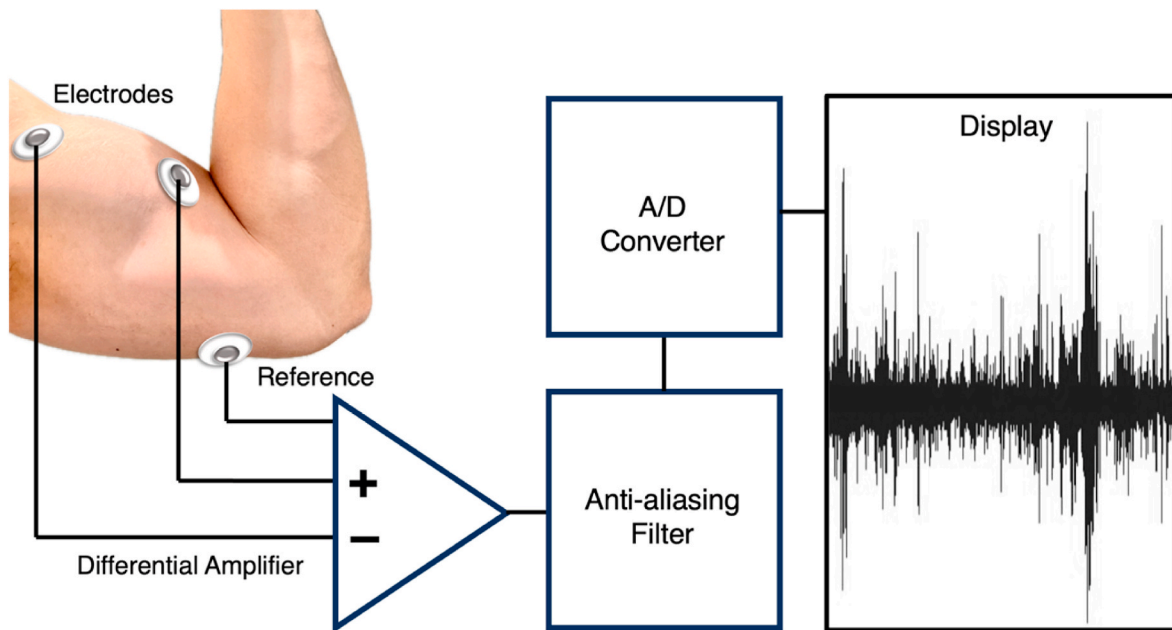


Fig. 4. Simplified block diagram of sEMG acquisition and display.

nerves and blood vessels associated with diabetic sensorimotor polyneuropathy (DSPN) causes a dysfunction in the motor, sensory, and autonomic nerves of the body as a result of dysfunction in the nerves. Several changes in gait parameters that appear to be specific to diabetes have been identified in the literature: slower walking speeds, and altered lower limb, trunk, and stride lengths, which appear to be decreased with diabetes. Using an EMG, it is possible to monitor abnormal muscle activation. For example, altered muscle activity plays a role in gait alterations in diabetic individuals (Gomes et al., 2011; Haque et al., 2020; Sawacha et al., 2012; Watari et al., 2014). Furthermore, sEMG can be employed to non-invasively acquire electromagnetic signals from the intestine, offering a diagnostic approach for conditions such as constipation, diarrhoea, and other disorders affecting the digestive tract (Khan et al., 2019).

Similar to EEG, the number of individual EMG channels or electrodes determines the spatial resolution of the EMG measurement, allowing for the simultaneous recording of multiple muscles or muscle groups. Each channel corresponds to a specific muscle or region of interest. Having more channels provides the ability to capture EMG signals from different muscles or specific regions, enabling comprehensive muscle assessment and analysis. Furthermore, a higher sampling rate allows for capturing more detailed temporal characteristics of the EMG signal, providing an accurate representation of rapid changes in muscle activity and finer motor control analysis. Table 2 lists several commercial EMG products with various channel numbers from 2 to 64 and sampling rates from hundreds of Hz to thousands of Hz.

3.4. Electrocardiography

Cardiovascular diseases have emerged as a significant global health concern due to unhealthy lifestyles and dietary habits. They encompass a range of conditions, including heart attacks, and are responsible for a substantial proportion of worldwide mortality. According to the WHO, cardiovascular diseases contribute to over 31% of total deaths, making them a leading cause of mortality globally (Rehman et al., 2021). Addressing risk factors and promoting heart-healthy behaviours are crucial in combating this growing health burden. Research findings indicated that individuals who receive an early cardiac diagnosis face a significantly higher mortality rate (Lai et al., 2011).

Detecting abnormalities in the heart is crucial for diagnosing cardiovascular conditions, and among the available biopotential signal acquisition methods, ECG or EKG is widely preferred, which is a non-invasive technique that analyses the heart’s rhythm by capturing electrical activity. In the 1880s, Augustus Waller, a British physiologist, was the first to record human heart electrical activity using a capillary electrometer (Besterman and Creese, 1979). In the early 20th century, Willem Einthoven introduced the string galvanometer, a highly sensitive instrument that could record and measure cardiac electrical activity, enabling the recording of precise and accurate ECG waveforms (Barold, 2003). The primary components of ECG waveforms, namely the P-QRS-T complex, provide valuable insights into the type and nature of cardiac abnormalities (Lai et al., 2011), as shown in Fig. 5. By examining these components, healthcare professionals can determine the presence of

Table 2

Commercially available EMG devices in the market with their features, and performance parameters.

Device Name	Brand & Country	Main Features	Number of Channels	Sampling Rate	Website
Trigno Avanti	Delsys Inc., USA	Wireless EMG system for research and clinical use with high signal quality and noise reduction	Up to 16 channels	192 kHz	https://delsys.com/trigno-avanti/
FreeEMG 1000	BTS Bioengineering, Italy	Portable EMG device for clinical and research use	Up to 16	Up to 4000 Hz	https://www.btsbioengineering.com/products/freeemg/
EMGWorks®	Delsys Inc., USA	EMG data acquisition and analysis software	Up to 64	Up to 4096 Hz	https://delsys.com/emgworks/
PowerDot 2.0	PowerDot, USA	Wireless electrical muscle stimulator with customizable settings for sports performance and rehabilitation	2 channels	Up to 200 Hz	https://www.powerdot.com/
Noraxon Ultium	Noraxon USA, Inc., USA	Wireless EMG system for research and clinical applications	Up to 16 (expandable to 32)	Up to 6144 Hz	https://www.noraxon.com/products/ultium/

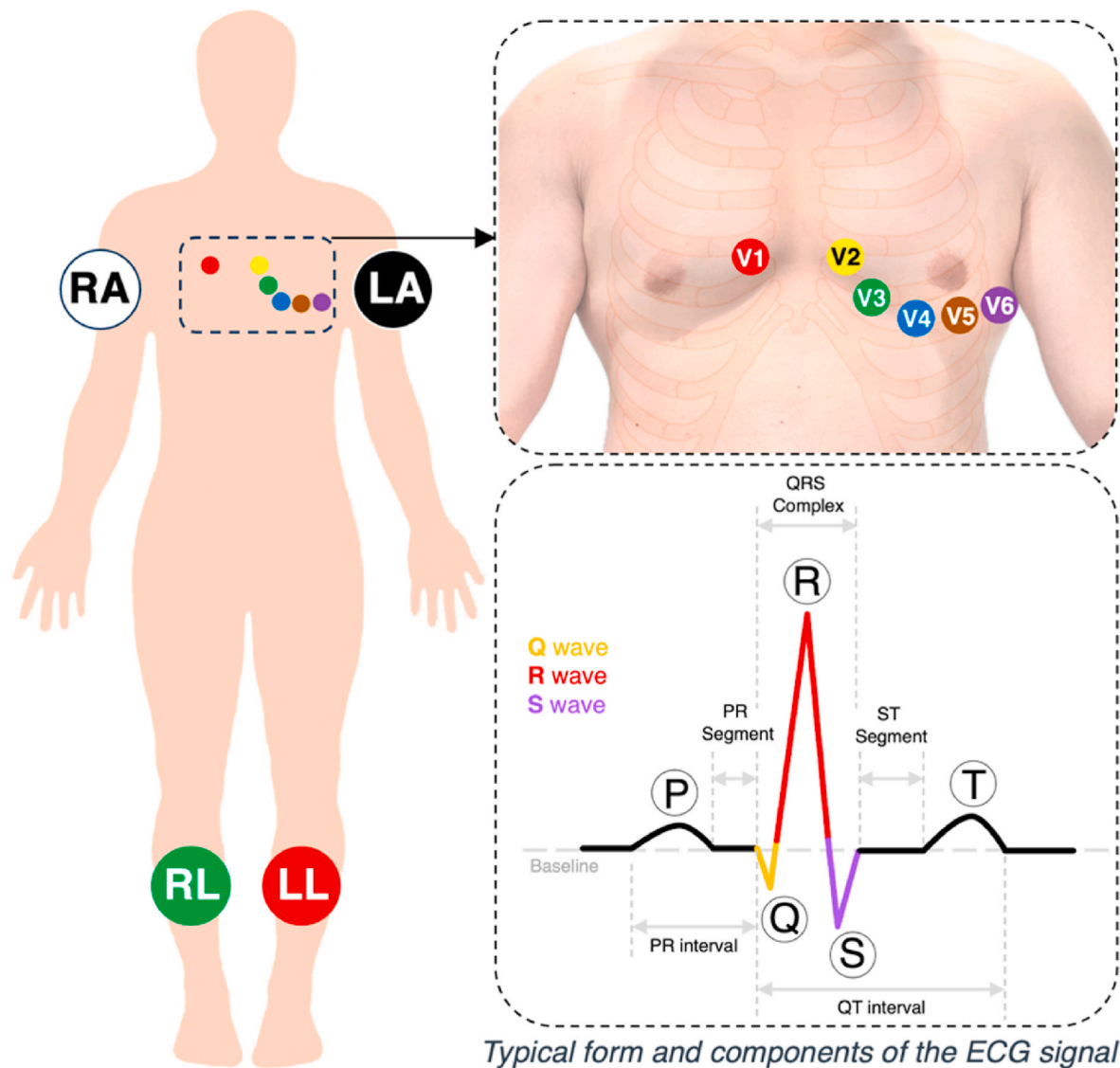


Fig. 5. Typical form and components of the ECG signal and the standard 12-lead ECG electrode placement: RA (Right Arm): on the right arm; LA (Left Arm): on the left arm; RL (Right Leg): on the right leg; LL (Left Leg): on the left leg; V1: in the 4th intercostal space to the right of the sternum; V2: in the 4th intercostal space to the left of the sternum; V3: midway between V2 and V4, in the 5th intercostal space; V4: in the 5th intercostal space at the midclavicular line; V5: in the anterior axillary line at the same level as V4; V6: in the mid-axillary line at the same level as V4 and V5.

arrhythmias, ischemia, myocardial infarction, and other cardiac conditions, aiding in timely diagnosis and appropriate treatment planning.

The types of ECG measurements can vary from clinical settings to wearable devices. In a clinical setting, the 12-lead ECG is considered the non-invasive gold standard (Khunti, 2014), which provides a comprehensive view of the heart's electrical activity by recording electrical signals from 12 specific locations on the body (i.e., chest, arms, and legs), as shown in Fig. 5. The 3-lead ECG (Maheshwari et al., 2014) and 5-lead ECG (Kaewfoongrunsi and Hormdee, 2017) are also applied for continuous monitoring during procedures or in situations where a full 12-lead ECG is not necessary. For instance, a Holter monitor is a portable device that records ECG continuously over a 24 to 48-h period, which typically uses three to five leads and allows for the assessment of cardiac activity during normal daily activities (DiMarco, 1990).

Because ECG gel electrodes are unsuitable for long-term monitoring, researchers are continually striving to develop more stable and comfortable ECG electrodes to enhance the user experience and improve the accuracy of cardiac monitoring. Their efforts have led to the creation of innovative electrode materials and designs that offer better skin

adhesion, reduced motion artifacts, and increased comfort during prolonged use (Arquilla et al., 2020; Chlahawi et al., 2018; Cui et al., 2022; Liu et al., 2023; Yapici and Alkhidir, 2017). Wearable ECG devices offer the convenience of continuous or on-demand monitoring outside of clinical settings, such as personal health monitoring, fitness tracking, and early detection of cardiac abnormalities. These devices are designed to be worn on the body, such as on the wrist, chest strap, or integrated into clothing, as shown in Table 3. Compared to the clinical ECG settings, the portability and continuous monitoring capabilities of wearable ECGs allow for convenient and prolonged heart activity assessment. Moreover, long-term data collection facilitates trend analysis and treatment evaluation. However, accuracy and precision may be compromised in wearable ECGs due to the limited number of leads and motion artifacts. Besides the contents summarized in the table, other features are also important, such as whether the product can provide continuous measurement and battery life. Professional interpretation of wearable ECG data may be necessary for accurate clinical decision-making.

Table 3

Commercially available ECG devices in the market with their features, and performance parameters.

Device Name	Brand & Country	Form	Number of leads	Heart event detection	Website
Zio XT/AT	iRhythm Technologies, Inc. (United States)	Patch adhered to the chest	1	Heart rate, arrhythmias, atrial fibrillation, bradycardia, tachycardia, and pauses.	https://www.irhythmtech.com/providers/zio-service/zio-monitors
KardiaMobile 6L	AliveCor, (United States)	Patch held in hands or adhered on chest	6	Heart rate, atrial fibrillation, bradycardia, tachycardia, and normal sinus rhythm	https://www.kardia.com/kardia-mobile-6l
QardioCore	Qardio (United States)	Chest strap	1	Heart rate, arrhythmias, heart rate variability, and ST segment changes	https://www.qardio.com/qardio-core-wearable-ecg-ekg-monitor-i-phone/ https://support.apple.com/en-us/HT208955
Apple Watch (series 4 and later version)	Apple Inc. (United States)	Watch on the wrist	1	Heart rate, heart rate variability, normal sinus rhythm, and atrial fibrillation.	https://www.hexoskin.com/collections/kits/products/hexoskin-pro-kit-mens
Hexoskin smart shirt	Hexoskin (Canada)	Shirt	3	heart rate, heart rate variability (HRV), R-R interval, ST segment, and other ECG waveforms such as P-wave, QRS complex, and T-wave	

4. Imaging modalities techniques

4.1. Computed tomography

CT is a medical imaging technique that uses X-ray technology to generate detailed cross-sectional images of the body, which provides valuable diagnostic information by producing images that reveal internal structures, tissues, and organs with great clarity and precision (Goldman, 2007). CT scans are frequently used in clinical settings because of their rapid availability, fast acquisition, high sensitivity, specificity, reproducibility, and high power of spatial and temporal resolution (Ciccione et al., 2016). CT scanners consist of a large circular machine that houses an X-ray tube and a detector array. During the CT scan, the X-ray tube rotates around the patient, emitting narrow beams of X-rays that pass through the body, as illustrated by Fig. 6. The detector array measures the X-rays that pass through the patient and converts them into electrical signals. These signals are then processed by a computer to construct cross-sectional images, also known as tomographic slices, which can be viewed from various angles (Kalender,

2006).

CT technology has evolved over time since the first CT scan (“The Nobel Prize in Physiology or Medicine, 1979,” 2023). More advancements in imaging techniques and equipment design have been carried out, such as multidetector CT (MDCT) scanners that can capture multiple slices simultaneously, enabling faster scans and higher-resolution images (Dalrymple et al., 2005; Karcaaltincaba and Aykut, 2010), contrast-enhanced CT for tumour diagnosis (Miles et al., 2012) and CT angiography for visualizing blood vessels and enhancing the detection of certain conditions (Kumamaru et al., 2010; Lell et al., 2006).

CT scans are particularly useful for diagnosing a wide range of medical conditions, including injuries, tumours, infections, and abnormalities in various body systems, such as the brain, chest, abdomen, pelvis, and extremities. The images produced by CT scans offer detailed information about the size, shape, and density of different structures within the body, allowing healthcare professionals to identify and evaluate abnormalities or diseases. For instance, CT is able to detect ground-glass attenuation, bronchial wall thickening, centrilobular nodules, and mucoid impaction, in addition to ground-glass attenuation,

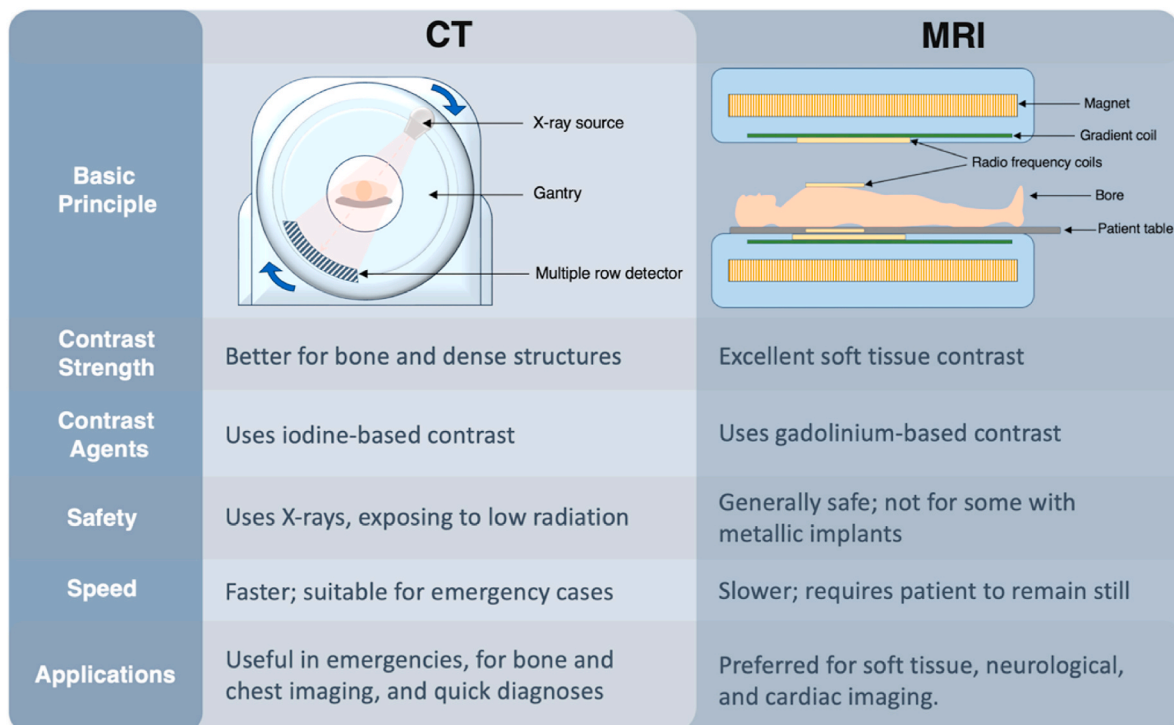


Fig. 6. Comparison between CT scan and MRI.

to be helpful in diagnosing community-acquired pneumonia (Tanaka et al., 1996). Furthermore, CT angiography offers a wide spatial resolution, making it possible to differentiate intramural haematomas (IMH), penetrating aortic ulcers (PAUs), and aortic dissections (ADs). When there are two lumens within the aorta, which are separated by an intimal flap inside the aorta, the diagnosis of AD can be confirmed (Evangelista et al., 2010). Radiation toxicities associated with urinary and gastrointestinal injuries can be predicted using CT image features (Mostafaei et al., 2020). Moreover, CT scans can also be used for identifying plaque in the brain, which is the cause of ischemic stroke, which can be identified. As a result of CT, it is possible to quantify fibrous plaque thickness, plaque calcification, ulcers, intraplaque haemorrhage, and the presence of a lipid-rich necrotic core within the plaque (Fabiani et al., 2020). There have also been instances in recent years when CT scans have been used to diagnose breast cancer (Jafari et al., 2018) and COVID-19 pneumonia (Hani et al., 2020). Furthermore, the integration of CT scans with advanced deep learning tools, such as COVNet, along with feature extraction techniques like Grey-Level Co-occurrence Matrix (GLCM) and Discrete Wavelet Transform (DWT), has proven valuable in extracting relevant information from CT scan images (Li et al., 2020; Öztürk et al., 2021). These advanced computational methods enable the identification of specific patterns, textures, and features within the CT images, facilitating the accurate characterization and classification of various medical diseases.

Overall, CT plays a crucial role in modern medicine, providing valuable diagnostic information that aids in the detection, characterization, and management of various medical conditions. Its ability to produce detailed cross-sectional images has made it an indispensable tool in clinical practice, assisting healthcare professionals in making accurate diagnoses and guiding appropriate treatment decisions.

4.2. Magnetic resonance imaging

MRI is a sophisticated medical imaging technique that utilizes a combination of strong magnetic fields, radio waves, and computer algorithms to generate detailed cross-sectional images of the human body (Katti et al., 2011). The first successful MRI experiment took place in the 1970s by a team of researchers led by Paul Lauterbur and Raymond Damadian (Geva, 2006). Over the years, significant progress has been achieved in improving the image quality, reducing scan times, and expanding the clinical applications of MRI, offering a non-invasive and versatile approach for visualizing anatomical structures, soft tissues, and organs with exceptional clarity and without exposing patients to ionizing radiation.

The underlying principle of MRI involves the alignment and manipulation of hydrogen atoms within the body, which emit distinct radiofrequency signals when subjected to a magnetic field (Brown et al., 2004). The main principle of MRI and the differences from CT scan have been illustrated in Fig. 6. By precisely detecting and analysing these signals, MRI scanners can construct highly detailed images that provide valuable diagnostic information for a wide range of medical conditions, such as stroke (Adam et al., 2018), Parkinson's disease (Chau et al., 2020), Alzheimer's disease (Chandra et al., 2019), intracranial hypertension (Kwee and Kwee, 2019) etc. MRI can also be used as a prominent tool for breast cancer diagnosis (Jafari et al., 2018) by providing information on various actions, including the staging of breast cancer, breast discharge, premalignant lesions, evaluation of microcalcifications, and residual tumours in operated patients to clinicians (Sardanelli et al., 2010). Compared with CT scans, MRI is found to be more sensitive to detecting water within tissues as a consequence of tumours, stroke, and other clinical syndromes (Obenaus and Badaut, 2022). Early cerebral ischemia can be precisely diagnosed using molecular MRI based on changes in calcium concentration in the tissue (Savić et al., 2019). Additionally, DL techniques can be utilized to extract useful data from MRI scans and improve the system's accuracy and robustness (Hasan et al., 2019).

In recent years, several advanced improvements have been made in MRI technology in the clinical setting, enhancing its diagnostic capabilities and patient experience. The development of high-field MRI systems, such as 3T (Wattjes and Barkhof, 2009) and even 7T (Ladd et al., 2018) MRI, has led to improved image resolution, signal-to-noise ratio, and faster imaging times (Regatte and Schweitzer, 2007), allowing for more detailed visualization of anatomical structures and subtle pathological changes, aiding in the early detection and characterization of diseases. Additionally, fMRI measures changes in blood flow and oxygenation in the brain, providing insights into brain activity and connectivity (Bandettini, 2012). fMRI has revolutionized neuroscience and clinical research, enabling the mapping of brain functions, such as examination of the brain systems underlying the behavioural deficits manifested in schizophrenia (Gur and Gur, 2010) and autism spectrum disorders (ASDs) (Dichter, 2012). Furthermore, Dynamic Contrast-Enhanced MRI (DCE-MRI) involves injecting a contrast agent to study tissue perfusion and vascular permeability (Sourbron and Buckley, 2013). It is widely used in oncology for tumour characterization, assessment of treatment response, and monitoring of anti-angiogenic therapies (Hylton, 2006; Miles et al., 2012; Padhani, 2002; Turkbey et al., 2009). In recent years, there has been a growing adoption of AI techniques in the field of medical imaging, specifically for tasks related to anatomical organ segmentation, optimization of imaging sequences, and automated diagnostic applications, such as automated biometric foetal measurements and the identification of both congenital and acquired abnormalities (Meshaka et al., 2022) and prostate cancer (Sunqrot et al., 2022).

4.3. Ultrasound imaging

Ultrasound (US, also called sonography or ultrasonography) is a medical imaging diagnostic technique to construct a real-time image of internal body structures and measure some characteristics such as distances and velocities. The inception of the US can be traced back to the early 20th century following the discovery of the piezoelectric effect by Pierre and Jacques Curie in 1915. Building upon this scientific breakthrough, pioneering researchers such as George Ludwig and Ian Donald played significant roles in developing the US for medical applications, particularly in the fields of obstetrics and gynaecology. Over the years, technological advancements have propelled ultrasound into a widely used imaging modality, offering real-time visualization and non-invasive diagnostic capabilities in various medical specialities. (Campbell, 2013; Newman and Rozycki, 1998). The US is composed of sound waves with a typical frequency range from 2 MHz to 10 MHz for clinical purposes, which are significantly higher than the upper limit of human hearing. Frequency is determined by the sound source rather than the medium (Aldrich, 2007). The main principle of US imaging can be briefly described as follows: US pulses are emitted into target tissues using a probe (i.e., transducer), then US pulses echo off tissues with different reflection properties (i.e., acoustic impedance) and return to the probe, which is then used to record and display the information as an image, as illustrated by Fig. 7. Several types of US images can be formed with different information, such as Amplitude mode (A-mode), Brightness mode (B-mode), Motion mode (M-mode), Doppler mode, etc. (Cobbold, 2006).

US is widely applied in obstetrics and gynaecology for various purposes in pregnancy (Merz et al., 2023), including confirming pregnancy viability (Naert et al., 2022), estimating gestational age (Eggleston et al., 2022), monitoring foetal growth and development (Salomon et al., 2019), assessing placental health (Schiffer et al., 2021), and detecting abnormalities in the foetus (Drukker et al., 2021). Moreover, US is commonly used to image organs, tissues, and musculoskeletal systems throughout the body, including but not limited to the liver, gallbladder, pancreas, spleen, kidneys, bladder, uterus, ovaries, and prostate, which helps in diagnosing conditions like tumours (Madsen and Rasmussen, 2011), cysts (Gaines and Sampson, 1989), abscesses (Froehlich et al.,

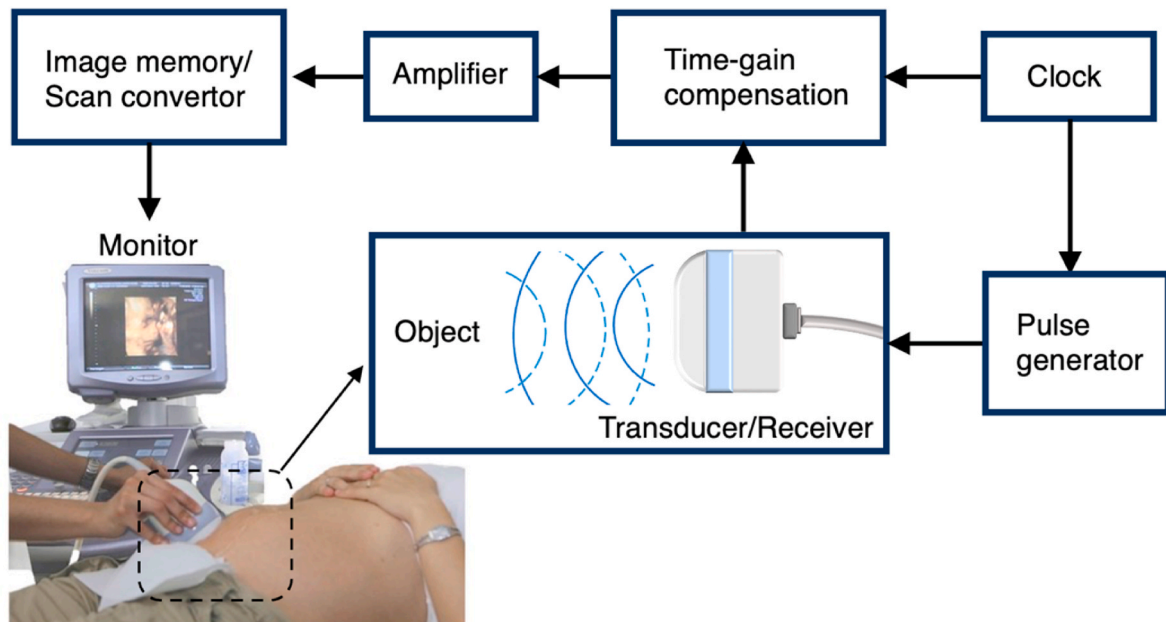


Fig. 7. Schematic depiction of image production by an ultrasound device.

2017), and fluid collections (Wagner et al., 2019). The US also plays a crucial role in emergency settings, which is used to rapidly assess trauma patients for internal bleeding (Harrois et al., 2013), evaluate abdominal pain (Jang et al., 2014), detect pulmonary oedema (Touw et al., 2015), and guide procedures such as central line placement or thoracentesis (Keenan, 2002). The use of diaphragm US can be useful for diagnosing diaphragmatic dysfunction, assessing the dysfunction’s severity, and monitoring the disease’s progress (Patel et al., 2022).

Echocardiography is a specialized US technique used to evaluate the structure and function of the heart, providing detailed images of the heart chambers, valves, and blood flow patterns (Oh, 2007). Furthermore, doppler US can measure blood flow velocity and direction, and detect blockages, stenosis, and blood clots, aiding in the diagnosis of conditions like deep vein thrombosis, arterial occlusions, and aneurysms

(Subramani et al., 2022). Interventional US encompasses a diverse array of percutaneous procedures that utilize US guidance for accurate and real-time visualization (Bianchi and Zamorani, 2007). This technique enables the precise positioning of needles for a range of interventions, including biopsies, drainage of fluid collections, administration of joint injections, and the performance of nerve blocks (Cardinal et al., 1998).

4.4. Electrical impedance tomography

EIT is a low-cost non-invasive technology that uses the electrical impedance of a substance to reconstruct an image of its internal structure (Brown, 2003), as illustrated in Fig. 8. The physical basis is that different materials have different electrical conductivities, and the medium distribution can be obtained by judging the electrical conductivity

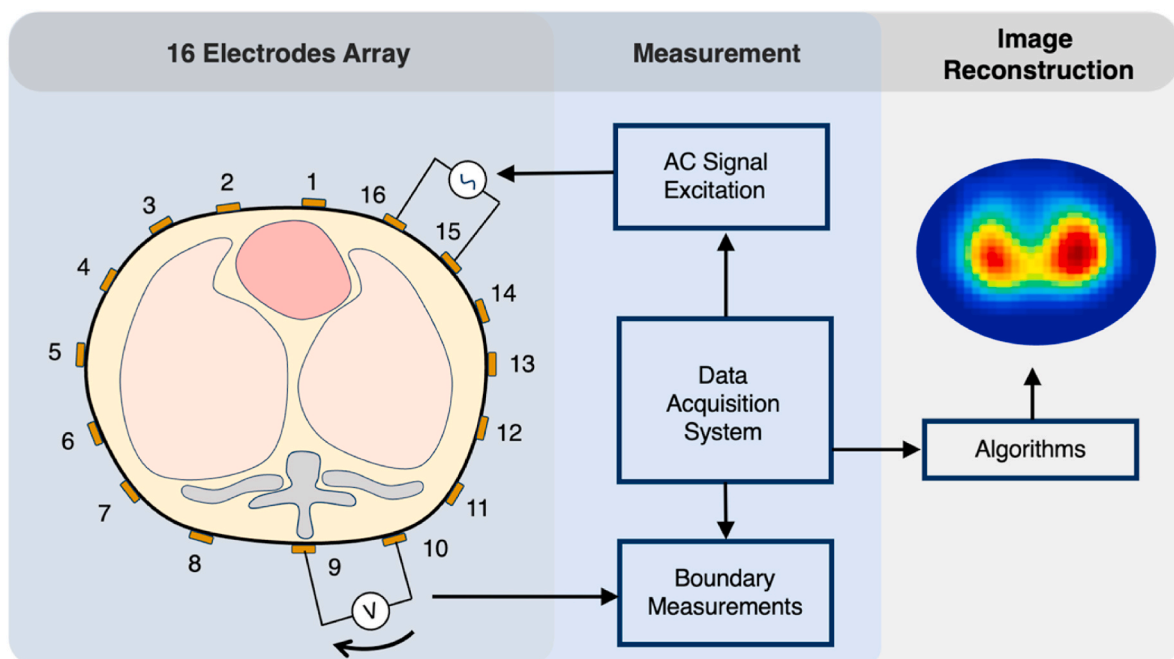


Fig. 8. 16 electrodes EIT system.

distribution of the sensitive field. The data collection of EIT mostly adopts the working mode of current excitation voltage measurement. Specifically, when an external current excitation signal is applied, a time-varying electromagnetic field will be generated inside the substance. The distribution of electrical conductivity in the object field will then change, and the distribution of the electrical current field changes as well, causing a change in the electrical potential distribution. Consequently, the voltage value measured at the boundary of the field also changes (Mansouri et al., 2021). The change in the boundary voltage value reflects the change in the conductivity inside. Thus, the distribution of the conductivity inside can be calculated by an image reconstruction algorithm to produce a visual image of the internal structure of the substance.

The earliest research on bio-impedance imaging worldwide was an impedance camera fabricated by (Henderson and Webster, 1978). Research on EIT was then begun at Sheffield University by (Barber et al., 1983). Due to the broad application prospects of EIT, it has attracted a

large number of researchers. In the early 21st century (Holder, 2002), there were more than 30 research groups from the United States, the United Kingdom, Russia, Germany, France, Sweden, Japan, and India that were researching EIT. In contrast to the structural imaging of CT, EIT is a kind of functional imaging. Although EIT is not as good as CT in terms of image resolution, EIT technology can obtain the electrical properties of tissues or organs related to human physiology and pathology through electrodes placed on the surface of the human body. Not only does it reflect the anatomical structure, but it is unique in providing functional image results.

As a new medical imaging technology, EIT has the advantages of being portable, non-invasive image detection and monitoring, which has a wide range of potential clinical applications (Adler and Holder, 2021). The electrical conductivity of tissues in the human body varies due to different health conditions, so some physiological or pathological changes can cause changes in electrical conductivity, especially in the initial and recovery periods. Some clinical research focused on the

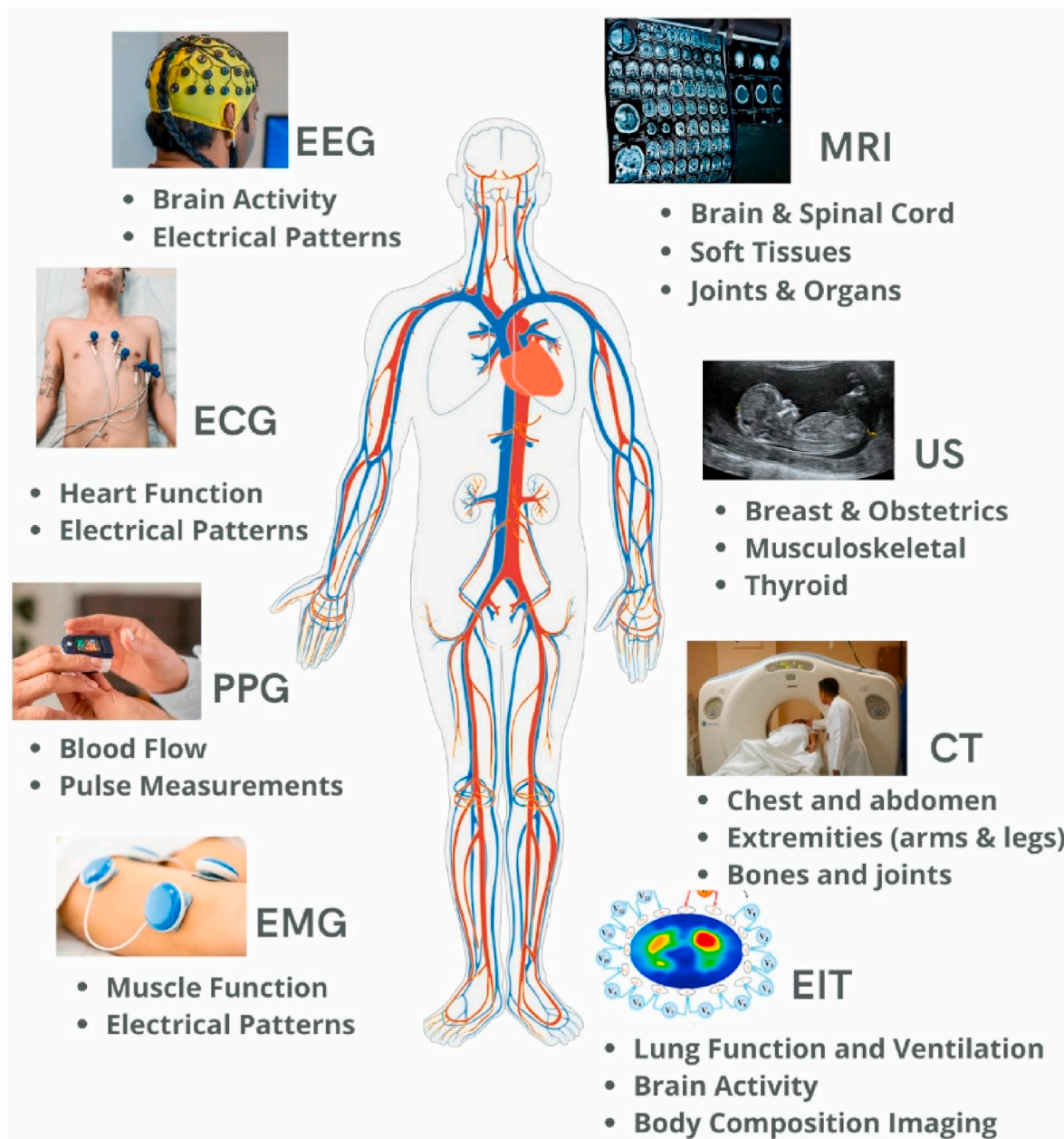


Fig. 9. Various non-invasive monitoring techniques.

following aspects: gastrointestinal and oesophageal functional imaging, pulmonary functional imaging, brain functional imaging, and cardiac functional imaging (Oh et al., 2007; Zlochiver et al., 2007). While EIT holds promise as a non-invasive imaging technique, it is important to note that its clinical utility is still being investigated, and further research is needed to establish its widespread use in various medical applications. Technology is evolving, and ongoing studies are aimed at refining its capabilities, validating its accuracy, and exploring new clinical applications (Khodadad et al., 2018; Li et al., 2022; Simini et al., 2018; Zhang et al., 2023; Zhu et al., 2021). A recent meta-analysis has been carried out with 8 trials, a total of 222 participants, indicating a thorough evaluation and robust evidence supporting the use of EIT-based individual Positive End-expiratory Pressure setting as a superior choice for patients with acute respiratory distress syndrome in terms of both safety and effectiveness (Yu et al., 2023).

5. Advantages and limitations

Non-invasive diagnostic techniques play a pivotal role in modern healthcare, enabling the assessment and monitoring of various physiological parameters, as shown in Fig. 9. This section aims to compare and analyse the advantages and limitations of commonly employed techniques with regard to their functionality, efficiency, cost, and accessibility, including PPG, ECG, EEG, EMG, US, CT, MRI, and EIT. An in-depth understanding of the strengths and limitations of different diagnostic techniques empowers clinicians and researchers to make well-informed decisions about their utilization in clinical practice and their potential for further advancement. Additionally, recognizing the weaknesses of current techniques drives research and development efforts toward addressing these limitations and developing innovative solutions.

Compared to invasive monitoring, the non-invasive techniques represent distinct approaches to assessing physiological parameters in clinical practice. Invasive methods, necessitating professional training,

are predominantly managed by healthcare experts, involving the insertion of catheters or other invasive devices. However, they pose a heightened risk of infection due to the necessary insertion of instruments into the patient's body (Blot et al., 2007). Conversely, some non-invasive techniques typically require less training for patients, such as wearable PPG and ECG devices. More importantly, non-invasive techniques reduce the risk of infection, offering patient-friendly, comfortable options for a broader range of clinical scenarios. Fig. 10 shows several characteristics of non-invasive diagnoses from a patient's perspective.

This paper presents a comprehensive categorization of non-invasive diagnostic techniques into two distinct groups: Surface Measurement and Imaging Modalities. Surface measurement techniques involve the application of sensors or electrodes on the skin to capture physiological signals. For instance, PPG monitors changes in blood volume, offering valuable insights into cardiovascular parameters. EEG captures brain electrical activity, aiding in the assessment of brain function and the detection of abnormal patterns. EMG records muscle electrical signals, enabling the diagnosis of neuromuscular disorders. ECG quantifies the electrical activity of the heart, facilitating the evaluation of cardiac rhythm and abnormalities. Such surface measurements exhibit several advantageous features, including their non-invasive nature, patient comfort during measurement, real-time data acquisition capabilities, affordability, and portability. More importantly, these techniques provide immediate feedback, allowing for continuous monitoring and timely interventions. However, it is worth noting that surface measurements have inherent limitations in terms of their ability to visualize internal structures and precisely locate abnormalities due to their reliance on numerical data of average response rather than providing detailed anatomical images.

While surface measurement techniques offer valuable real-time data acquisition and convenience, they are inherently limited in terms of their capacity to provide comprehensive anatomical visualization. Consequently, they may be more suitable for applications where

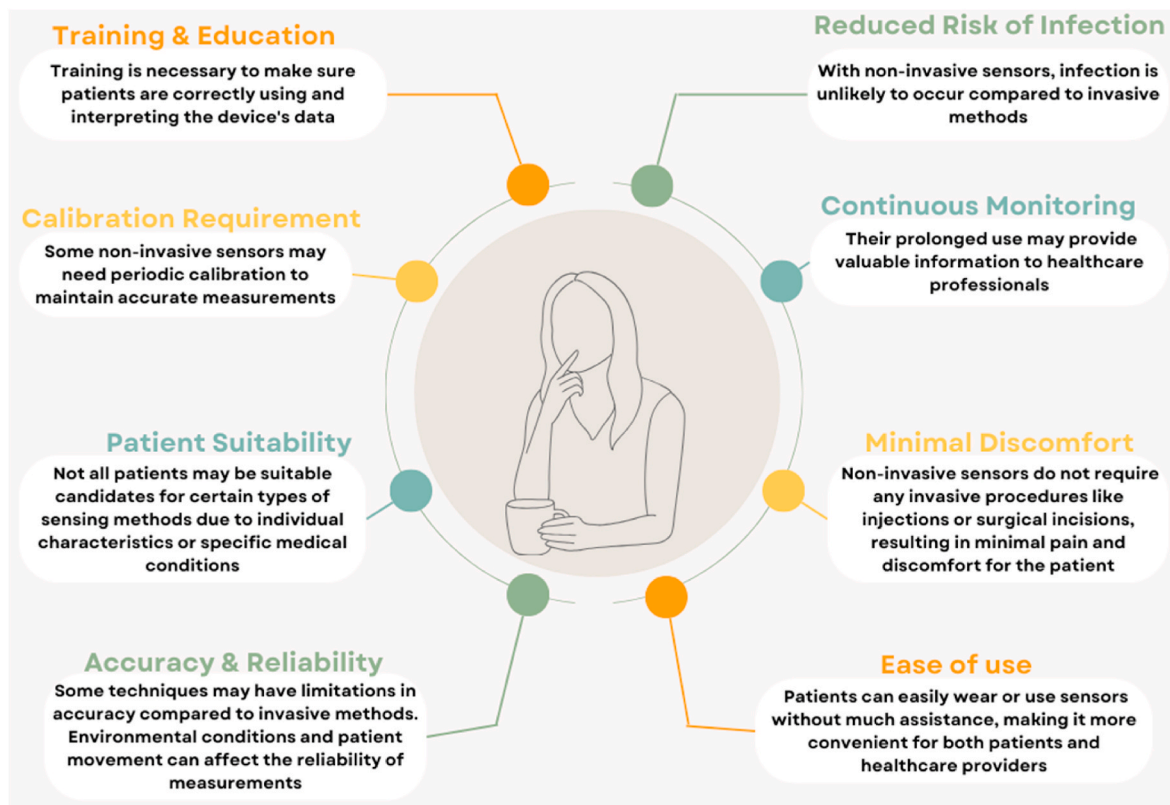


Fig. 10. Characteristics of non-invasive diagnoses from a patient's perspective.

continuous monitoring of physiological parameters is required. In contrast, imaging modalities such as CT, MRI, US, and EIT offer detailed anatomical images, facilitating precise localization of abnormalities and comprehensive structural evaluation. CT combines X-rays and computer processing to produce cross-sectional images, offering exceptional anatomical detail and the ability to visualize bones, organs, and tissues with high resolution. During the global COVID-19 pandemic, CT scanning played a pivotal role. In a comprehensive systematic review and meta-analysis encompassing sixteen studies involving 3186 patients, it was revealed that chest CT scans exhibit remarkable sensitivity, underscoring their significance as a valuable asset for early detection and effective epidemic control (Xu et al., 2020). MRI utilizes strong magnetic fields and radio waves to create detailed images with superior soft tissue contrast, making it particularly valuable in assessing brain and spinal cord abnormalities, as well as musculoskeletal conditions. In a recent investigation, the diagnostic precision of MRI for the identification of tarsal coalition and its concurrent pathologies was scrutinized. The findings underscore the remarkable efficacy of MRI, which displayed a noteworthy sensitivity of 95.8% and a specificity of 94.3%, coupled with exemplary inter-reader agreement. This study advocates for the regular adoption of MRI in the clinical assessment of patients presenting with foot pain and suspected tarsal coalition, notably emphasizing the safety advantage it holds over CT by obviating the need for radiation exposure (Marth et al., 2023). Another retrospective study assessed MRI's accuracy in determining depth of invasion (DOI) in tongue cancers, indicating a strong correlation between MRI and histologically detected DOI, with MRI demonstrating reliability for predicting DOI and moderate accuracy for superficial tongue cancers (Mair et al., 2021).

Both CT and MRI offer 3D imaging capabilities, allowing for enhanced visualization and facilitating treatment planning and surgical interventions. US is a versatile and efficient diagnostic tool that offers rapid assessment of a wide range of medical conditions. Its proven accuracy and cost-effectiveness have made it a widely embraced imaging technology. The utilization of US, as compared to alternative imaging methods, enhances cost-efficiency in patient diagnosis and management (Bierig and Jones, 2009). A comparison study investigated the accuracy of US and CT in diagnosing common causes of acute abdominal pain (Van Randen et al., 2011). In a sample of 1021 patients, CT demonstrated higher sensitivity in detecting appendicitis and diverticulitis compared to US, while both modalities showed similar sensitivity for cholecystitis. In another retrospective study comparing the diagnostic accuracy of abdominal US, CT and MRI in evaluating various intra-abdominal organ systems, MRI demonstrated the highest accuracy in diagnosing hepatic, adrenal, and pancreatic diseases, as well as free intraperitoneal fluid. US was found to provide the most accurate diagnoses for gallbladder disease, and either CT or MRI was suggested as the most appropriate initial imaging modality for detecting renal disease (Noone et al., 2004). EIT measures electrical impedance changes within tissues to create real-time functional images, enabling continuous monitoring of physiological processes. However, compared to the sophisticated imaging modalities, EIT has limitations in terms of resolution, depth penetration, and clinical validation. A recent study evaluated the diagnostic accuracy of EIT for breast cancer based on 12 studies and 5487 patients, revealing that EIT exhibits a sensitivity of 75.88% and specificity of 82.04% (Rezanejad Gatabi et al., 2022). They suggested that EIT may serve as a valuable complementary method alongside mammography, while its sensitivity could not be compared with the sensitivity of MRI.

However, it is important to consider certain factors when utilizing imaging modalities. The cost of equipment and maintenance, along with the need for specialized training and interpretation, may make these modalities less accessible in certain settings. The diagnosis cost of using these techniques can vary depending on several factors, including the specific procedure, geographical location, healthcare facility, and insurance coverage. In general, imaging modalities (i.e., CT and MRI) tend

to be more expensive compared to surface measurement techniques due to the advanced technology involved, the need for specialized equipment, and the interpretation of images by radiologists or specialists. Additionally, the use of contrast agents in certain imaging procedures can also contribute to increased costs (Yan et al., 2007). According to (Saini et al., 2000), the costs per technical relative value unit were \$28.74 for the US, \$20.95 for CT, and \$17.69 for MRI (in US dollars). The technical costs per examination for US, CT and MRI were \$50.28, \$112.32 and \$266.96, respectively. It is important to note that the cost of these techniques can vary widely depending on the specific clinical indication, the complexity of the procedure, and the healthcare setting. Some procedures may require multiple imaging modalities or repeated measurements over time, which can further increase costs. For example, in the case of suspected scaphoid fractures, the overall cost per patient of performing CT, MRI and US tests were approximately £202, £302 and £113, respectively (Jenkins et al., 2008).

The accessibility of diagnostic techniques to the general population is also influenced by healthcare system characteristics, geographic location, and socioeconomic factors. Surface measurement techniques normally exhibit higher levels of accessibility for the general population. These techniques are frequently employed across a range of healthcare settings, encompassing hospitals, clinics, and even personal home monitoring devices. Their relatively affordable nature, portability, and wide availability contribute to their broader accessibility, enabling a larger segment of the population to benefit from their diagnostic capabilities. According to the latest global report of PPG Biosensors Market Size and Share ("PPG Biosensors Market Size & Share [2023 Global Report]," 2023), smart wearables commonly utilize PPG for heart rate monitoring, which accounted for the largest share (40.1%) in 2022 and is expected to grow significantly during the forecast period. According to the analysis conducted by Data Bridge Market Research ("Wearable Electrocardiogram (ECG) Monitors Market Size & Research Report - 2029," 2022), the global market for wearable ECG monitors is projected to experience significant growth in the forecast period from 2022 to 2029. The anticipated compound annual growth rate for the market is approximately 23.9%. In 2021, the market was valued at USD 2.13 billion, and it is expected to reach USD 11.83 billion by 2029. A comparative study investigated the accuracy of wearable PPG and ECG heart rate monitors, showing a slight difference of ± 5 beats per minute between the two technologies when HR reached around 155–160 beats per minute, which indicated that wearable PPG technology can be considered accurate with some consideration of experimental design implications (Weiler et al., 2017).

In contrast, imaging modalities like CT and MRI may encounter limitations regarding availability. Factors such as cost, specialized equipment requirements, and the need for skilled healthcare personnel for operation and interpretation contribute to potential barriers to accessibility. These imaging modalities are typically found in larger medical centres or specialized facilities, with access contingent upon various factors, including referrals from healthcare practitioners, insurance coverage, and appointment waiting times. As one example, a recent WHO survey showed that the availability of mammography, an important screening tool for breast cancer, is one per 47,000 people in high-income countries but one per 5.7 million people in low-income countries. The availability of CT scanners is one per 170,000 people in high-income countries but one per 3.8 million in low-income countries ("Medical devices: an area of great promise," 2023).

Additionally, some imaging techniques have specific contraindications or limitations, such as MRI incompatibility with certain implanted devices (Miller et al., 2016) or the limited penetration depth of US (Ng and Swanevelder, 2011). It is crucial to weigh the advantages of detailed anatomical visualization provided by imaging modalities against their potential drawbacks, considering the specific clinical context and patient needs. Research and development efforts, propelling the advancement of diagnostic methodologies. By assessing each technique's capabilities and constraints, healthcare professionals can

optimize their usage, tailor their approach to specific clinical scenarios, and contribute to the ongoing evolution of diagnosis techniques, ultimately leading to improved patient care and outcomes. Further, Table 4 and Table 5 presents various applications as well as challenges of different non-invasive techniques.

6. Future direction

The advances in non-invasive diagnosis techniques have opened new avenues for future development, driven by the advantages and limitations observed in the mentioned modalities. This review identifies several key directions:

1. Integration of Multiple Modalities

The combination of complementary diagnostic techniques holds promise for more comprehensive and accurate assessments. Integrating the strengths of different modalities can provide a more holistic understanding of physiological processes, enabling a more precise diagnosis of complex conditions.

2. Miniaturization and Portability

There is a growing demand for miniaturized and portable diagnostic devices that can be used at the point of care and facilitate remote monitoring. Future developments should focus on reducing the size and complexity of diagnostic tools, ensuring portability, ease of use, and widespread accessibility across different healthcare settings.

3. Advanced Signal Processing and Analysis

Further advancements in signal processing techniques, including ML, pattern recognition, and AI, can significantly enhance the diagnostic capabilities of non-invasive techniques. These approaches enable automated interpretation, data-driven decision support, and the identification of subtle patterns or biomarkers that may go unnoticed by human analysis.

Table 4
Applications of various non-invasive diagnosis techniques.

Technique	Applications
PPG	Monitor blood oxygen levels, heart rate, and other vital signs. Used to measure changes in blood volume and identify abnormalities in heart or lung function.
EEG	Diagnose epilepsy, brain injury, sleep disorders, and monitor brain activity during surgeries or research studies. Used to study the electrical activity of the brain and identify abnormalities in brain function.
EMG	Assess muscle function, diagnose neuromuscular disorders, and monitor muscle activity during surgeries or research studies. Used to study the electrical activity of muscles and identify abnormalities in muscle function.
ECG	Diagnose heart rhythm disorders, heart attacks, and monitor heart function during surgeries or research studies. Used to study the electrical activity of the heart and identify abnormalities in heart function.
CT	Diagnose injuries, tumours, infections, and abnormalities in various parts of the body, including the brain, lungs, abdomen, and bones. Used to create detailed images of internal organs and tissues.
MRI	Diagnose injuries, tumours, infections, and abnormalities in various parts of the body, including the brain, spine, and joints. Used to create detailed images of internal organs and tissues without using ionizing radiation.
US	Diagnose pregnancy, heart disease, and other medical conditions that affect internal organs and tissues. Used to create images of internal organs and tissues using high-frequency sound waves.
EIT	Monitor lung function, blood flow, and brain activity. Used to create images of the distribution of electrical conductivity in the body and identify abnormalities in tissue function.

Table 5
Challenges of various non-invasive diagnosis techniques.

Technique	Potential Problems/Misinterpretations
PPG	<ul style="list-style-type: none"> • Motion Artifacts: Susceptible to motion interference. • Limited Depth: Mainly measures surface blood flow. • Sensor Placement: Requires precise placement for accuracy.
EEG	<ul style="list-style-type: none"> • Noise and Artifacts: Prone to various types of noise. • Limited Spatial Resolution: Offers weaker spatial precision. • Scalp Conductance: Conductive scalp may affect readings. • Cost and Accessibility: Accessible but equipment and expertise can be costly.
EMG	<ul style="list-style-type: none"> • Crosstalk: Signals from adjacent muscles can overlap. • Signal Variability: Amplitude can fluctuate. • Cost and Accessibility: Accessible but may require specialized equipment.
ECG	<ul style="list-style-type: none"> • Noise and Interference: Vulnerable to electrical interference. • Signal Quality: High-quality data can be challenging to obtain.
CT	<ul style="list-style-type: none"> • Radiation Exposure: Involves ionizing radiation. • Limited Soft Tissue Contrast: May lack soft tissue detail. • Cost and Accessibility: Moderately expensive, accessibility varies.
MRI	<ul style="list-style-type: none"> • Cost and Accessibility: Expensive and not universally available. • Claustrophobia: Some patients may experience discomfort. • Metallic Implants: Can disrupt imaging.
US	<ul style="list-style-type: none"> • Operator-Dependent: Quality varies with operator skill. • Limited Penetration: Challenges in imaging deep structures.
EIT	<ul style="list-style-type: none"> • Spatial Resolution: Limited spatial clarity. • Noise Sensitivity: Susceptible to environmental noise. • Calibration: Requires proper calibration for reliability.

4. Improved Imaging Resolution and Speed

The ongoing refinement of imaging modalities should prioritize improvements in resolution, speed, and image quality, especially for EIT systems. Higher-resolution imaging allows for better visualization of anatomical structures, while faster imaging techniques reduce scan times and improve patient comfort and compliance.

5. Personalized Medicine Approach

The future of non-invasive diagnosis lies in embracing a personalized medicine approach. Incorporating patient-specific factors, such as age, sex, genetics, lifestyle, and environmental influences, into diagnostic assessments can lead to more tailored and targeted interventions, optimizing treatment outcomes and patient care.

6. Cost-effectiveness and Affordability

As non-invasive diagnostic technologies continue to evolve, it is crucial to address cost-effectiveness and affordability concerns. Innovations that reduce manufacturing costs, enhance efficiency, and streamline workflows can ensure broader accessibility and equitable distribution of diagnostic tools across diverse healthcare settings.

7. Long-term Monitoring and Data Integration

Developing non-invasive diagnostic tools capable of long-term monitoring and seamless integration with other data sources, such as wearable and electronic health records, holds significant potential. This approach enables continuous monitoring of patient health, facilitates early detection of abnormalities or disease progression, and supports data-driven decision-making for personalized treatment plans.

Additionally, researchers and manufactures are expected develop the future generations by considering the specific requirements from professionals. Fig. 11 illustrates several necessary perspectives from doctors. By pursuing these directions, future non-invasive diagnosis techniques can advance the field of medicine, enabling earlier and more accurate diagnoses, optimizing patient outcomes, and transforming healthcare delivery.

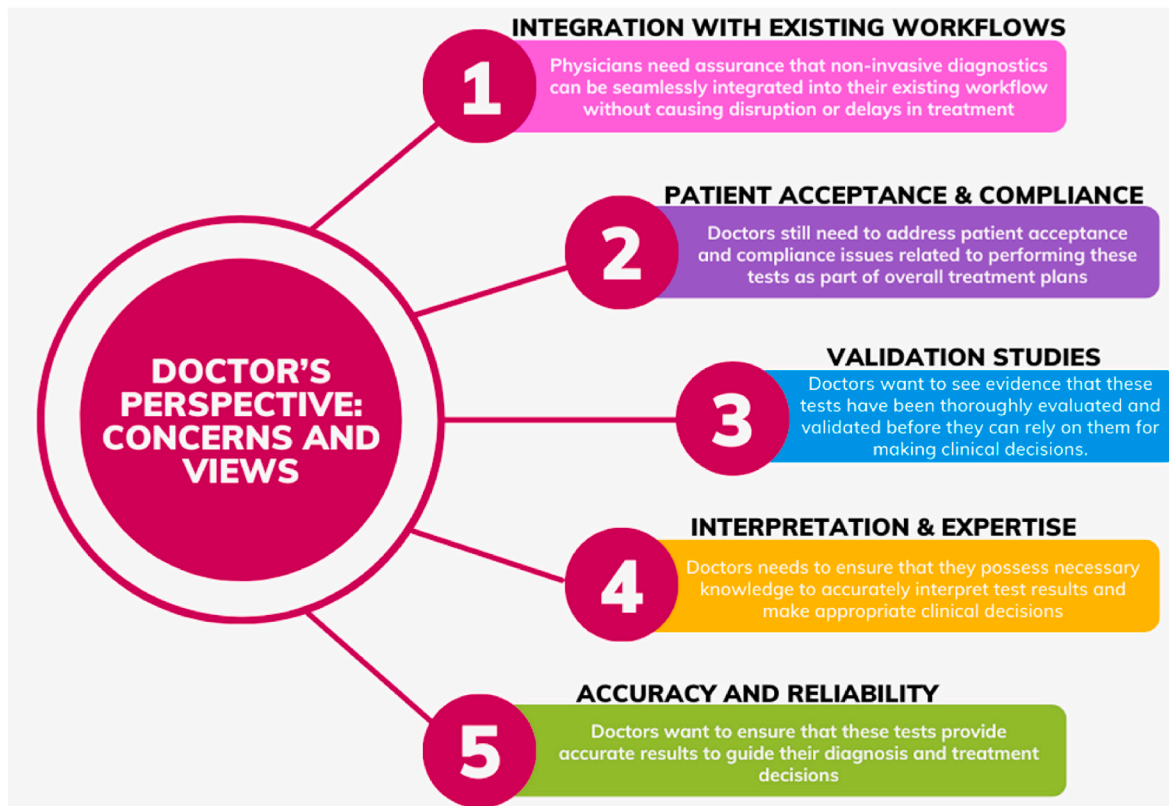


Fig. 11. Requirements of future non-invasive diagnoses from a doctor's perspective.

7. Conclusion

In the face of the growing global burden of diseases, the demand for non-invasive, painless, cost-effective, and easily accessible diagnostic tools has witnessed a significant upsurge. This review article aims to provide a thorough understanding of non-invasive surface measurement and imaging modalities. While there have been substantial advancements in non-invasive diagnostic techniques, the pressing challenge lies in transforming these methods into portable, reliable tools. This review delves into the historical foundations, fundamental principles, and contemporary developments in various non-invasive techniques, with particular emphasis on the promising applications of EEG, ECG, and EMG in monitoring brain, cardiac, and muscular activities. Furthermore, it explores the capabilities of imaging modalities such as CT, MRI, and US in providing intricate anatomical insights, enabling precise anomaly detection and comprehensive structural assessments. Notably, PPG emerges as a widely adopted technique in wearable devices, while EIT demonstrates potential as a cost-effective imaging method with a burgeoning interest in ongoing advancements. Additionally, this review outlines a strategic roadmap for future progress, highlighting the importance of integrating diverse diagnostic methods to conduct thorough assessments and enhance diagnostic precision. It also underscores the need for a keen focus on miniaturization and portability to meet the escalating demand for point-of-care and remote monitoring solutions. To further enhance accuracy, the incorporation of advanced signal processing techniques, including AI and ML, is recommended, as they play a pivotal role in heightening diagnostic capabilities. Moreover, we believe the improvement in imaging resolution and speed, with a particular emphasis on enhancing EIT systems, which are crucial for achieving better anatomical visualization and heightened patient comfort. The concept of adopting a personalized medicine approach, which takes into account individual attributes, takes centre stage in the quest to optimize treatment outcomes. The article accentuates the significance of cost-effectiveness and affordability, advocating for innovative solutions

that streamline manufacturing costs, enhance workflow efficiency, and ensure equitable access to these diagnostic tools across diverse healthcare settings. We are confident that the future of non-invasive diagnostic techniques holds the promise to enhance medical practice, facilitating swifter and more precise diagnoses, elevating patient care, and transforming the landscape of healthcare delivery at large.

Author's contribution

Yang Yu: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Bhavya Jain:** Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Gautam Anand:** Conceptualization, Methodology, Writing - Review & Editing, Supervision. **Mahdi Heidarian:** Writing - Review & Editing. **Andrew Lowe:** Resources, Supervision, Project administration, Funding acquisition. **Anubha Kalra:** Writing - Review & Editing, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Institute of Biomedical Technologies (IBTec), Auckland University of Technology, New Zealand.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yang Yu reports financial support was provided by Institute of Biomedical Technologies (IBTec), Auckland University of Technology.

Data availability

No data was used for the research described in the article.

Acknowledgement

This study was conducted at the Institute of Biomedical Technologies (IBtec), Auckland University of Technology and Department of Electronics and Communication Engineering, Galgotias College of Engineering and Technology.

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