Graduate thesis

NTNU
Norwegian University of Science and Technology

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Identifying needs in the field of electrocardiogram analysis to increase the accuracy of ECG interpretation

Qualitative Research

Graduate thesis in Global Health
Supervisor: Vikram Singh Parmar
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ABSTRACT

Background

Electrocardiography records the heart's electrical signals through electrodes placed on the chest, producing a graph of voltage versus time. The ECG is not only used for diagnostic purposes, but also for heart monitoring, biometric recognition, and even has a potential to decode basic emotional state of a human. The accurate ECG interpretation enables the detection of heart abnormalities and the timely management of life-threatening conditions. Since cardiovascular diseases are a leading cause of death worldwide, making accurate interpretation is crucial for early diagnosis and appropriate treatment. However, the accuracy of ECG interpretation varies among medical professionals, including cardiologists and non-cardiologists, leading to the need for improved education and training. The challenges in ECG interpretation are discussed in this research, including limitations of computerized interpretation, variations in teaching methods, deficiencies in ECG training, and the need to distinguish normal ECG features from abnormal. Factors such as athleticism, sex, and ethnicity also influence ECG interpretation and must be considered for accurate diagnosis and personalized healthcare.

Methodology

To identify the needs for improvement in ECG education and technology, face-to-face interviews were conducted with cardiologists, health providers, scientists and a single semi-structured interview with medical students. The data collected has been analyzed and three grounded theories have been constructed, opening for discussion on possible changes in educational methods and automatized interpretation algorithms in order to evaluate accuracy in ECG interpretation and diagnosis.

Results

The findings from this research identified three needs in the field of electrocardiogram and discuss possible solutions for improvement in this field. The first identified need is based on feedback from medical students and physicians and speaks for an interactive tool for ECG interpretation self-education and practice. The existing online platforms and ECG apps have been explored. It has been found that none of the existing solutions fully satisfied the identified needs. Adjustments and improvements for the interactive tool have been proposed in the discussion.

The second identified need speaks for the creation of a Norwegian ECG database that would provide real-case examples and contribute to machine learning. This idea was discussed with a cardiologist and a professor who expressed their opinions on the process of such a data collection.

The third identified need speaks for implementation of a "machine-human collaboration" course in medical education programs to enhance understanding and trust in machine interpretation. The author believes that educating medical students about the capabilities and limitations of technology would lead to more effective collaboration.

Conclusions

Even with the fast-evolving innovations in the field of heart diagnostics there are still opportunities in ECG interpretation practice to improve the accuracy of ECG analysis and enhance the efficiency of use of technology in healthcare settings.

Keywords

electrocardiogram, heart diagnostics, ECG interpretation

TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

CVS - cardiovascular system

HR - heart rate

CO - cardiac output

ECG - electrocardiogram

MRI - magnetic resonance imaging

CCTA - coronary computed tomography angiogram

CIE - computerized interpretation of the electrocardiogram

HRV - heart rate variability

1. INTRODUCTION

1.1 PHENOMENA OF THE STUDY AND THE REASONING BEHIND CHOICE OF THE TOPIC

1.1.1 Cardiovascular health and cardiovascular monitoring

The human heart is our inner "engine room" and our most vital life-supporting organ (1). The heart is responsible for pumping blood and supplying the body with oxygen and nutrients. It also removes metabolic waste such as carbon dioxide from all tissues in the body.

Unfortunately, the cardiovascular system (CVS), and especially the heart, is commonly prone to disease. According to the data provided by the World Health Organization (WHO), cardiovascular diseases (CVDs) accounted for 32% of death causes worldwide in 2019 (2). This makes CVD the leading cause of death globally. Most of the CVDs are reversible or treatable with early diagnosis (2) A significant number of the cases with CVDs are related to behavioral and lifestyle factors such as inactivity, elevated level of stress, imbalanced diet, exposure to toxic environments and misuse of alcohol, tobacco and certain drugs (3)(4). Interventions will thus often include motivational aspects in order to aspire people to adopt and sustain healthy behaviors (5). Health policies that create conducive environments in order to make healthy choices available and affordable might benefit cardiac health and prevent CVD. Even so, high quality and well-timed heart diagnostics may allow the initiation of management of life-threatening heart diseases through medical supplies and through suitable adjustments of lifestyle and diet. Neglected heart problems, on the other hand, could lead to further complications and rapid lethal outcomes (5).

Heart monitoring with electrocardiography (ECG) serves many diagnostic and monitoring purposes in the cardiac field and has also shown potential in other fields (6). In order to fully utilize the potential of this method of assessment, accurate interpretations by the operating clinicians are crucial. Improvement in the quality of ECG interpretation will complement the management and treatment of cardiovascular diseases.

1.1.2 The heart and heart assessment

The heart consists of four chambers and four one-way valves. Together with a comprehensive set of arteries and veins, the heart represents our cardiovascular system (CVS) that regulates the normal flow of blood within the body (1). In order to respond rapidly to the changing requirements of the body's tissues, the heart rate (HR) and contractility are regulated by the nervous system, hormones, and a number of other factors (1). In other words, according to our physical state, emotional response, and type of ongoing activity, our heart pumps the "fuel" through our cardiovascular system with a required rhythm and pace. Therefore, heart rate and cardiac output (CO) vary in response to the needs of the body's cells for oxygen and nutrients under varying

conditions. With the listed functionalities, heart work not only affects but also reflects the function of the other life-supporting systems in our body. Heart diagnostics allow detection of pathological deviations in heart activity and heart monitoring enables it to reflect on the body's response to stress, recovery, and even non heart related pathologies (1).

An accurate assessment of the heart can provide valuable information about the function of the cardiovascular system and requires an understanding of its various functions (mechanical, electrical, chemical) (7). A cardiovascular assessment includes several initial subjective and objective assessments followed by deep assessments using diagnostic equipment. The initial subjective and objective assessments may uncover signs of potential dysfunction (7). It consists of a clinical interview and physical examination to uncover symptoms that may indicate heart related disorder. The assessment may include inspection through palpation, auscultation of heart sounds and cardiac output (1). The heart diagnostics may include blood tests, electrocardiograms (ECG), exercise stress tests, echocardiograms (ultrasound), coronary angiograms, magnetic resonance imaging (MRI) and coronary computed tomography angiograms (CCTA) (7).

1.1.3 Electrocardiography across different fields

The high global prevalence of cardiovascular diseases (and frequent subsequent deaths) makes ECG a widely employed diagnostic tool. Electrocardiography (ECG) is one of the simplest and fastest test methods used to evaluate the heart. It is also cost-effective and non-invasive. With electrodes attached to the chest of the human body, an electrocardiograph produces an electrocardiogram (ECG) which is a recording of the heart's electrical activity through repeated cardiac cycles. The electrocardiogram presents voltage versus time of the electrical activity of the heart, shown as a graph (8). Nowadays, electrocardiograms are not only a diagnostic tool that allows the assessment of cardiac structure and function in medical settings. It is widely used for heart monitoring in home patient care and acute care, in cardiac pre-participation evaluation for athletes, biometric recognition and emotion recognition. Some developed countries incorporate ECG screening into public health programs for specific populations, such as athletes or individuals at higher risk of cardiac events. This approach aims to detect potential cardiovascular issues early on. At the same time, ECG plays a critical role in emergency medicine all around the world, aiding in the rapid diagnosis of conditions like acute myocardial infarction (heart attack) (9). Standardized protocols for ECG interpretation in emergency settings are crucial for prompt decision-making.

A detailed analysis and accurate interpretation of the electrocardiogram is important since heart work not only affects but also reflects the function of the life-supporting systems in our body. Heart monitoring enables it to reflect on the body's response to stress, recovery, and even non heart related pathologies.

Since the late nineteen forties, when ECG was implemented in diagnostic medicine, it has been the most essential tool used for heart work assessment and has undergone gradual modifications and improvements (10). The modern ECG device is relatively compact, the material used in the electrodes is more than accessible and the number of electrodes has been reduced from 12 to 2. The data recorded can be represented in a digital format with high accuracy and the whole constructor can be wireless. Moreover, devices based on electrographs are widely used across

different fields: for diagnostic purposes in medicine, scientific research, health and performance measures in fitness and professional sport.

Medical professionals, including physicians, nurses, and technicians, undergo standardized training in ECG interpretation. When it comes to ECG interpretation, the professionals that need to analyze heart activity through ECG features can be divided into two main groups: cardiologists and non-cardiologists. Among non-cardiologists there are doctors of all kinds, nurses, physiologists, technicians and paramedics, professionals of acute care, scientists, medical assistance of homecare, sport medicine professionals, sometimes coaches and even athletes. While ECG recordings are collected through computerized electrocardiographs and tracings are standardized through universally adopted recording electrode positions, there are no established standard methods for teaching ECG interpretation or reporting ECG findings that are evidence based (11). Late records prove that faculty training and teaching formats for ECG interpretation vary between countries and institutions (12). Multiple studies question the reasons for low accuracy in ECG interpretation and encourage taking steps toward finding an optimal way for education in that area (11–13). The reviews that investigate the accuracy of ECG interpretation demonstrate significant variation in correct identification of abnormalities on ECGs (13). Among cardiologists, the percentage of correct identification is between 53% and 96%. Among non-cardiologists, the same percentage is between 36% and 95% (11,13,13,14). Furthermore, there is not always an agreement between the interpretations of the same data.

A recent review showed that the median accuracy on ECG interpretation between physicians of all training levels was 54% (15). The accuracy varied widely across studies, and the authors discussed differences in training, differences in skill and differences in assessment design as possible explanations for the large variations. They conclude that physicians at all training levels had deficiencies in ECG interpretation, even after educational interventions.

Generally, competence in pathology interpretation has shown to be lower than competence in recognition of the basic wave forms and segments (16). One study from 2015 assessed skills in ECG interpretation among medical students and concluded that medical students in their clinical years have a good level of competency in interpreting the primary ECG parameters. However, their ability to recognize ECG signs of life-threatening disorders and common heart abnormalities is insufficient (16).

1.1.4 Standardization

ECGs are integrated into the healthcare systems of many countries, facilitating quick diagnosis and timely intervention. The standardization of ECG interpretation allows for seamless communication among healthcare professionals globally.

Different organizations and societies around the world have developed guidelines and criteria to standardize ECG interpretation. There are two particular standards that help to ensure consistency in ECG analyses globally. First is the standard from the American Heart Association (AHA) which

provides widely accepted standards for ECG interpretation. Their guidelines cover a range of topics, including normal ECG patterns, arrhythmias, and ischemic changes. The AHA recommendations are widely used in the United States and influence ECG interpretation practices around the world (17). Second is the standard from the European Society of Cardiology (ESC). The ESC offers guidelines on the diagnosis and management of cardiovascular diseases, including recommendations for ECG interpretation. The ESC guidelines cover a broad spectrum of cardiac conditions and are regularly updated to reflect the latest research. These guidelines are influential in Europe and are also adopted by healthcare professionals internationally (18).

It is important to note that while these organizations contribute significantly to ECG interpretation standards, some regulatory bodies in individual countries, local medical societies, also provide guidelines tailored to regional needs and healthcare systems. Additionally, ongoing research and advancements in technology continually shape and refine ECG interpretation standards globally. International Society for Computerized Electrocardiology (ISCE) focuses on advancing the application of computers in electrocardiology and contributes to standardization through research and collaboration in computerized ECG interpretation (19). The World Health Organization (WHO) emphasizes the importance of ECG as a diagnostic tool for cardiovascular diseases. While the WHO does not provide specific ECG interpretation standards, its global influence supports the integration of ECG into public health initiatives and healthcare systems worldwide (20). The Asia-Pacific Heart Rhythm Society (APHRS) representing the Asia-Pacific region, contributes to ECG interpretation standards specific to the needs and characteristics of populations in this geographic area. They collaborate with other international societies to ensure alignment with global best practices (21). The International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) primarily focused on laboratory medicine but plays a role in standardizing cardiac biomarkers, which are often used in conjunction with ECG findings for a comprehensive cardiovascular assessment (22). The National Institute for Health and Care Excellence (NICE - UK) is based in the United Kingdom and provides guidelines for the National Health Service (NHS) on various healthcare topics, including cardiovascular diseases. Their recommendations influence ECG interpretation practices in the UK and can have an impact on international practices.

1.1.5 The importance of accurate ECG interpretation

Improvements in the quality of ECG interpretation may complement the management and treatment of cardiovascular diseases. Heart attack and Cardiac Arrest are the main causes of mortality (20). Prevention in both cases requires early diagnostics and attentive ECG interpretation. Many of the underlying causes can be identified by ECG abnormalities. However, distinguishing cardiovascular pathology can be challenging due to noise caused by power-interference or chest movement, and signal variability created by physiological adaptive changes to a lifestyle or underlying pathologies. Automatic ECG analysis might also contribute to inaccurate ECG interpretation; even with fast evolving technology the algorithm interpretation still varies in accuracy based on the underlying electrocardiographic rhythm, and often results as a delay in finding the correct diagnosis that is necessary to provide appropriate treatment (23).

1.2 THEORETICAL BACKGROUND

In this chapter I will introduce the context for the research and present a summary of key studies on challenges in ECG interpretation. The literature review for the chapter was based on publications found in a database of biomedical literature, PubMed, and from searches for scientific publications on Google Scholar. Specific searches were done in the medical journals BMJ and JAMA.

1.2.1 Challenges in ECG interpretation

Challenges in ECG interpretation do currently exist despite efforts to standardize. Common issues are variations in equipment quality, differences in interpretation skills, and disparities in access to healthcare. Literature reviews from the last decade show that many studies have been dedicated to the extensive use of ECG and its automatization (14,24,25). Big interest lies in self-monitoring, ECG e-learning and ECG machine learning. However, a number of studies from the last decade that concern late innovations and methodologies in the field of ECG highlight the problem of imperfection in ECG interpretation (14,26–28). Even if these studies point to imperfection of ECG interpretation, no literature was found on which features of the electrocardiogram that are particularly challenging to interpret, and which pathologies that are particularly hard to recognize. At the same time, articles that are dedicated to the topic mention the following problems: limitations in computerized ECG analysis and reliance on it from medical professionals (13,24,29,30), time limitations for teaching material representation, and variety in constructing the curriculum from an educational perspective (11–13,27), lack of hours for practice and insecurity in skills gained from student perspective (11,14,16,26), challenges related to differences in ECG due to sex, ethnicity and activity level of a patient (31,31,32).

1.2.2 Challenges in learning

According to the literature's description, electrocardiography and heart disease is a broad topic that during medical training must be covered in a most compact way. The curriculum may vary between institutions. Students and young professionals might not reach sufficient levels of confidence and competence in analyzing electrocardiograms and therefore might need to gain skills on automatic ECG interpretation later in their practice (13). Sufficient levels of competence in this sense include a basic understanding of electrical heart activity and principles of electrocardiogram as well as an ability to recognize common pathological patterns. A literature review on ‘learning, teaching and assessment’ from 2019 found that traditional teaching methods consist of lecture-based classes and group practices (13). For medical studies, practices of ECG interpretation focus mostly on memorizing separate parts of electrical signals of the heart and morphological patterns of ECG rhythms, such as the shape of the ECG complexes and associating them with disease. It is mentioned that the major limitation of pattern memorization is that it does not contribute to the knowledge acquisition of the concepts for electrical forces responsible for the shape of the waves and complexes (13). It provides little correlation between the ECG waveforms and the actual three-dimensional nature of the heart. Practical hours and workshops in ECG interpretation should be an integral part of skill development. Different teaching models suggest that a good practice course in EEG interpretation must consist of 100 to 1000, and even up to 34400 hours of ECG record interpretation in a year to gain the skill. Still there is not a direct correlation found between the number of years spent in practice and accuracy in interpretation (13,33). It is hard to argue which

of the aspects of ECG learning that have more or less value. An overview of competency in ECG interpretation among medical students and health professionals, shows mixed results that are not clearly correlated to the integrated learning method. A study from Poland showed that competency among medical students in ECG interpretation was higher among those who reported self-learning (13). Additionally, most students reported that the amount of ECG classes during medical education was too low. This may indicate that qualitative and quantitative deficiencies exist in the teaching of ECG interpretation at Polish medical schools. Studies on ECG interpretation skills of South African Emergency Medicine residents also report that self-learning was the most frequently used method to learn ECG interpretation. Junior and senior groups of students felt that the current level of ECG training was not adequate and that they had to mostly rely on self-study to improve their skills (26). Another European study among emergency department (ED) residents tested the effectiveness of an e-learning program in order to enhance ECG interpretation skills (14). They concluded that the e-learning program made for this study may be an effective tool for the ED residents. They do however point out the need for a larger European study to evaluate ECG interpretation skills among ED residents before the implementation of ECG e-learning strategies. Currently, there is a paucity of data on the best possible method of ECG interpretation teaching. Two earlier studies (from 2008) have stressed the importance of formal ECG training via lectures or seminars with small groups of students, and found that ECG competency can be improved among medical students by way of web-based ECG training (13,34). They found that ECG interpretation was best accomplished by the incorporation of a blended pedagogy, consisting of didactical and e-learning formats evaluated through summative assessment.

1.2.3 Challenges with computerized interpretation of electrocardiogram

The computerized interpretation of electrocardiogram (CIE) is used worldwide. Its implementation into health care began in the 1950's and algorithms for analytical software have been improving up to this day. Seventy years have passed, and each ECG record taken is followed by an automatic interpretation. This invention aims to contribute to medical care by reducing physician reading time and increasing the accuracy of interpretation (29,30). There have however been limitations in terms of accuracy of machine analysis, and despite ongoing improvement in ECG algorithms there is still a high risk of CIE misdiagnosis (29). Most of the interpretation mistakes occur due to recording errors. Good data quality is defined by readability and precision in recorded measurements of the electrocardiogram. The right settings and an accurate placement of electrodes play a major role in analysis and prediction of diagnosis. Both noise and artifacts can occur during recording and disturb the signal quality. Artifacts usually give a visible deviation on the record while noise can be within the frequency band of interest and can manifest similar morphologies as the ECG itself (35). The presence of those can confuse the findings, and while we still cannot avoid the presence of noise, muscle and breathing artifacts in the record, there are strategies to reduce it. Apart from noise disturbances, the computer makes its own errors, sometimes critical, in its incorrect detection of arrhythmias, pacemakers, and myocardial infarctions. Due to a chance of error, it is required that all computerized statements should be checked by physicians who have the advantage of knowing the clinical context that is unavailable to the computer. It is believed that the computer and physicians together, now provide the most accurate ECG interpretations

available (30). Even though these technologies promise to facilitate the work of cardiologists, interpretation mistakes have created some skepticism towards CIE from experienced specialists. Inaccuracy of machine analysis creates mistrust towards implemented technology (30). At the same time, a literature review found that physicians in their first years of practice and inexperienced specialists tend to rely on machine interpretation as a result of insecurity in their own interpretation skills (23). The literature claims that a byproduct of such reliance is reduced focus on ECG education across medical training programs (23). The current status of automated ECG interpretation is reviewed, with suggestions for improvement (23).

1.2.4 Challenges in distinguishing normal ECG feature from abnormal

According to studies from the last two decades, the interpretation of electrocardiograms requires a comprehensive understanding of various individual factors that can influence heart physiology, electrical changes and adaptation. Three crucial considerations in this regard are athleticism, sex, and ethnicity.

First, athletic individuals often exhibit ECG patterns that differ from sedentary individuals due to their increased cardiac adaptations (36). It is vital to recognize these differences in order to avoid misinterpretation or unnecessary interventions. Secondly, sex-related disparities can impact ECG interpretation, as men and women may display different ECG patterns and risk profiles for certain cardiac conditions (37). The consideration of sex-specific differences could benefit the accuracy of diagnosis and thus promote appropriate treatment. Lastly, ethnicity plays a role in ECG interpretation since certain cardiac conditions can be more or less prevalent or present, among different ethnic groups (31,38). In understanding these variations, equitable and personalized healthcare may be ensured, as certain ECG abnormalities may be more common in specific populations. One literature review highlighted a critical need for physician education in modern ECG interpretation that distinguishes normal physiological adaptations with consideration to athleticism, sex and ethnicity from distinctly abnormal findings suggestive of underlying pathology (37). Accounting for athleticism, sex, and ethnicity might thus be essential in the comprehensive analysis of ECGs, leading to more accurate diagnoses and tailored management strategies.

1.3 THE RESEARCH FOCUS

Summarizing the theoretical background, I identified needs in the field of electrocardiogram reflected from literature. The findings show an association between inaccuracy in ECG interpretation and low levels of competency in ECG analysis among young medical professionals. Reviews and studies on teaching methods and assessment of competence in ECG interpretation suggest changes in educational methods for ECG learning (13–16). At the same time, other findings refer to imperfection of algorithms in ECG machine analysis (25).

Identified needs from the theoretical background:

Identified need 1: There is a need for new tactics in teaching the basics of ECG for scientists and medical professionals. The representation of theoretical knowledge suggested to be focused on deeper understanding of the heart's electrical nature, and its correlation with potential pathologies.

Identified need 2: There is a lack of practical sessions of ECG interpretation for medical students and junior doctors. This leads to a low competence in recognizing health issues, reflected by consequential deviations on electrocardiogram.

Identified need 3: The most skill gained in ECG interpretation is by self-learning therefore, there is a potential for improving and developing tools for self-education and practice in the field of ECG.

Identified need 4: There is a need for new addition to machine algorithms for the interpretation of ECG in individuals, with an adjustment to genetic or acquired traits.

1.3.1 Aim of the study

The research aim of this thesis is to identify areas of needs for improvement in the field of ECG interpretation that could invest in elevating the accuracy of ECG interpretation. I want to approach the aim by collecting versatile opinions on which challenges that are most commonly met in the early practice with ECG interpretation and that need to be addressed in order to develop an analytical skill. During the research I will also investigate the relevance of challenges in ECG interpretation identified in the review of the theoretical background.

This research is based on a collection of interviews that will be analyzed in order to identify the first needs of improvement in the field of ECG interpretation. The needs are the base on which strategies for increasing accuracy in ECG interpretation can be built.

1.3.2 Thesis structure

The remaining parts of this thesis are structured as follows: The methodology section illustrates how the research was conducted by explaining the design of the study, the data collection process and analysis behind it, as well as introducing participants and representing processed data in a readable format; The findings section includes the conclusions drawn from collected data and theories built on it; In the discussion I highlight identified problems in the field and give an overview on possible steps towards improvements; The summary section I present the final conclusions.

2. METHODOLOGY

2.1 STUDY DESIGN

2.1.1 Qualitative research

In this study I identify the needs for improvement via analysis of a collection of interviews. I use a qualitative research method in order to collect and explore experiences from ECG interpretation. Via a collection of face-to-face interviews, I aim to discover challenging aspects of ECG analysis and interpretation.

The research is focused on finding gaps in knowledge, understanding or skills for the variety of professionals that are involved in ECG interpretation. Since low accuracy in interpretation is a global issue, it creates an interest for the study of whether there are common aspects of challenge for specialists of different levels and fields. The interviews were focused on reflection on the challenges presented in the literature review and open questions about challenges in ECG interpretation.

The study claims originality through extension of current ideas.

2.2 DATA COLLECTION

To answer the question about what the most common challenges in the beginning of practice with ECG interpretation are, this research approaches the aim by looking at it from different perspectives. Coming to the selection of interviewees, I chose to have a variety of specialists involved in ECG interpretation. Since nowadays the need in ECG analysis touches a variety of fields, from emergency medicine to professional sport, the interest of the study is to find common challenging aspects of ECG interpretation, putting a priority on the global needs for improvement. I wanted to hear how specialists of different backgrounds approach the interpretation process and where they find it difficult to work with.

Among the participants for this study there are physicians, cardiologists, medical students, research leaders and teachers; all directly involved in working with ECG.

The face-to-face interviews are the preferred method of data collection due the diversity of the background and occupation in relation to ECG of the participants.

2.2.1 Participants

During the research I reached seven participants and provided six interviews (*Table 1*). All the participants underwent a basic or higher medical education, underwent an ECG interpretation training or a course, were or are currently involved in ECG recording or analysis in their practice.

The participants differentiate in their background an occupation in relation to ECG. The interviews were conducted face-to-face in person or via zoom, in English and Russian languages; all transcripts are represented in English.

Table 1. List of provided interviews.

1	Face-to-face interview (physical)	Daily manager and associate professor in the facility of blood circulation and medical imaging. Involved in research projects that include ECG testing.
2	Face-to-face interview (physical)	Physician in practice. Assists research that involves ECG testing, controls exercise testing with ECG recording for patients with implanted loop recorder
3	Face-to-face interview via zoom	Cardiologist in practice, supervisor of PhD students in cardiology. Involved in ECG interpretation for diagnostics and research with ECG recording.
4	Face-to-face interview (physical)	Physician in practice. Involved in Initial interpretation of ECG records on order to sort patients between those who needs further diagnostics and who does not.
5	Face-to-face interview via zoom	Senior lecturer on ECG course. Researcher, faculty Biomedical Engineering. Participates in research with ECG testing. Mostly tests healthy volunteers and athletes.
6	Semi-structured interview with 2 participants (physical)	1. Doctor in practice at emergency room and medical student in a 6^{th} year of study. 2. Medical student in a 6^{th} year of her study. NTNU faculty of health

2.2.2 Interview guide

The interview guide (*APPENDICE A*) was assembled according to the aim of the research. The questions were adapted according to the interviewee while based on the set of themes chosen for the research. Bellow I represent the general questions that represent the themes of the interviews:

1. What specialists are occupied with ECG interpretation nowadays?
2. What can data from ECG analysis serve for?
3. What are the specifics of learning/working/teaching ECG?
4. What was the assessment of competence in ECG interpretation skills?
5. What are the easy and difficult parts of learning/working/teaching ECG interpretation?
6. How does the collective work affect the quality of ECG interpretation?
7. What role does software play in ECG analysis?
8. What are the possible improvements that could ease the learning/working/teaching experience?
9. What is the role of international knowledge exchange in increasing accuracy of ECG interpretation?

2.2.3 Conducting interview.

In total, six interviews were conducted in this study. There were three face-to-face interviews in person with specialists at their work location at the agreed date and time and two interviews conducted via zoom. One semi-structured interview with two students belonging to the same group of study.

2.2.4 Data management and ethical considerations

All the interviewees were familiarized with the topics of the research and findings from literature review of thisthesis. The participation form was created and given to each interviewee (*APPENICE B*). The audio recordings of the interviews were stored on the PC of the data collector. No personal or sensitive data were collected in the interviews. We made written transcripts of the interviews where the names and contact data of the participants had been deleted. The contact data of the participants were kept in a locked cabinet and not shared with anybody by the researcher until the end of the work with this research. The notification form for data processing was filled in and sent to sikt.no for approval.

2.3 ANALYSIS

2.3.1 Introducing Grounded Theory and identifying needs from theoretical background.

The Grounded Theory is a methodological approach to collection and analysis of qualitative data. The Grounded theory method consists of systematic, yet flexible guidelines (interview guide in our case) for collecting and analyzing qualitative data (opinion, experience, and ideas) to construct theories from the data itself (39).

The method of Grounded Theory was chosen for this study because it follows an inductive approach to analysis, allowing researchers to build concepts and theories based on observations and patterns within the data. It aims to capture the rich details of the interview contexts. This is especially valuable when the topic has not previously been studied in depth. The chosen method is also particularly useful for this study because the goal is to develop a theory that is grounded in the data itself. Rather than starting with preconceived hypotheses, we look for patterns and themes to emerge organically from the data.

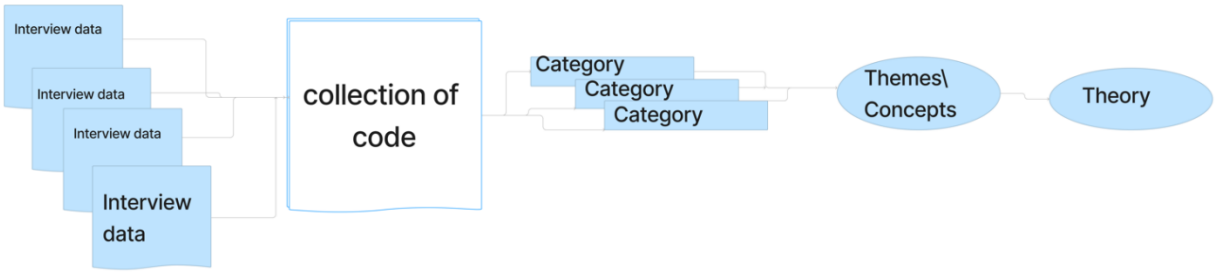


Figure 1. Analytical process with Grounded Theory method

With this method I intend to identify the needs in the field of electrocardiography and propose possible steps that can be taken towards elevating the accuracy in ECG interpretation. With the method of Grounded theory, we may refine the concepts and theories from the literature review as they progress through the study after analyzing the interviews. The source of the theories is human experience and reflection on learning/teaching electrocardiogram, working on interpretation and interaction with EEG supplementing technology.

In the initial steps of this study, I identified the needs of improvement in the field of ECG using the theoretical background. I incorporated and introduced these needs into the interview with the research participants. However, I remained receptive to the participants' opinions, suggestions, and emerging topics related to the topic on challenges and improvements in the field of electrocardiography. Employing the flexibility of the Grounded Theory Method, I adapted the questionnaire to the specific experiences of the participants, collecting qualitative data. This data served as the foundation for generating and developing key theoretical concepts through the analytical process across the collected data (*Figure 3, p 30*).

2.3.2 Data Analysis

With the Grounded theory method, I systematically analyzed and derived the concepts from interview data using following steps:

Step 1: The Data collection consisted of transcriptions of six audio recordings from conducted interviews.

Step 2: The analysis began with open coding, breaking down the data into discrete parts. Line-by-line codes were assigned to segments of the data that represent concepts or ideas.

Step 3: I organized the data by grouping related codes from interview transcripts together – axial coding. Based on relationships between codes we formed categories.

Step 4: With selective coding we made core categories that emerged from categories in the previous step. Core categories are central to understanding the phenomenon of this study and they gather opinions and experiences from the interview around the topics from the interview guide.

Step 5: After the coding process is finalized the goal is to develop comprehensive and well-defined needs in the field of ECG interpretation and answer the study question. I will present the analyzed content of the interviews in chapter 2.5, data is represented via themes that were identified through the coding process.

An example of the coding process is presented in *APPENICE C*. This example shows sorted data based on common topics of the conversation with participants, correlated issues that occurred through reasonings, thoughts and ideas. It allowed me to recollect the pieces of data from all the interviews through their relationships into one single coherent context for further analysis.

2.4 REPRESENTATION OF INTERVIEWEES

In conducting my research, I gathered experiences from seven individuals from two different nations who were involved in learning and/or teaching and/or working with electrocardiograms. All the participants had a medical background that included a course on ECG recording and interpretation. All the participants had experiences from recording and interpreting ECG. The region of education/practice and the level of experience and occupation in relation to ECG interpretation were not among including or excluding factors in this study.

Table 2. Table of interview participants

X1	X1 is a daily manager and associate professor at the faculty of blood circulation and medical imaging. His work involves research projects that include ECG testing on a population in the risk group for cardiovascular disease. X1 had an ECG recording and interpretation course organized by the institution where he conducts research. X1 assists ECG recordings, uses ECG machine interpretation of ECGs. Norwegian

X2	X2 is a physician and a postdoctoral fellow at the department of blood circulation and medical imaging. X2 assists cardio-tests on a treadmill and monitors changes on ECG during the cardio tests test. X2 has high medical education and has his practice in the department of cardiology. Norwegian
X3	X3 is a professor in cardiology and a leader in sport cardiology in Norway. She is in a 60% position as a cardiologist and 40% as a professor. She has experience from teaching ECG to medical students and has a few PhD students for supervision. Norwegian
X4	X4 is a physician at the beginning of practice. X4 has a high medical education. X4 practice ECG interpretation in an emergency room and gets ECGs from patients with chest pain for an initial interpretation. Norwegian
X5	Medical student of a final (6th) year of study. X5 also works as a junior doctor at the emergency room. Norwegian
X6	Medical student of a final (6th) year of study. Practice ECG interpretation at the institution of study. Norwegian
X7	X7 is a Senior lecturer at the faculty of Biomedical Engineering. X7 has basic medical education and has undergone courses on ECG for engineers. X7 has years of experience in conducting research related to ECG. X7 gives lectures on ECG for engineers and conducts research with ECG data collection from athletes and healthy volunteers. Russian

2.5 INTRODUCTION TO CONTENT ANALYSIS

After the transcription and coding process was done, I sorted data according to the themes that were discussed in the interviews (*Figure 2*). With respect to the specialization of each of the participants some topics of the conversations were looked upon with either a wider or a more narrow scope. This would depend on whether the interviewee had more experience from learning, teaching, or working with ECG interpretation. The content of the conversations are presented through following themes:

- Specifics of ECG education
    - Teaching perspective
    - Learning perspective
- Experience from working with ECG analysis
- Technology trends and challenges
- Thoughts on improvement in educational methods
- Necessities in technological supplementation
- ECG in global perspective. Reflection on collaborations
- Discussion on proposed solution

X1 Involved in research projects that include ECG testing.	X2 Assists cardio tests on a treadmill and monitors changes on ECG of a patient.	X3 Cardiologist involved in research	X4 Doctor in his first years of practice	X5; X6 Undergo the curriculum on ECG	X7 Participates in research with ECG testing.	Participants / Identified common topics
Specifics of educational program in ECG interpretation. Learning	Specifics of educational program in ECG interpretation. Learning	Specifics of educational program in ECG interpretation. Teaching	Specifics of educational program in ECG interpretation. Learning	Specifics of educational program in ECG interpretation and Reflection Learning	Specifics of educational program in ECG interpretation. Teaching	**Specifics of Education**
					Experience from self-education: tactics and challenges	
Experience from ECG use and analysis. Challenges and benefits	Reflection on work with ECG interpretation	Reflection on work with ECG interpretation	Reflection on work ECG interpretation	Reflection on ECG recording and interpretation	Experience from ECG use and analysis. Challenges and benefits	**Experience from working with ECG**
Reflection of Automatic Interpretation (AI)	Reflection of Automatic Interpretation (AI)	Reflection of Automatic Interpretation (AI)	Reflection on machine analysis	Reflection on ECG automatic interpretation (AI)		**Technology trends and challenges**
		Problem of self-interpretation of the results from heart monitors				
	Thoughts on how ti increase effectiveness of education		Thoughts on improvement	Discussion on improvements		**Thoughts on improvement in educational methods**
	Thought on improvement in machine analysis	Thoughts on improvement	Things that make a difference			**Necessities in technological supplementation**
			Thoughts on international collaborations		Discussion on international knowledge exchange	**ECG in global perspective**
		Athletes heart				**Discussion on proposed solution**
		Discussion on necessity database for machine learning				

Figure 2. Main Themes for analyses

2.6 THEMES

In this chapter I will present, themes generated by the coding process and structured into a readable content. Each theme gives an overview of the collection of experiences from interview

participants related to the same topic. Based on this content, the needs for improvement were identified and presented as findings in the following chapter.

2.6.1 ECG SPECIFICS OF EDUCATION

This theme represents the concept of teaching strategies when it comes to heart work and electrocardiogram. I discuss the necessity and details of ECG education from a teaching and learning perspective, options for self-education, access to learning materials, possibilities in international exchange of knowledge, challenges that medical students meet undergoing an ECG curriculum and reflection on the examination process. In the end of the chapter I present proposed thoughts on improvement of educational strategies.

2.6.1.1 Focus of teaching

In our interview concerning the specifics of educational systems on ECG across the world, a senior lecturer from the faculty of Biotechnical engineering X7 proposed that for medical students the arrangement of education relates to the structure of the healthcare system. It seems to X7 that cardiology is a separate direction in medicine with its own study program for education in each country. At the same time, educational programs for biotechnical engineers often depend on specialists who are available for teaching.

'*Unfortunately, it is difficult to find a specialist for a position in a very specific direction. At our faculty I am the one who does scientific work in the field of heart work, so I have an ability to teach it to our students.'*

He also commented that it would be beneficial for universities and students internationally if there was a standard in education of the basic principles. However, educational programs often adapt to the specialists who are available, not the other way around, and this may be a problem.

When I asked X7 about specifics of ECG curriculum for engineers, he pointed out that there should be a universal fundamental knowledge for both medical and biotechnical specialists on how the ECG is being formed and how a change on ECG reflects a specific pathology. However, nowadays a deep understanding of pathology and additional knowledge in ECG interpretation for engineers comes from self-learning if they choose ECG as a tool for their scientific work.

When a professor in cardiology (X3) responded to the same question in relation to medical students, he/she said that basic knowledge in ECG is compulsory across many fields:

'*It is basic for all doctors and nurses, and everyone has to have a basic knowledge. It is like the blood pressure, you must know your ECG, as compulsory for every specialty.*'

According to X7, however, the understanding of the work of the heart is engineering rather than a medical task. He finds that such an understanding includes an insight into the action potential of cardiomyocytes which is directly associated with formation of electrocardiogram (potassium-sodium pump and ion exchange between the cell and extracellular substance, it affects the action potential, the sum of the action potentials of all cardiomyocytes forms an ECG). He thinks that the

understanding of ECG formation gives a clue on why particular changes in ECG are related to a pathology. It allows you to '*untwist this chain back to the cause*.' He believes that is what they focus on when teaching engineers.

I asked X7 about how he compiles his ECG course. He explained that he uses both Russian and foreign literature to compile his ECG course. Some of them show pathologies through differences in ECG patterns while others point on changes in the chemical process. When updating his lectures, X7 has to go through a collection of sources and gather information piece by piece. He has noticed that the work of Ion exchange has been interpreted differently in different books. He anticipates that this could be due to a wide range of release time (20-30 years difference). He presumes that something has changed with time in the understanding of the process and therefore the books were edited. Another explanation might be that the authors simply see these processes differently.

X7 explains that the curriculum for engineers in biotechnology consists of two parts: a medical and a technical part. The medical part includes a two-year program with physiology, anatomy, pathological physiology and pathological anatomy. Students spend 4 hours per week attending lectures on this subject. X7 does not remember ECG having been introduced in those lectures. He says that ECG is being introduced in his lectures of biomechanics where he dedicates one or two lectures on biomechanics of the heart in his course. He starts with the Sodium Potassium Pump which explains polarization and depolarization of a membrane, the action potential of the cell, then the conducting system and how it all together formed into a single cardiogram. There is also a lecture about electrical heart activity in a course of biophysics. If students choose to work with ECG as a part of their thesis, they will learn essential details of the heart activity as self-study. For those students to whom X7 gives help and directions he recommends books and articles on that matter that he collected himself.

X7 thinks that only a few engineers choose to work with ECG interpretation since there are many other more trendy directions for a working career. ECG, in terms of interest, attracts students as a tool, for example, to evaluate the body's reaction to a load. It is used as a tool to help to solve other challenges.

When discussing curriculum on ECG for medical students Dr. X3 reflected:

'I guess it's different for specialties. I guess it doesn't really matter how you learn as long as you end up with the same result and knowledge. And it is so easy to test with ECGs because there is a correct answer and there is a wrong answer.'

Dr. X3 mentioned that in her teaching practice she adapted her ECG course according to a specialty of her students. It depends on the part of the process of ECG recording and interpretation that the specialist takes part in:

'So I spend a lot of time with the nurses for them to place the electrodes in the correct position and they also have to rub it to get good signals since signal quality. A correct placement of electrodes is everything.'

2.6.1.2 Strategies for Learning

X3 says that in terms of learning ECG there are many internet courses to follow. She believes that ECG learning is simple to standardize and also to test the knowledge of the interpreter because there is only one way to interpret ECG; she points to standards made by the European society of cardiology. She believes that there are plenty of sources for those who want to learn electrocardiogram interpretation.

In contrast to her opinion, T brought up a problem of some online studies that are offered but not always serve an educational purpose. He thinks that from a business point of view, specialist oriented programs are not profitable. The goal is to get enough students to make a profit without considering the outcome of the education that is provided. He gives an example of online courses provided by commercial organizations:

*'It seems to me that now there is such a problem that education is considered as a business and it is important for them [*commercial organizations*] to establish the process. Especially in terms of additional courses. The question is which of them really want the student to understand something and become a professional?'*

He says that with the variety of people and their background it was difficult to estimate the effectiveness of the material presented, as it was not adjusted for any of the fields or levels of previous knowledge:

*'That is, people [*commercial organizations*] have adjusted the process of how to teach but it have not adjusted how to make people come out as professionals.'*

X7 gave me his personal view on how he sees the structure of ECG based courses: First, the basics, biophysics and biomechanics of the actual cardiac contraction, in order to understand the process from how impulse is born to where we begin to see some change when we put 2 electrodes. The second is everything related to ECG registration: leads, various methods of applying electrodes. And then morphological analysis itself: P-wave, R- peak , Q-wave; what they are responsible for. And then - pathologies, as structural changes on ECG.

'*X7: As a cardiologist* (compared to engineer), *in addition to the fact that you understand what is happening, you should understand what needs to be done.'*

My interviewee, Mr. X1 who is an associate professor in the Department of circulation and medical imaging at NTNU, has experience from attending a one-day educational course provided by the university with focus on ECG interpretation. He joined the course outside his main study program. The course was held by a cardiologist and provided by his university and targeted specialists with a completed degree. He had basic knowledge of heart activity from his master

program in Exercise physiology. The course enabled Mr. X1 to work with ECG testing and gain more knowledge and practical experience.

'It was pretty simple. It was maybe one whole day with theory. The cardiologist gave us some underlying theory of how to interpret that ECG and then we looked at some cases, and then we just started to do it in the lab afterwards. So it was just a one day course, so it was not too long but it gave us a little overview over there.'

2.6.1.3 Lack of practice in ECG interpretation for medical students

In my conversations with medical students (X5, X6) and doctors in practice (X2, X4) I asked about their reflections on educational programs. They all described the method of education as 'spiral learning'. Basic knowledge on heart work and electrocardiogram was introduced in the first years of the educational program and the knowledge of pathologies would gradually build on the next years. All interviewees said that the most part of the ECG course consisted of theoretical material.

X5 and X6 thought the time between their learning of heart pathology and then applying this knowledge to practice was very long. They also felt that the practical part of the education on ECG interpretation was rushed compared with the amount of theoretical knowledge that was given. X6 said that she would like to have additional time given for practicing ECG with a professor.

Mr. X2 reflected that ECG interpretation is considered a quite difficult subject and requires students to focus thoroughly on theoretical knowledge first and then go through considerable amounts of practice. He believes that the ability to imply theoretical knowledge into practice in cardiology makes learning more effective. Remembering his years in medical school he said:

' *I'd say that during school most focus was on the theoretical aspects and less on practicing it. And of course, as with a lot of things, if you're to become good at something you really need to do it a lot and practice it in actually doing it. So it's harder to learn ECGs without having a patient or clinical setting or something to relate to*.'

Summarizing, X2 thinks that the learning of ECG interpretation should start with theoretical knowledge; looking at the textbooks and the examples of different pathologies. He thinks the textbook knowledge is more accessible when you have some practical experience, e.g a patient who has a heart problem and access to an ECG related to it.

When talking about his experience from working in a class, X4 reflected that he always found the ECG interpretation classes to be hard. He did not think that ECG interpretation was intuitive for him and found it difficult to understand what he was looking at. He says that what he remembers from the school material on ECG now is the physiology behind it, and the patterns that represent pathology is something he needs to revise.

2.6.1.4 Self-learning. Struggle of finding sources and platform for practice

I happened to have my interview with X5 and X6 on the day they were preparing for their next lecture on ECG interpretation. It was supposed to be the last lecture for attendance in the course. They said that just before we met for our talk they teamed up to go through study material from previous lectures and practice interpretation together. X5 mentioned that there were no organized workshops from the faculty for ECG interpretation practice, and students often gather together to help each other out in analysis. It drew my attention and I asked them whether I could take a look at the practice material they were using. Both agreed.
It was printed PDF format ECGs, resolution was quite small and there were no interpretations attached. On my question on what was source of the material they said:

'X6: That's just something that we have found ourselves.
X5: We were just two now and we just, you know, printed a lot of ECG's and then went through them. But we don't have anything like that from the faculty that is in Norwegian, Norwegian standards. We don't have that.
X6: No, so now we practiced on…
X5: …I think it's maybe American…
X6: …yeah, American standards, so it's like a difference in recording speed, they use 25 mm per second and in Norway we use 50mm per second. So we practice on something that we don't use, kind of.'

Junior doctor X4 had a different strategy for self-learning in ECG interpretation. His choice was video records with examples and explanations of cardiac pathologies on the internet. He reflects that video material did not stick well to his memory and also mention the problem of difference in standards of ECG recording speed:

'… I've always wanted to be good at ECGs, so I have seen videos, then I remember it for maybe one week and then it is all gone. So I'm not sure how we could make that easier to remember and it's also tough to practice online when you are working at Norwegian hospitals you get different… it looks different just because of the 25mm per second vs 50mm per second.'

In terms of theoretical material X4, X5 and X6 reflected very positively on lectures that they had during the school years, however all wished for more practice time on ECG interpretation with an experienced cardiologist. With the limited time for the ECG course they did not have time to practice with the lecturer:

'…I think what I would learn from the most now is actually interpreting the ECG with somebody who knows what they're looking at. Because there's those small things that you usually don't see and I wouldn't be able to pick up. I would catch a huge myocardial infarction but I wouldn't catch some kind of arrhythmia that I've never seen before, yeah.'

2.6.1.5 Knowledge evaluation

As we discussed specifics of education I asked my interviewees X5, X6 and X4 how the internalized knowledge was evaluated. X5 and X6 answered that to test their knowledge on ECG interpretation students get one or two multiple choice questions as a part of the yearly exam. X6 thought that if the answer would have to be represented in a written form instead it would be a better test. X4 said that for examination of the knowledge on ECG there was an oral exam and multiple choice questionnaires. He remembers the oral examination as it went terribly for his whole class. He presumes the reason was the settings that they were in. There was too little time to go through step-by-step analysis of ECGs. He recalls how he started to stumble and missed things. X6 said that the study program gives an order to follow on ECG interpretation and it feels like you need time and practice to get used to the steps of analysis. X5 and X6 think that the study program expects students to dedicate their time on practicing in the areas they are interested in during practical weeks and on their own:

'I think they rely on us to interpret and learn through the practical weeks when we are learning to look at ECGs. They say to us all the time 'look at as many ECGs as you can, interpret and ask the doctor's around you to interpret it with you'. I mean, they never have time to do that.'

When I asked what part of knowledge from ECG course students feel the most confident about, X5 and X6 answered they think that most medical students understand the basics of the electrical heart activity, but recognition of pathology comes easier to the students who have been working in the cardiology department besides their studies.

I remembered a part of my conversation with professor X7 where he said that he thinks that knowing basics of physiology and electromechanics of the heart activity is essential for understanding the change in ECG. His opinion is that it will allow doctors to realize how to treat pathology medically, because if one understands the process of infraction, he has a realization on how to deal with it.

2.6.2 PROPOSED STRATEGIES TO INCREASE EFFECTIVENESS OF ECG EDUCATION

One of the focus points of my research was to find which steps in teaching methods could be taken in order to improve the effectiveness of education. Based on the challenges represented above my interviewees gave a few suggestions.

2.6.2.1 ECG database of a local standard

Medical student X6 said that they have been shown ECG examples on the lectures by the professor. With time framing, he had to rapidly go through the cases, she could not remember them and she never got those examples as a document with answers. She thinks it would be nice to have something similar to that.

In her turn, X5 said that she would like to have an online testing module that is free where she could look at ECGs that have been taken in Norway and interpreted in Norwegian standards with answers. Right now she pays to access platforms that she thinks should be available for free. She suggests making MCQs that one can go through for ECG interpretation training to see what he knows and where the challenges are:

'In an app I'm unsure if I can see the ECGs enough but still an app or a website actually. Do you know that website that we now use, there's what's his name … OK I mean at the MCQ database. I mean they are doing some research on how medical students learn, I think. And they have all the MCQs and you can go through tests and examples time and time again and then you kind of see what you know and don't know. Something like that would be perfect for ECG training. So, somebody needs to do it and nobody does, maybe they don't have time. And the way they put up the MCQ is good, it works. It would work for many different things.'

I highlighted the thought of having a Norwegian database where there is a collection of ECGs with interpretation and diagnosis represented as a quiz or questionnaire for practice to a junior doctor X4 and he gave me an example of a platform that represented a similar idea but for a different field of study. He points to the fact that they have good examples and a big library to look through. He says it is a helpful tool for both: when you are learning and when you are in your practice. He says that he does not know of a similar platform for Norwegian ECG:

'Yeah ,great! Like I know for radiology there is this amazing website called https://radiopaedia.org/ and just you can search anything and then you find example images you can scroll through so it's a huge library. Just that making it easier to recognise for both: when you are learning and when you are in practise. But as far as I know we don't really have something like that for Norwegian ECGs. And that's just because we have this old tradition of 50mm per sec.'

Being pretty interested in the topic of ECG records database existence in Norway, for student use or for machine learning, I wondered about it in my conversation with professor in cardiology X3. In her response she said that to her knowledge, there is no such a thing, However, she assured, one can apply for it. She pointed to Norwegian population database 'The Hunt', saying that they are able to run a project on collecting required medical data for research.

2.6.2.2 Interactive tool for ECG interpretation practice

When I asked fellow doctor X2 about what he would wish to have back in the school days to complement his ECG learning progress he mentioned a lack of opportunity in seeing real-life cases, where one can see patients with ECG and diagnosis correlated. He also gave me an idea of having an interactive tool for practicing ECG interpretation. He said that it would complement and contribute to the learning experience:

'Maybe two things. Maybe one thing would be nice to see more patients with a given problem and the ECG correlated to that given diagnosis or problem to that patient. It would be nice because this way of learning is very efficient, I think. And also, I would say, maybe it existed but I did not

have it, like an app to watch a lot of ECGs or quizzes or … it is also a nice way to repeat knowledge, I think. So, an interactive tool like that I guess would be nice.'

2.6.3 TECHNOLOGY TRENDS AND CHALLENGES

2.6.3.1 Remote monitoring vs testing in clinical settings

To start my questionnaire about participants' experience from interaction with the technologies for ECG diagnostics, I decided to inquire about how and what for ECG recording is conducted. Since among my interviewees there were specialists from not only the cardiological department I found it interesting to know whether remote monitoring, like heart monitors that are popular on the market, play a role in science and medicine.

First, I found out that research projects that X1 and his team were engaged with included cardio-stress tests on a population with a high risk for cardiac disease, one of them is run on a population with an artificial cardiac pacemaker (ACP) implanted in the heart. I wondered about whether heart measures for that kind of test can be executed through remote monitoring like heart monitors. X1 explained that for the safety of the tests and for the good measurements cardiac-stress tests are conducted in the clinic and under supervision of one or two cardiologists:

'No, we do all the testing here. There are no… I don't think they have remote devices on that project, but we have other projects that have. But that's only watches that are measuring R-R from the heart. But it's not good enough. So if we want to have good measurements, we need to take them in here.'

'...We have had a large project with people with… What's it called? It's some kind of heart starter and a pacemaker. And when we turn off that device during testing… (because the device gives a shock when the heart rate is too high) so, we don't want them to get shocked on the treadmill. So we turn off the device during their cardiac-stress test but then we have two cardiologists together with us, one that reads electrocardiograms all the time and the other one that is ready with the defibrillator.'

Very luckily for me, one of the cardiac-stress tests happened to be at the location of my interview with X2. He invited me to join him for a control of the test, which is run on a population with Inter fibrillation that has an implanted loop recorder, a type of heart-monitoring device that records heart rhythm continuously for up to three years. As we were watching an online ECG record of a patient walking on a treadmill, X2 told me that a loop recorder allows doctors to investigate the amount of atrial fibrillation in the heart at all times. Every night the loop recorder sends the recordings to a mobile phone which transmits it to a web portal where doctors can access it. However, for the tests and additional measurements the ECG is recorded in the clinic with a 12-lead ECG device. He explained this as there is more information when several leads are being used:

'Yeah, and often you can see, for example, when she stops exercising, it's easier to get more out of the other leads. Here there is a lot of noise. Then when she stops exercising you can get some more information from them.'

On my question on how useful modern heart monitors are in cardiology, X3 said that they use specific types made for patients not the ones for athletes. She said that heart monitors for sport are useful for tracing infection in the body as it will show a higher resting heart rate in the morning(compared to a personal norm). She also mentions that sometimes use of heart monitors by people who don't know how to interpret the data might be a nuisance for cardiologists. If people don't know what is normal they start to stress over the results they get:

'No, but that is a simple watch. Ours are for the patients not for the sport athletes. So they monitor their athletes according to a resting HR for example. The resting heart rate is a bit high in the morning. That might be that they are overtrained or they might have an infection in the body, yeah so, then I have to check what is what. But it is also very… It is a nuisance for us cardiologists. Because patients have watches but they don't know how to interpret them. And they come and say: 'Oh my heart rate varies so much during the day'. Yeah, that's why you are alive, this is normal. It's called heart rate variability, if you don't have any heart rate variability you would soon die. So it's a huge annoyance as well. Because people don't know it is normal. And they say: 'Oh my heart can increase to 190 there must be something wrong with me'. Well, that is perfectly normal.'

2.6.3.2 The problem of noise interference with ECG record

Next topic in my interview guide was dedicated to challenges in ECG interpretation. As I tasked the participants with a pretty broad question about where they feel confident and where they are challenged when it comes to ECG analysis, they all tend to lead the conversation towards a discussion of the quality and readability of ECG records. In turn I wondered about the technical and human aspect of the ECG recording process and analysis.

Cardiologist X3 explained that ECG machines come with analysis and noise reduction, but the equipment and software quality is different from machine to machine. There are some things that might disturb the signal even if the settings are right and this has to be considered. One of the important things is having the right placement of the electrodes and making sure that they are fresh and not dry:

'So first of all the most important thing is that it's going to be very good signals and you have to be sure that you are actually putting the electrodes on the right places.

You always have to check if you get an ECG that is not normal, you have to check that the electrodes have been placed right, at the right spot and retake it to be sure.'

Doctor X2 who is involved with ECG interpretation, he referred to this problem saying machine interpretation often gives false positive results, and he is presuming that it comes from the noise that is caused by muscle artifact, power and wiring:

'I don't think the algorithm which is in our system is good at all. If the algorithm says it's not a normal ECG it's a very high likelihood that it's a normal ECG. So it's quite a bit of false positives that's my view of it. What can alert false positives? I think it is based on benign findings, yeah, maybe noise.'

Experienced from cardiac stress-tests X2 points to one of the outcome measures for the study being the maximum heart rate. Testing is conducted in controlled settings as a safety measure. He says that when testing elderly people with ECG you find additional underlying pathologies that might also confuse the findings. At the same time there is a lot of noise from movement of the thorax and use of muscles in the upper body during the cardiac test. In these settings, good placements of the electrodes play a big role.

X4 feels that machine interpretations are mostly confusing and scary because they say '*something that is obviously not true*'. He says that machine interpretation is not something you add so much clinical value to or use in your decision making:

'I wonder why it is (machine interpretation) *not getting better or why it is not better yet. But maybe it's because of all that noise you get on an ECG. The bottom line could be if they are shaking or they are just grabbing a glass of water then you ruin the whole ECG because you had a huge band.'*

Referring to her experience from working in an ambulance X5 says that placing electrodes for ECG record in emergency situation is hard, especially when patient is in pain and it leads to a lot of noise in the data recorded:

'Interpreting that is very difficult. Unless it's like a standard infraction, ST elevation or something else that's super standard, it's difficult to interpret it. Because there will be too much noise on the ECG. I'm getting the patient who is in pain, who is afraid, who's sweaty … and I can't place the electrodes, that is like a huge thing that I struggle with, when patients are actually sick.'

2.6.3.3 ECG machine interpretation. The problem of trust

X3 says that cardiologists do not purely rely on machine interpretation while, as she thinks, non-cardiologists rely on it too much without looking at ECG itself. But at least, she believes, it gives them an idea of what might be going on.

Therefore, I followed up on medical students and non-cardiologists with a question about their reflection on ECG machine interpretation.

In her answer X5 recalled that the first time they did interpretation in groups she had been told to not rely on the numbers given from the machine. However, she finds machine analysis useful when she is working in an ambulance. She uses it when she does not have much time to monitor the ECG readings herself. After taking an ECG she sends the recording to a cardiologist for an interpretation in any case, but she uses machine interpretation to act on a situation while waiting for an answer from a cardiologist. She makes it a point to state that a warning of a pathological process in the heart from machine interpretation is helpful in terms of triggering an action in an emergency situation:

*'If there's an ECG that has been taken and it (*machine interpretation*) can tell me that this is probably a reentry tachycardia of some sort I would be grateful. I will still send it to a cardiologist to have it interpreted but I would rather it said that than not, yeah. Because I will not get that from*

the numbers, not at the level I'm right now. No. But if it says that this is probably some kind of arrhythmia I would send it to somebody and I think that's kind of the thing I would use it for right now.'

X5 added that with machine interpretation the biggest issue is the trust in represented results . She thinks there is a direct correlation between trusting machine analysis and using it.

Doctor X4 gave a similar reference, saying that when getting an ECG record he also gets a machine interpretation on top of the page. He claims that in all his training he was strictly taught that he can't trust it and that there are only a few things he pays attention to, such as numbers that represent pulse or that are related to the QRS complex:

'I mainly don't trust it because that's what I've been told by the other doctors. But as I said, if it was always correct and always true I guess I would use it.'

The problem of trust was also mentioned by X2 as we talk about his reflection on working with machine interpretation. He thinks that automatic ECG analysis is not based on Artificial Intelligence (AI), however he does believe that its' implementation would help medical specialists to avoid misdiagnosis and reduce false negatives when it comes to ECG interpretation. Right now he does not trust machine interpretation and only uses it as a backup when making a diagnosis:

'I have the way I use the automatic interpretation. I always try to look at it at first, make my own view of the ECG and then I use it like a backup: 'does it say something I haven't found?' And then if it says: 'oh listen that' and I will have a look at it and if I agree… . But I never trust automatic interpretation because they miss quite often.

Being aware of the misdiagnosis problem from machine analysis, I found it necessary to get a comment on it from a member of Biomedical Engineering. Mr. T has experience from working on software design and ECG for diagnostics in biomedicine, he gave me his vision on current ECG analysis supplementation. He has the opinion that an electrocardiogram analysis for him, as an engineer, is seen as numerical changes in intervals, amplitudes and ratios, rather than from the perspective of pattern recognition that reflects a pathology. As a result, automatic analysis is more often used to detect arrhythmias or definite pathological heart rhythms.

2.6.3.4 Discussion on how to improve usability of ECG machine interpretation

After discussing the topic of ECG software supplementation I wondered what could make it easier for the eye of a doctor to cooperate with technology.

In response, X4 told me about changes that came with the recent update of the journaling database system in his hospital. The example he made was an update for ECG software that he called 'an ECG on screen'. He says that now among the tools there is a "zoom in" and "zoom out" feature along with a ruler to make measures. He recognises that the more you zoom in the more noise you get, and he finds it confusing. Among the changes that make sense for him, there is one where there are several ways to 'stack the Leads'. So the leads can be sorted as a 'graph through the heart'. He feels like that small change made it much easier for him to read electrocardiograms.

While trying to come up with an idea of what could improve an interaction with machine analysis, X4 proposed that having an example of a similar pathology next to the one suggested by automatic interpretation could help him avoid confusion.

'*Maybe if there was some kind of display with their example of ECG and the pathology that they refer to, maybe that could come next to what you're looking at so you can compare.'*

Another answer I got was from doctor X4. He said that for him the most important thing is to get a warning from the machine about the findings that are highly irregular for the population tested.

I have to mention that i got the same comment from X1 during our conversation about the meanings of cardiac stress tests:

'... I think the most challenging stuff is all the other things that could be wrong with a heart that we don't know about. ... Because that's the thing that we are most worried about. It's an emergency situation during the tests.'

In her turn, X3 says that looking into the future she would like having an artificial intelligence for ECG interpretation, with analysis according to a 'sports heart'. She believes that it could help cardiologists in the future for the purpose of ECG screening for the top athletes in Norway, using syncope. She says it would take a lot of capacity from her and her colleagues.

Agreeing on the necessity in considering the athleticism of a patient during ECG interpretation, doctor X2 added that ethnicity plays a role in analysis as well. Professor X1 suggests that diversity in athleticism and ethnicity of a population might complicate the process of machine learning.

X5 also suggests that it is possible to take up signal quality and focus on AI machine learning assistance for ECG interpretation, as it will help non-cardiologist. She explains that there is enough data on what is normal, abnormal and borderline to do so. While there is also plenty space for new research on how to gain more information from an ECG record:

'There is a lot of information that is not used. So there are plenty of different ways of trying to prove the way we should analyze ECG. Of course we need to have some machine learning where there is a lot of research now. There would be much more intelligent ways to look at the ECGs but there's a lot of things we still don't know, in the transition phases during cardiac arrest for example.'

3. FINDINGS

To answer the aim of this study, I will give an overview of the needs in the field of electrocardiogram that were identified via interviews in this study. By addressing those needs we might contribute to the improvement of accuracy of ECG interpretation. The findings will form the basis for further discussion on possible solutions in chapter 4.

In this study, I intended to identify where and how the participants experienced challenges in their mastering and performance of ECG interpretation skills. Having collected and analyzed the data with the Grounded Theory method, I made a purposeful selection of the data. The selection was based on the research question and themes emerging across the data. After documenting and reflecting on the emerged themes I developed the concepts of the needs for improvement (the "memoing" stage). I then compared the new data with the data from the theoretical background of this thesis to make sure that findings add significant insights to what we already know ("saturation check" stage). Finally, I synthesized data into coherent needs and insights that I will present as Findings in this chapter.

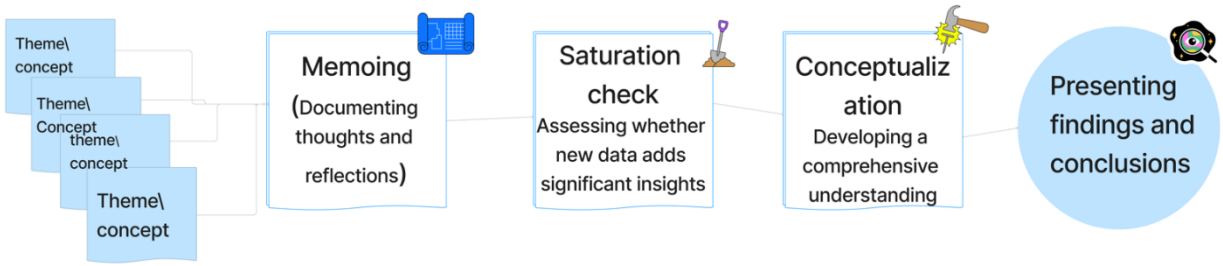


Figure 3. Flowchart of the process from concepts to conclusions with Grounded Theory method.

3.1. Finding 1: The need for an interactive tool for ECG interpretation practice and Norwegian ECG database

From the analyses of chapter '2.6.1. ECG SPECIFICS OF EDUCATION' I found that basic knowledge of electrical heart activity and electrocardiogram is fundamental and compulsory for those involved in testing and diagnostics using ECG methods. The strategies and quality of educational programs for medical professionals on ECG differ between countries and specialties and might depend on local standards of ECG diagnostics around the world. For engineers and researchers, it might also depend on the availability and competency of the specialists that can present the material. When scientists and engineers are involved in projects with ECG diagnostics, there is a need to gain knowledge on the subject in addition to the courses given the university program. The interviewees in my study did not actively express a need for standardization of educational methods, but they all thought that different perspectives on interpretation and analysis

could be beneficial for various reasons. They also expressed a considerable interest in international collaborations between cardiologists and institutions.

The interviewees mentioned that the medical education on ECG was intensive and mostly focused on the theoretical aspects. With limited time frames, the practical parts of the courses would be rushed through. The medical students and doctors in this study reported a lack of practical hours in ECG analysis, and thereby experienced a lack of confidence in ECG interpretation. This is in line with the findings in the literature review in this thesis. Interviews with medical students and professionals in Norway, revealed that there is a lack of workshops and web-platforms that could compensate for the disbalance between theory and practice given during their medical education. This is also in line with the findings in the literature review in this thesis. In particular, the interviewee were requesting ECG taken according to Norwegian standards, with relevance to local population and with detailed representation of interpretive process.

While there is a wide range of possibilities for ECG self-education through online theoretical courses, it still seems to be challenging to find an effective and trusted source of knowledge. According to collected data there are no findings of a complete web-based program on ECG with examples and comprehensive representation of analysis and interpretation for practice. There were also no findings of a coherent database on ECG with respect to local standards and populations in Scandinavia.

Insight 1.1: There is a need for an interactive tool for ECG interpretation practice and learning with the focus of teaching analytical processes of interpretation and a cause-outcome relationship.

Concept 1.1: In order to build confidence and improve skills in ECG interpretation, medical professionals need a lot of practice which is not always possible to achieve through traditional educational programs. There are online offers for ECG interpretation practice, but they don't satisfy the needs of medical students and practitioners in Scandinavia. Interactive platforms that will focus on training analytical thought processes and step-by-step analyses for ECG interpretation, using real-life cases and offering detailed explanation of interpretation for deeper understanding of cause-outcome relationship, will help to elevate the level of competence in ECG diagnostics.

Insight 1.2: There is a need for an ECG database in Norway in order to supplement educational programs with real life cases and examples that are relevant to local standards and populations.

Concept 1.2: As I found through the interviews, accessing ECG examples for learning, practicing and evaluating skills in interpretation has been a challenge for the participants. The collection of ECGs from the Norwegian population can serve as a foundation for knowledge for local medical institutions and provide a source of practice to their students.

3.2 Finding 2: The need to implement a ‘machine-human collaboration’ course in educational programs for medical students.

From the analyses of chapter ‘2.6.3. TECHNOLOGY TRENDS AND CHALLANGES’ we can conclude that the quality of equipment and software for ECG diagnostics vary between machines. Machine interpretation of electrocardiogram is based on numerical changes in intervals, amplitudes and ratios rather than pattern recognition. As a result, automatic analysis is more often used to detect arrhythmias or to define pathological heart rhythms. Machine interpretation is highly likely to give a false positive result due to insufficient noise reduction or biological artifacts: movement of the thorax and use of muscles in the upper body, and additional underlying pathologies might also confuse the findings.

Therefore, there is a problem of trust towards ECG machine interpretation among medical specialists in this study. Even though there is a high probability of incorrect interpretation, the educational programs still do not include training of collaboration with software for ECG diagnostics. Findings show that machine analysis currently does not bring significant clinical value in making a diagnosis. There is also a significant gap between the specialists who don’t trust machine interpretation and those who rely on it excessively.

In order to get reliable measurements during testing and provide correct diagnosis, medical specialists and scientists prioritize precision and conductivity when placing the electrodes. Even with the possibility of remote heart monitoring, most of the ECG records are taken in clinical settings. Contributing to the right conditions for ECG recording helps to insure higher data quality for further analysis, although this does not completely reduce interference of noise and artifacts.

Insight 2: There is a need to implement a ‘machine-human collaboration’ course in educational programs for medical students. In order to build competence and trust in such a collaboration it is important to give an understanding and update on capability and limitations of supplementing software and hardware in medicine. Thereby elevating the effectiveness of machine implementation in medicine.

Concept 2: It should be an essential part of the educational process to build an understanding of how technological innovations serve the purpose in diagnostics and analysis of electrocardiograms. It seems like most of the medical students and the specialists involved with ECG testing have a good understanding of the basics of electrical activity of the heart, and are well familiar with the process of ECG recording and analysis. However, there is a vague perception on the technical aspect of the interpretational process of machine analysis. It creates confusion with findings represented from the software and results in reduced effectiveness of ‘human-machine collaboration’ in diagnostics. Providing a clear understanding of the basic principles the software operates on, and what role it plays in the analytical process could help to build a stronger relationship with technology through awareness rather than dependency.

4 DISCUSSIONS

In this chapter, I will discuss whether findings from this study add valuable insights to the existing knowledge on the needs for development in the field of ECG interpretation. I will extend the topic with a brief overview of how the identified needs have been approached at present. I will also present the thoughts collected from the interviews on how identified needs could have been approached in order to create a difference.

Considering the given timeframe for this study, this chapter will only give suggestions towards possible solutions to the needs represented in the Findings.

4.1 The needs for strengthening ECG learning and practice

The first finding identifies the need for an interactive tool for ECG interpretation practice. For the participants: X2, X4, X5, X6, who addressed this need in the interview, I had a follow-up question related to how they could see or imagine such a tool. From their responses, I have highlighted the following central words (*Figure 4*):

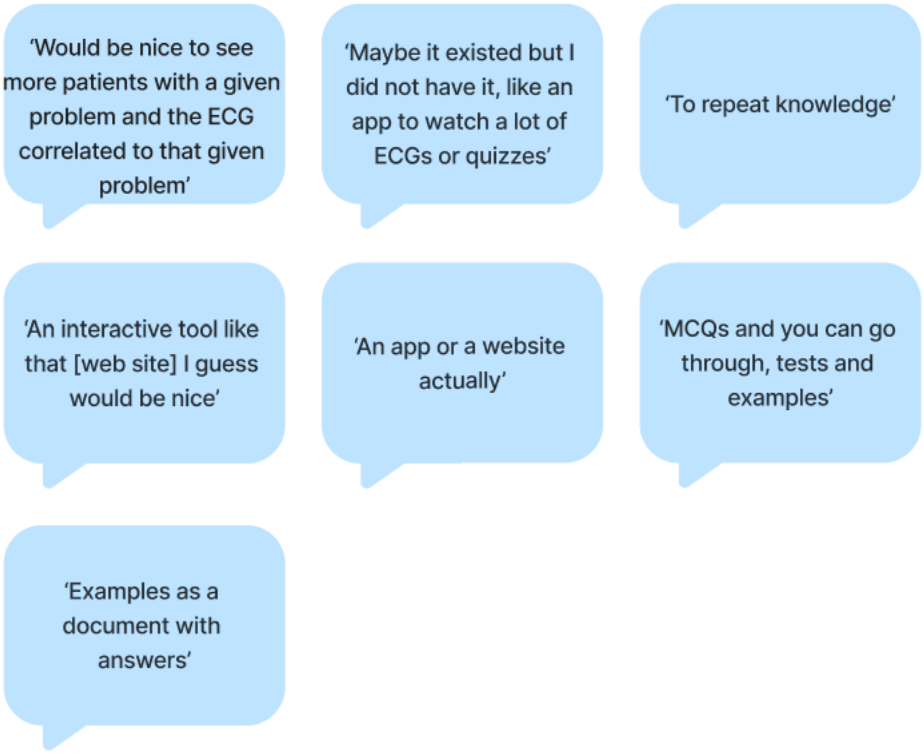


Figure 4. Central words from the interviews that describe an ECG education tool

To this day, the online search,performed for this thesis, showed six competitive offers for online ECG interpretation education and practice (*Figure 5*).

A systematic review 'Educational software applied in teaching electrocardiogram' from 2018, suggests that educational software can bring significant results to ECG teaching referring to the fact that several studies have addressed the struggles in teaching ECG using traditional methodologies (40). There were 17 types of softwares dedicated to ECG education. The majority are composed as tutorials (52.9% or 9 out of 17). However, the results indicated that most of them (58.8% or 10 of 17) were developed to be available for local access, as in a desktop or laptop type of personal computer. At the time, none of the mobile apps were available for revision (40). Currently, the trend is to develop platforms with Internet access as well as interactive apps. While there are several apps available for ECG education now, there has been no review on quality or effectiveness of such innovation.

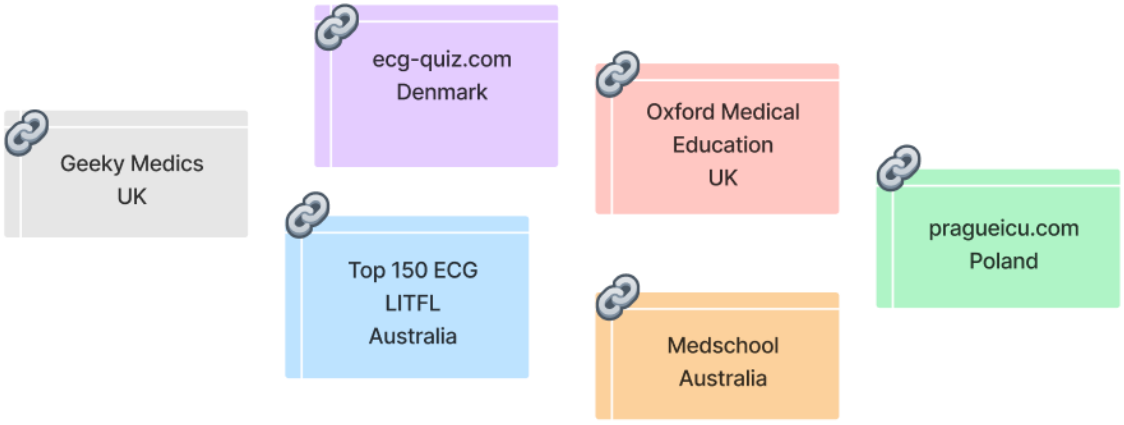


Figure 5. Top competitive offers for online ECG interpretation education

The review (40) also shows that in 52.9% (9 of 17) of the studies, represented by the tutorials, the students would read a textual material on the subjects covered and view images, diagrams of ECG, videos, and/or animations. In 35.3% (6 of 17) the learning tasks were represented by simulators with an option of interaction. Only for 11.8%, represented by problem solving, the proposal for a learning task was based on the availability of problems encountered in the real world (40).

The interviewees in this study emphasized the importance of availability, interactivity and necessity of problem-solving options for a desirable ECG education tool.

Since ECG is one of the most used diagnostic tests in medicine (40) and the area of its' use is still expanding, it is essential to focus on effectiveness and availability of learning tools and methods in the field of electrocardiogram.

While existing solutions might not entirely respond to all the desired criteria, all together they represent a solid database for a new modernized web-platform. Considering how technology is evolving to this day and looking into the future, a web platform for ECG learning and practice that would be accessible on the PC and a phone, could serve as a good tool to develop the skill in ECG interpretation. Many developers, companies and consumers are focusing on reducing internet's carbon footprint, increasingly adopting green IT practices (41). Therefore, the strategy of strengthening ECG learning and practice could be based on sourcing a new educational concept on existing data spaces. Not only would it complement the increase in accuracy of ECG interpretation, but it would also make internet usage more effective.

In this chapter I will give a brief example and visualization if an idea of a modernized web-platform for ECG education (*Table 3*). The key concepts of the idea are as follows:

1. The access to the platform is free available

2. The knowledge is collected internationally. Theoretical materials and ECGs for practice are presented with a reference to a source. This way we can ensure that: 1) the reader knows the region and population studied in a case; 2) each university is able to represent their vision on structure of ECG curriculum; 3) readers are able to see the difference in standardization for ECG recording and interpretation in different regions of the world and 4) easy navigations through the knowledge base for users of any levels and backgrounds

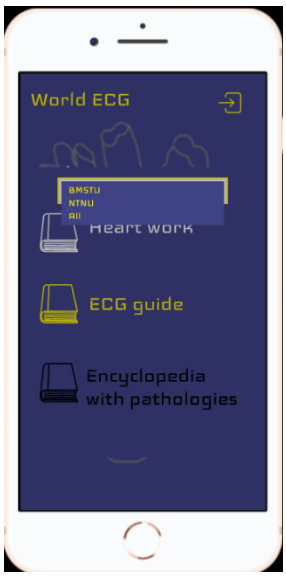
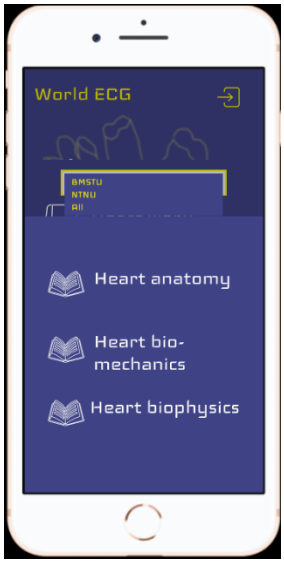
3. With international collection, the library would have sufficient amount of theory, cases and practice kits related to ECG

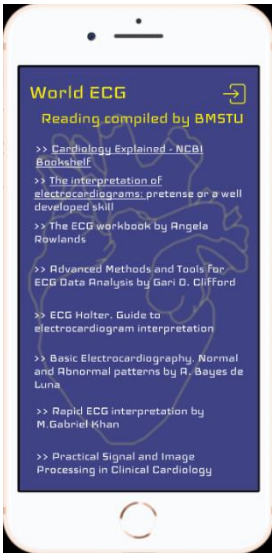
4. The cases represented for learning and practice have a detailed description of the patient's history that also includes personal features such as ethnicity, sex, region of residence and athleticism

5. The disclosure of a new aspect or a knowledge in the field would not require the repetition of the basic but a simple reference to previously created data

Table 3. modernized web-platform for ECG education

	The fundamental principle is to navigate the user through the database. It is desirable for a user to find a type of practice that will serve the goals considering an interest and background.
	Proposing the variety in methods for learning and practice is a good way to insure assimilation of knowledge. For example, a web platform for ECG education could give an access to: Library of theoretical knowledge, examples of ECG cases with detailed explanation of an interpretive process, practical tasks and quizzes, global perspective vision of ECG (including standards, innovations and up-to-date research)

	Even when the web-platform is based on collection of universal knowledge it still might be important to represent various educational methods since different regions of the world might have their own perspective on educational process.
	The idea of ‘collected knowledge’ is to share existing data though a library of links instead of creating another data storage. The web-platform could serve as more of a navigator through the representation of educational materials and strategies created around the world.

	For example, by choosing an institution or organization – creator, and a theme of interest the web-platform would give you a pathway to a source of desirable library or practice.

To summarize, focusing on organizing the existing data collection, making it world-wide accessible and up-to-date would be an investment into fast and fluid knowledge transaction and assimilation. It would provide simple and accessible ways to the libraries of fundamental knowledge and up-to-date information about research and innovation related ECG, and therefore complement into developing an interpretative skill. It would also create a way of building new knowledge without repeating fundamentals but adding to existing base and therefore serve the goal to reduce the internet's carbon footprint by minimalist approach of navigation instead of copying the data.

4.2 The need for a Norwegian ECG database

According to my findings, if such a thing as the Norwegian ECG database existed, it would contain a wide range of real-case examples for learning and practice, with emphasis on the local population and its' ECG features. It could also be a source for machine learning for future AI interpretation. I have discussed this idea with cardiologists and a professor (X3). In her opinion, Norway is a country that is not as populated as many European countries, which led her to question whether there is enough data for machine learning. At the same time, the possibility of creating such a database seemed very possible to her:

'*If you want to research the public you can just apply for that … We have some really good population databases like 'The Hunt' so there you have all information about patients when it comes to comorbidity and everything actually. So, they can probably run a project there if they want to.'*

The direction of scientific research in electrocardiograms at present tends to be more focused on detailed analysis of ECG features, proposing that we could read more from electrocardiograms in the future than we do now. X3 also believes that there are going to be more possibilities in the future in terms of how much we can tell about the health state of a person from a single ECG:

'There is a lot of information that is not used. So, there are plenty of different ways of trying to prove the way we should analyze it. Of course, we need to have some machine learning but there's a lot of research. There would be much more intelligent ways to have a look at the ECGs but there's a lot of things we didn't know in the transition phases during cardiac arrest for example.'

When it comes to machine learning, a wide and diverse database with descriptive analyses plays an essential role in designing software for data analyses. From that point of view, running a project on ECG data collection might become an investment into the future of the healthcare system. Doctor X2 commented on this topic with following:

'So, I don't think we have AI interpretations available in our clinic right now. I think that will come. I think it's obvious that it would probably help us to avoid misdiagnosis and reduce false positives when it comes to ECG interpretation.'

4.3 The need for implementation a 'machine-human collaboration' course in educational programs for medical students

Through the interviews with medical professionals about innovation and technology in ECG, I found that there are mixed feelings about getting a diagnosis through machine interpretation, especially among less experienced specialists. It seems like there is an insufficient level of understanding about how and why the software makes certain decisions. The participants in this research reported that they have experienced that machine interpretation has given the wrong diagnosis on a regular basis. When machine analysis does not correspond with their personal interpretation, it creates hesitation if there is no understanding of why it came up with that diagnosis. Multiple confrontations with misdiagnosis from the software, results in distrust toward the technology and reduces efficiency of 'machine-human' collaboration.

Most of the interviewees wished to know what results of machine interpretation are based on. Junior doctor X4 expressed it as:

'I guess for software it would be nice if it maybe calculated some sort of probability of the diagnosis it's made. … Maybe if there was some kind of display with their example of ECG and the pathology that they refer to, maybe that could come next to what you're looking at so you can compare.'

Currently, innovations in technology are moving fast. There are strategies for improving machine interpretation, most of them focus on dealing with noise interference as this is the major factor for analytical error. Research is focused on improvement of algorithms for machine learning (35), development of AI for ECG interpretation (8), design of ECG denoising algorithms for software (28) and noise reduction schemes for hardware (40). Even though there are big prospects for technology in ECG diagnostics, it is important to remember every innovation needs its time for

complete development and is not perfectly developed from the beginning without further testing. Therefore, while using innovations, medical specialists should be aware of its capabilities and limitations in order to make the most from their collaboration with technology.

Based on my thoughts above, I propose the implementation of a 'machine-human collaboration' course as a part of the basic educational program for medical students. Firstly, I anticipate that gaining knowledge about technological advantages and areas of error would create a better understanding of how to use technology for diagnostics in the most effective way. I also anticipate that it is possible to build trust towards machine analysis through planting an understanding of what the analytical algorithms are created for. And lastly, I believe that if developers would get a chance to represent their medical innovations to doctors and medical students that have direct interest in their product, it will strengthen collaboration between biotechnical engineers and medical professionals.

4.4 Potential weaknesses or bias

This research could have been expanded to include a wider range of health care providers that are involved with ECG testing like nurses and general practitioners to get a bigger variety of experience from interacting with ECG testing.

The research could also have included a higher number of participants to gather more experience on the topic. In this study I was able to collect six interviews, this number might be insufficient. Therefore, for future research inclusion of a bigger number of interviews is recommended to collect more details related challenges in ECG interpretation.

This study was intended to gather experiences on an international level, however, most of the interviewees were from the same region. Further research on the topic might benefit from focusing more on the global perspective and including participants from different countries.

5 SUMMARY

This chapter presents a summary of the findings from the conducted research of this study that aimed to identify the needs in the field of ECG in order to improve the accuracy of electrocardiogram (ECG) interpretation. Through interviews and grounded theory analysis, the research identified needs in the field, leading to the discussion of potential solutions.

The findings show the fundamental importance of basic knowledge of electrical heart activity and electrocardiogram (ECG) for those involved in testing and diagnostics using ECG methods. Educational programs for medical professionals in this field vary across countries and specialties, often influenced by local standards and the specifics of ECG diagnostics globally. While scientists and engineers engaged in ECG projects may need additional knowledge beyond their university programs, analysis of interviewees did show a need for standardization but valued diversity in perspectives and educational methods. The findings emphasize the intensity of theoretical aspects in medical education on ECG, often at the expense of practical training, leading to reported confidence gaps in ECG interpretation among medical students and doctors. Analysis of the interviews also revealed a lack of workshops and web platforms to address the theory-practice imbalance, with a specific request for ECG content representation tailored to local standards and population.

Despite various possibilities for ECG self-education, including online theoretical sources and commercial courses, the research identified challenges in finding effective and trusted knowledge sources. Notably, there is no discovery of a complete web-based program on ECG with comprehensive examples and analysis for practice, and no coherent ECG database aligned with local standards and populations in Scandinavia.

The study concludes with two key insights and corresponding concepts. Insight 1.1 emphasizes the need for an interactive tool for ECG interpretation practice, specifically designed to teach analytical processes and cause-outcome relationships. Concept 1.1 suggests that interactive platforms focusing on training analytical thought processes and step-by-step ECG analysis, incorporating real-life cases and detailed explanations, can enhance the competence of medical professionals in ECG diagnostics. Insight 1.2 highlights the need for an ECG database in Norway to supplement educational programs with relevant real-life cases. Concept 1.2 proposes that such a database, drawn from the Norwegian population, can serve as a foundational knowledge source for local medical institutions and facilitate skill development in ECG interpretation for students.

Findings from this study also show the variability in the quality of equipment and software used in electrocardiogram (ECG) diagnostics, with differences observed across machines. Machine interpretation of ECG relies on numerical changes in intervals, amplitudes, and ratios rather than pattern recognition, often leading to automatic analysis being used primarily for detecting arrhythmias or defining pathological heart rhythms. However, this approach is susceptible to false positive results due to insufficient noise reduction or biological artifacts.

The interview analysis shows that trust among medical specialists in ECG machine interpretation is compromised by the high likelihood of incorrect results. This lack of confidence has led to a significant gap between specialists who distrust machine interpretation and those who excessively rely on it. The current educational programs do not provide training on collaborating with software

for ECG diagnostics, as machine analysis is perceived to lack significant clinical value in making diagnoses.

Insight 2 proposes a need to implement a 'machine-human collaboration' course in medical student educational programs. The aim is to build competence and trust in such collaborations by providing an understanding of the capabilities and limitations of supplementary software and hardware in medicine, ultimately enhancing the effectiveness of machine implementation.

The concept 2 underscores the importance of integrating a comprehensive understanding of technological innovations into the educational process. While medical students and specialists may possess a solid grasp of the basics of electrical activity of the heart and the process of ECG recording and analysis, there is a noted vagueness in the perception of the technical aspects of machine analysis. This lack of clarity contributes to confusion with software-generated findings, diminishing the effectiveness of 'human-machine collaboration' in diagnostics. To address this, the text recommends providing a clear understanding of the basic principles that software operates on, elucidating its role in the analytical process, and fostering a relationship with technology based on awareness rather than dependency.

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APPENDICES

A. INTERVIEW GUIDE

Interview Guide

By Anna Boldireva
Global health master student
At NTNU

Research: Importance of accurate ECG interpretation. Qualitative research on learning, teaching, and working with ECG interpretation.

Research question: What are the needs for improvement in the field of ECG interpretation?

Brief introduction: Research is conducted in the field of ECG interpretation, in particular: features, methods and innovations of this diagnostic tool. Literature review for the last decade shows that many studies have been dedicated to the extensive use of ECG and its automatization. Big interest lies in the areas of ECG monitoring systems and machine learning. However, among the studies that talk about latest (within last decay) innovation and methodology in the field of ECG also report deficiencies in ECG interpretation skills among health professionals. Authors suggest that this problem should be addressed by improving educational technics in ECG interpretation and by providing upgraded software to alleviate ECG analysis.

What needs should teaching technics satisfy and what criteria should the software meet in order to provide analytical support for the interpretation?

Themes:

What specialists are occupied with ECG interpretation nowadays?

2. What can data from ECG analysis serve for?

3. What are the specifics of learning/working/teaching ECG?

4. What was the assessment of competence in ECG interpretation skills?

5. What are the easy and difficult parts of learning/working/teaching ECG interpretation?

6. How does the collective work affect the quality of ECG interpretation?

7. What role does software play in ECG analysis?

8. What are the possible improvements that could ease the learning/working/teaching experience?

9. What is the role of international knowledge exchange in increasing accuracy of ECG interpretation?

Interview questions:

Recording starts here!

1. Good day, could I ask you to introduce yourself and your field of work/ study?
2. What educational program have you undergo/ currently going through in terms of ECG interpretation? What was/is the length of the curriculum? How would you explain the design of the study?
3. Can you describe the way of learning that works the best for you, how did you imply it in your learning experience in ECG interpretation?
4. What were/are the teaching mechanisms in your study program (lectures, practices workshop…)? Which of them were/are more useful and which were/are less effective for you?
5. When analyzing ECG what steps you go through?
6. What potential scenarios when diagnosing by using ECG?
7. What was/is the most challenging in teaching/ learning/doing ECG interpretation?
8. When analyzing ECG where do you feel most confident?
9. What, in your opinion, are the specifics of ECG? Do you feel like there is an agreement on how to interpret the same ECG between different specialists?
10. What kind of software do you use for ECG interpretation?
11. How does the software ease your analysis?
12. Is the software multifunctional? Is there any function you are lacking or don't think you would use at all in order to provide a better interpretation?
13. How could software improve accuracy in ECG interpretation globally?
14. How was/is the evaluation of your ECG interpretation skills provided? Do you feel like it was justified?
15. How would you reflect on the learning program you provide/ go through in terms of effectiveness?
16. If you could change or modify the curriculum or teaching methods, what would the changes be?
17. Apart from the study program that you went through, have you spent any time on improving your ECG interpretation skills? Follow up: If not, did you feel satisfied with the knowledge you got? if yes, what did it take and what was the motivation or need?
18. Who (representatives of what industry), in your opinion, could benefit from having a knowledge in ECG interpretation? Follow up: In what way?
19. Would you agree that there should be a common principal in educational perspective (ECG interpretation) globally? Follow up: What principal would it be?
20. Is there anything you would like to add on the topic of this interview?

Recording stops here!

B. PARTICIPATION FORM

Consent form for Qualitative research

"Identifying needs and strategies for increasing ECG interpretation accuracy."

This form provides the information about the project and what participation will mean for you.

Purpose of the research:

The Cardiovascular diseases (CVD) are the leading cause of death worldwide, making accurate interpretation is crucial for early diagnosis and appropriate treatment. However, the accuracy level of ECG interpretation remains below desirable and varies among medical professionals, including cardiologists and non-cardiologists, leading to the need for improvement. The challenges in ECG interpretation are discussed in this research, touching on the topics computerized interpretation, variations in teaching methods, effectiveness of ECG training, and specifics of distinguishing normal ECG features from abnormal.

Based on the experiences from working/learning/teaching ECG interpretation gathered via oral interviews we aim to identify the needs for improvement.

Who is responsible for the research project?

Responsible for processing of data which is collected:

Anna Boldireva NTNU master student
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The project supervisor:

Vikram Singh Parmar, Institutt for nevromedisin og bevegelsesvitenskap, St Olavs Hospital
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Why are you being asked to participate?

You will be asked to participate because your work or/and education lies in the field of ECG and you have experience from analyzing electrocardiogram or/and using ECG machine interpretation for diagnostics or/and research.

What does it mean for you to participate?

Participation involves participating in interviews about experiences from working/learning/teaching ECG interpretation.

To participate in the study, you must sign this consent form. If you agree to participate, we will contact you about the time of the interview.

It is voluntary to participate

If you choose to participate, you may withdraw your consent at any time without providing any reason. All your personal data will then be deleted. It will not have any negative consequences for you if you do not want to participate or later choose to withdraw.

Your privacy – how we store and use your information?

We will only use the information about you for the purposes we have told you about in this writing. We treat the information confidentially and in accordance with the Privacy Policy.

All information will be processed without name, national identity number, address or other directly identifiable information.

Only responsible for the project student and project supervisor have access to a name that can find its way back to you. The list of names is not required for this project and is deleted right after data is processed. Data collected from you stored before it processed does not have a name indicator on it, only code by which only responsible for the project can identify you.

It will not be possible to identify you in the results of the study as be published.

What happens to your personal data when the research project ends?

The project is scheduled to end by the end of May 2023. Processing of data and publication will not be possible after the project ends.

What gives us the right to process personal data about you?

We process information about you based on your consent.

If you have questions about the study, or would like to know more about or make use of your

rights, please contact:

NTNU master student Anna Boldireva
faculty of medicine and health science
Bam95.rhn@gmail.com, +4798460453

Declaration of consent

I have received and understood information about the project

"Identifying needs and strategies for increasing ECG interpretation accuracy."

and have been given the opportunity to ask questions. I agree to participate in the interview

I agree that my data will be processed until the project is completed

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(Signed by the project participant, date)

C. EXAMPLE OF A CODING PROCESS

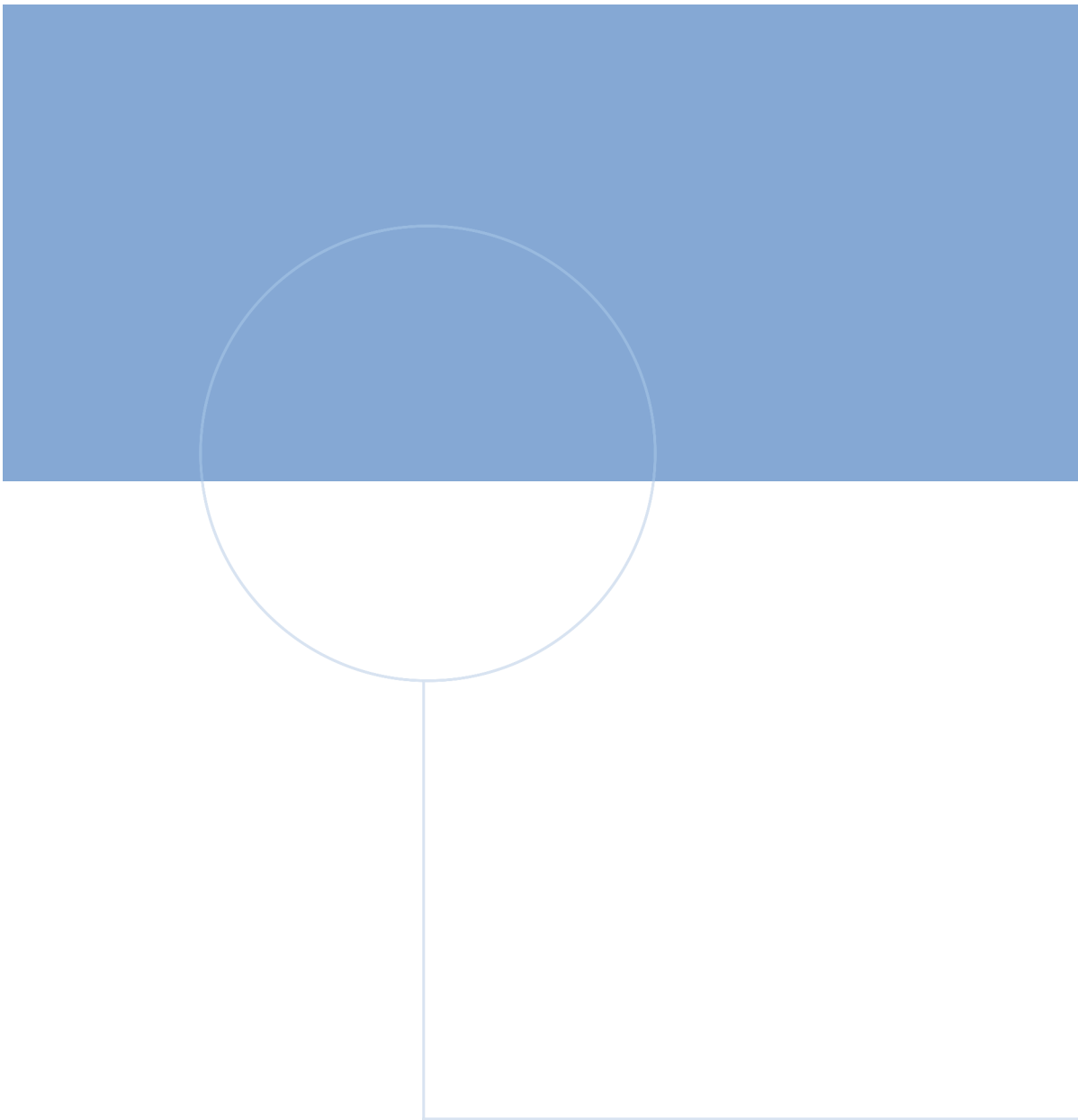
Open coding	Axial coding	Categories	Core categories
I'm a professor in cardiology at the department of circulation and medical imaging at NTNU. been educated in Sweden. First, I educated myself as an anaesthesia intensive care specialist, emergency medicine. But then I did some work at the cardiology department here in Trondheim and I really enjoyed it. So, I decided to work with both. Because it's really good to be able to take care of emergency situation as a cardiologist and it is very good to know cardiology anaesthesiologist and intensive care specialist. Leader in sports cardiology. So, that's right, yeah and also my PhD in cardiology and in ultrasound. I'm a professor. I 40% professor. So, 60% clinical work, 40% research. I have PhD students. I did teach medical students in ECG and all this and also paramedic students and so on and nurses.	X3 is professor in cardiology and leader in sport cardiology in Norway. She has PhD in cardiology and ultrasound and a few PhD students for supervision. She also has experience from teaching ECG to paramedic students and nurses.	**Who use and analyze ECG**	
it is basic for all doctors and nurses and everyone has to have a basic knowledge. It is like the blood pressure, you have to know your ECG, as compulsory for every speciality.	Basic knowledge in ECG is compulsory for every medical specialty.		**Specifics of educational program in ECG interpretation. Teaching**
I guess it's different for speciality. But there's so many good Internet courses on ECG that you could follow and do continuously. things are taught differently. But ECG should be simple. There is only one way to interpret ECG. It is probably easy to standardize. But from European society of cardiology there is a lot of standardized tests and so on. I guess it does not really matter how you learn as long as you end up with the same result and knowledge. And it is so easy to test with ECGs because there is a correct answer and there is a wrong answer.	X3 says that in terms of learning ECG there are many Internet courses to follow. She believes that ECG learning is simple to standardize it as well as test the knowledge because there is one way to interpret ECG, she points on standards made by European society of cardiology. She thinks that the way of learning ECG does not matter as long as you end up with the same result of knowledge.	Self-learning and testing	
Well, the machines they come with an analysis but we of course do not	ECG machines come with the analysis and noise		**Automatic Interpretation**

purely rely on that. Of course I check. we have a noise reduction in the machines and all that, you have to manipulate of course and there are some things that might disturb the signal. But the machine quality of the ECG is extremely different from machine to machine. Even if you do the correct right things you need to have electrodes that are not dry they have to be fresh and there's so many things. And some machines only take some electrodes so there is a lot of things that can go wrong.	reduction, but the machine quality is different from machine to machine. X3 says that they do not purely rely on machine interpretation. There are some things that might disturb the signal even if you do everything right and it have to be considered. One of the things is right placement of the electrodes and making sure that the are fresh and not dry.		**(AI). The problem of reliance**
If you are not a cardiologist you rely too much on a machine you don't even look at an ECG. you always have to check it, but it gives you an idea at least.	X3 says that non cardiologists rely too much on machine analysis without looking at ECG itself but at lest it gives an idea of what might be going on.	**Reliance on machine interpretation**	
in Norway and we have very good guidelines for ECG interpretation that is increase the sensitivity and the specifity of the ECG interpretation so there is not so many patients misdiagnosed today. But yes I do get a lot of referrals from colleagues about the ECG interpretation because the athletes as they train their heart, the heart gets enlarged and the electrical potential changes, so that will sometimes the ECG will look fun. But sometimes it's very serious and could potentially, I mean the patient could potentially have a fatal cardiac arrest. So we know what we have to do, yes. So first of all the most important is that it's going to be very good signals and you have to be sure and that you actually putting the electrodes on the right places. So I put a lot of time to the nurses for them to put the electrodes at the correct position and they also have to rub it to get good signals so that signal quality is everything and the correct placement. Otherwise you can get a very strange ECG and the diagnosi]= that the patient doesn't have at all. You always have to check if you get an ECG that is not normal you have to check that the electrodes have been placed	X3 gets referrals from her colleges about ECG interpretation for athletes because electrical potential doesn't fit the standard. But she points that in Norway there is a good guidelines for ECG analysis that increase sensitivity and specificity of interpretation and she says that there are not so many patients misdiagnosed today. X3 says that to prevent potential problems with misdiagnosis, like cardiac arrest, the most important thing is to get a good signal quality. To do so you need to please electrodes right. X3 puts a lot of time to nurses for them to put the electrode at correct position.		**Challenges with interpretation start with recording**

right, at the right spot and retake it to be sure.			
when there is an emergency you only need to know what kind of rhythm it is and then you only need one signal so that is not a problem. I don't agree. You never put a fully ECG on a patient that is in a car accident or that, of course but if they come with chest pain is important. so data single quality. That is the main thing for everything we work with. Interpretation is no problem.			
You know if we look in the future, then we discussing if we gonna enforce screening with ECG for the top athletes in Norway then we would need syncope. then I would like it artificial intelligence into the ECG so we can put… analize it according to a 'sports heart'. And then the machine would be loaded with all the things that are normal and things that we should be aware of. And that could help us for the future if we want to have screening because it would take a lot of capacity from me and my colleagues, that would be excellent. Ethnicity we have but activity level we don't have yet, so that would be a very good invention.	X3 says that looking into the future she would like having artificial intelligence into ECG with analysis according to a 'sports heart'. She believes that could help cardiologists for the future for the purpose f screening with ECG for the top athletes in Norway using syncope. It would take a lot of capacity from her and my colleagues.	**AI for 'sports heart analysis'**	**Thoughts on improvements**
it's gonna be good to take that signal quality and of course it is not very complicated to have this AI machine learning assistance ECG interprets, that should be rather simple. We know what is normal and we know what is not normal and we know what is borderline. So the machine would say: ' you know this might be this might be pathological check for example'	Future improvement in ECG X3 sees as taking up signal quality and focusing on AI machine learning assistance for ECG interpretation. She explains that there is enough data on what is normal, abnormal and borderline to do so.	Improving the signal quality	
we do research in the ECG. There is a lot of information that is not used. So there is plenty of different ways of trying to prove the way we should analyse it. Of course we need to have some machine learning that but there's a lot of research. There would be much more intelligent ways to have a look at the ECGs but there's a lot of	In ECG signal interpretation there is a lot of information that is not used X3 says. So there is plenty of different of trying to prove the way we should analyze it. There would be much more intelligent ways to have a look at the ECGs but there's a lot of things we didn't		

things we didn't know in the transition phases during cardiac arrest for example	know in the transition phases during cardiac arrest for example.		
ME: Do you know if Norway is doing the work in creating a database space for the machine learning. X3: We are not. Not to my knowledge, I don't think so. But that is something you can if you want to research public you can just apply for that. But Norway is a small country. But we have some really good population databases like 'the hunt' so there you have all information about patients when it comes to comorbidity and everything actually. So they can probably run a project there if they want to. : But you know, in Trondheim an NTNU … we happen to have a different focus.	On my question whether there is a database on ECG's for machine learning in Norway X3 answers that there is non to her knowledge. But she says that that is something I can apply for. She point on population database 'the hunt', that they can run project on collecting that data.		**Necessity of database for machine learning**
in Trondheim an NTNU we're really good at ultrasound. give completely different information, so for example in an athletes they may have a ECG that is concerning and then you do the echo and the morphological changes are not there yet but you can see there is a pathological ECG so you will follow the patient until they one day maybe we'll have some changes in the function of the heart. But the electrical potential changes is much earlier than the morphological changes.	Talking about athletes X3 says that they stress their hearts extremely and that is why we don't know why there are fatal cases. Even though the electrical potential changes happen much earlier than the morphological changes some disease might not show on ECG. To approach that problem medical professionals take the family the history of the top athletes she says. They try to trace if there is something that they have in their blood and genetically and the ECG then. That way they find some pathological changes but still miss but at least we find some.		**Athlete's heart**
if you are a top athlete you stress the heart extremely you never know so that's why we have the fatal cases. What I am saying is that you know some of the diseases into harsh or conduction, abnormalities or whatever or coronary artery pathology might not show on the ECG or the blood samples. So we all get surprises every now and then. Some things show, some			

things don't show. Some might get a disease later some might not so. We take the family the history of the top athletes…. we try to trace if there is something that they have in their blood and genetically and the ECG then. So that way we find some but we still miss but at least we find some.			
ME: so the heart monitor is useful for the cardiologist as well? No, but that is a simple watch. Ours are for the patients not for the sport athletes. The resting heart rate is a bit high in the morning that might be over train or they might have an infection in the body yeah so then I have to check what is what. But it is also is a very, it is a nuisance for us cardiologists. Because patients have watches but they don't know how to interpreted it. Because people don't know it is normal.	On my question on how useful modern heart monitors available on the market X3 says that they use specific types for patients not the ones made for sportsman. She says it is useful for tracing infection in the body as it will show higher resting heart rate measured in the morning. She also mentions that sometimes use of heart monitors by people who don't know how to interpret the data might be nuisance for cardiologists. If people don't know what is normal they start stress over the results they get.		**Problem of self-interpretation of the results from heart monitors**



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