Misplaced ECG electrodes and the need for continuing training

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Every day, more than 1 million ECGs are recorded (Pullan et al, 2005), with 300 million recorded every year in Europe (World Health Organization (WHO), 1981). However, a significant number of ECG operators record inaccurate ECGs (Rajaganeshan et al, 2008; Richley, 2016), which may be as a result of having received inadequate training (Wolff et al, 2012; Richley, 2016).

This literature review focuses on adult nursing, where standard 12-lead electrocardiography recordings (STLERs) are acquired mainly by nurses (Weatherburn et al, 2009; Khunti, 2014) and healthcare assistants (HCAs) (Weatherburn et al, 2009; Wolff et al, 2012). The rationale for the review is that 50–60% of nurses have been found to misplace the precordial electrodes (Rajaganeshan et al, 2008; Martinez et al, 2015).

Electrode accuracy is important as the ECG is the gold standard for rapid, non-invasive cardiac diagnostic testing (Khunti, 2014; British Cardiovascular Society (BSC) and Society for Cardiological Science and Technology (SCST), 2015) and an integral part of medical investigations in general (Hansen, 2006; BCS and SCST, 2015; National Institute for Health and Care Excellence (NICE), 2016). STLER results potentially influence the patient's treatment plan (Knight et al, 1999; Batchvarov et al, 2007; García-Niebla et al, 2009) and, if accurate, can help prevent irreparable damage to the heart muscle if interventions are performed in a timely manner (NICE, 2013).

A STLER is usually acquired for a patient who is deteriorating or acutely unwell (Lynch, 2014). It is important that electrodes are placed accurately (Schijvenaars et al, 2008; Sullivan and Hope, 2013) and the recording is of a high quality (Kligfield et al, 2007; Hazlewood et al, 2011; Derkenne et al, 2017) so it can be interpreted correctly (Wolff et al, 2012). Misplacement of electrodes could simulate ischaemia or infarction (Lehmann and Katona, 2012). To avoid misinterpretation, it is recommended that any deviation from the correct electrode position is documented on the recording (Campbell et al, 2017).

STLERs can affect treatment plans. In Weatherburn et al (2009), STLERs from 373 patients in primary care were interpreted: 76 had care pathways altered, 18 patients required acute admission; and 24 received hospital referrals. This was because ECGs depicted signs of bradycardia, pericarditis and myocardial infarction (MI). Fourteen cases were resolved by a change to patients' treatment in primary care, eliminating the need for hospitalisation.

All information at a practitioner's disposal should be considered. They should not make a diagnosis solely on the basis of a STLER (Baranchuk et al, 2009) as the ECG machine cannot differentiate between an extremely fit athlete with a low heart rate and a 70-year-old patient with bradycardia who requires a permanent pacemaker.

Accurate ECG electrode placement (EP) could also help the NHS, which spends more than £2 billion a year on heart failure (British Heart Foundation (BHF), 2016), to become more efficient in targeting the right patients while reducing financial waste on unnecessary treatments (Khunti, 2014).

Aim

The aim of this review was to investigate the evidence base regarding electrocardiograph operators' EP accuracy and the effects of misplaced electrode stickers when acquiring a STLER. The search question addressed was: 'What are the potential implications when health professionals misplace electrodes when acquiring a STLER?'

Abstract

More than 1 million ECGs are recorded every day. This literature review examined the accuracy of electrode placement (EP) when acquiring a standard 12-lead electrocardiograph recording (STLER), and the consequences of inaccuracy. The findings showed that EP accuracy varies from 16–90%, and standards and guidelines on EP are not being adhered to. Poor EP can mean under- or overdiagnosis, which can increase morbidity and mortality, or mean that patients receive unnecessary treatment or hospitalisation. Mandatory, appropriate training and assessment, including before an operator is allowed to acquire a STLER and refresher training for ECG operators, are recommended.

Key words

◆ Electrocardiogram ◆ Standard 12-lead electrocardiograph recording (STLER) ◆ ECG ◆ Patient assessment ◆ Training

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Methods

The population, intervention, comparison and outcome (PICO) format (Richardson et al, 1995; Huang et al, 2006), was used to form the search question. This is a popular approach to formulating evidence-based research questions in nursing (Bettany-Saltikov, 2012).

The population included a variety of health professionals who acquired a STLER: search terms used included nurs*, clinician, physician, technician and cardiologist. The intervention was performing an ECG: search terms included: 12-lead, ECG, EKG, electrocardiography and electrocardiogram. The comparison was performing an ECG through non-standardised EP: terms included electrode misplacement, accurate, accura*, position, placement, lead position and lead placement. The outcome was the potential effect on the patient from inaccurate EP. The search terms and results generated are shown in *Table 1*.

After deriving the search terms using the PICO format, electronic databases, including Medline and the Cumulative Index to Nursing and Allied Health Literature (CINAHL), were accessed; these are the two most appropriate databases for providing high-quality, accurate searches in nursing research (Subirana et al, 2005). Results were generated by using the search terms in a sequence of combinations using Boolean techniques (*Table 1*).

The inclusion criteria allowed papers published between 1996 and 2017 to be reviewed, which yielded 116 articles when CINAHL and Medline results were combined. This ensured the most up-to-date literature was included, while enabling a comparison between older studies. In addition, this could be used to determine if any progress had been made in the past 20 years or show whether history was repeating itself.

Following this, all duplicate papers were removed, leaving a total of 93 articles, which then had their abstracts read against the inclusion criteria of the search (*Table 2*). This resulted in 25 papers in the final selection for full-text review, from which five final articles were selected. The inclusion and exclusion criteria enabled the search to be refined to ensure only relevant literature that answered the initial search question was included in the final selection.

Additional searches were performed via reference lists of five remaining articles and these were checked to see if they had been cited by other researchers. Consequently, through a snowball effect, another 20 papers were found, of which 18 were included. This resulted in the inclusion of 23 articles in the final review to address the initial search question.

To ascertain the methodological quality of these final articles, a Critical Appraisal Skills Programme (CASP) (2013) tool relevant to the methodology of the articles was used. Following this quality-checking process, eight papers were excluded, as they did not meet the criteria or discussed telemetry or lead misplacement as opposed to electrode misplacement. This left a final total of 16 articles to undergo analysis using Braun and Clarke's (2006) thematic analysis framework.

Figure 1 demonstrates the selection process performed in attaining relevant articles for the review. This literature review was undertaken in January 2018 and a data extraction table (appearing in *Appendix 1* on pages 131–132 following the current article) was generated to minimise the risk of bias (Higgins and Green, 2008). These themes included:

- Misplacement of electrodes
- Anatomical differences
- Operator error
- Impact on diagnosis and management
- Training issues.

Theme 1. Misplacement of electrodes

Evidence suggests that misplaced electrodes could potentially alter the morphology of a STLER (Bond et al, 2012; Lehmann and Katona, 2012; Kania et al, 2014). Schijvenaars et al (2008) disagreed with regards to limb electrodes, stating that precise location was inconsequential if the electrode

Table 1. Search terms

Search	Keywords	CINAHL	Medline	Total
1	Electrode*	11861	159384	171245
2	Electrocardiogr*	37668	215318	252986
3	Accura*	90166	653275	743434
4	12–lead	2379	8147	10526
5	ECG OR EKG OR electrocardiogram	14741	82797	97537
6	Position OR lead position OR lead placement OR placement OR misplacement	84544	458675	543205
7	Nurs* OR clinician OR physician OR technician OR cardiologist	984085	1020842	2004873
8	S2 OR S4 OR S5	40742	234102	274843
9	S3 OR S6	169937	1082683	1252599
10	S1 AND S8 AND S9	358	1235	1593
11	S7 AND S10	69	78	147
12	Studies in the 1996–2017 time frame	59	57	116

Table 2. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Various disciplines acquiring a standard 12-lead electrocardiograph recording (STLER)	Study was able to compare staff in different disciplines	Study was not discussing STLER
Electrode placement for STLER	Studies of STLER discussing electrode placement and misplacement	Non-standard positions that make comparisons difficult, e.g. Mason-Likar, dextrocardia or children
Telemetry and portable electrocardiography	None	Electrodes tend to be on torso and generally not all 10 are used
Instructional articles for electrode position	None	Articles that stipulate positions but do not discuss consequences of misplacement
Electrode misplacement	If electrode studies were about electrode placement accuracy	Lead misplacement, as the electrodes may be in correct locations but misplaced leads will affect the STLER differently, depending upon lead and electrode combination
Article date	Papers published between 1996 and 2017	Papers published before 1996 could be out of date
Environment	Any environment	None
Type of study	All	None

was placed on the correct limb. This may be because the limb electrodes' positions are within a larger, more prominent area with the exact position having an insignificant effect on the STLER (Rajaganeshan et al, 2008). However, limb electrodes are frequently placed on the torso. Jowett et al (2005) showed that limb electrodes placed on the torso of 100 patients exhibited 18 false signs of heart disease and eight false MIs, meaning that five MIs were not shown.

A common theme is that the six precordial electrodes V1–V6 are the most frequently misplaced of the 10 electrodes (Wenger and Kligfield, 1996; Rajaganeshan et al, 2008; Bond et al, 2016). Misplaced precordial electrodes can incorrectly show ventricular hypertrophy and anteroseptal infarction leading to misdiagnosis (Herman et al, 1991). Additionally, Schijvenaars et al (1997) showed that electrode misplacement caused significant changes in myocardium infarction classification in up to 6% of ECG interpretations. Furthermore, V1 and V2 misplacement can result in the recording of false anterior infarctions and poor R-wave progression, and V3 and V4 may simulate anterior infarction if placed too high (Kligfield et al, 2007).

This review found that V1 was the most commonly misplaced electrode overall (Wenger and Kligfield, 1996; Rajaganeshan et al, 2008; Bond et al, 2012; Richley et al, 2013; Martinez et al, 2015; Bond et al, 2016), with cardiologists misplacing it 84% of occasions, nurses 51% and technicians 10% (Rajaganeshan et al, 2008). Additionally, Wenger and Kligfield's (1996) study noted that V1 was being generally placed too high, reaching the second intercostal rib space on occasion, as opposed to its recommended position in the fourth; this is consistent with more recent studies (Rajaganeshan et al, 2008; Bond et al, 2016).

The evidence suggests that misplacement of electrodes can have a detrimental effect on a patient, and that electrode misplacement has been historically poor and an issue that has not been addressed.

Theme 2. Anatomical differences

Anatomical differences can result in electrode misplacement. The American Heart Association (AHA) recognises that it can be difficult for ECG operators to place precordial electrodes V4, V5 and V6 on women with a large mass of breast tissue (Kligfield et al, 2007). This may be in conflict with standardised electrode positions, as the guidelines state that the precordial electrodes V4, V5 and V6 should be placed under rather than on top of the breast (Campbell et al, 2017).

Research by Colaco et al (2000) suggests that electrodes placed under the breast can be up to three intercostal spaces from the AHA and SCST stipulated position; they also noted they could not conclusively show that electrode position was linked to voltage/morphology changes. In contrast, a case study by Derkenne et al (2017) argued that electrodes under the breast changed the morphology of ST elevation so that it looked normal on the STLER. Macfarlane et al (2003) found a decrease in voltage/morphology size on V3 when over the breast; no change on V4; and an increase on V5 and V6 on STLERs. However, the prevalence of poor R-wave progression was not enough to definitively state if it corresponded with breast size. In contrast, Rautaharju et al (1998) measured the impact of an increase/decrease to the voltage/morphology on STLER positioned over a woman's breast; results showed a non-significant increase/decrease in voltage/morphology on the STLER.

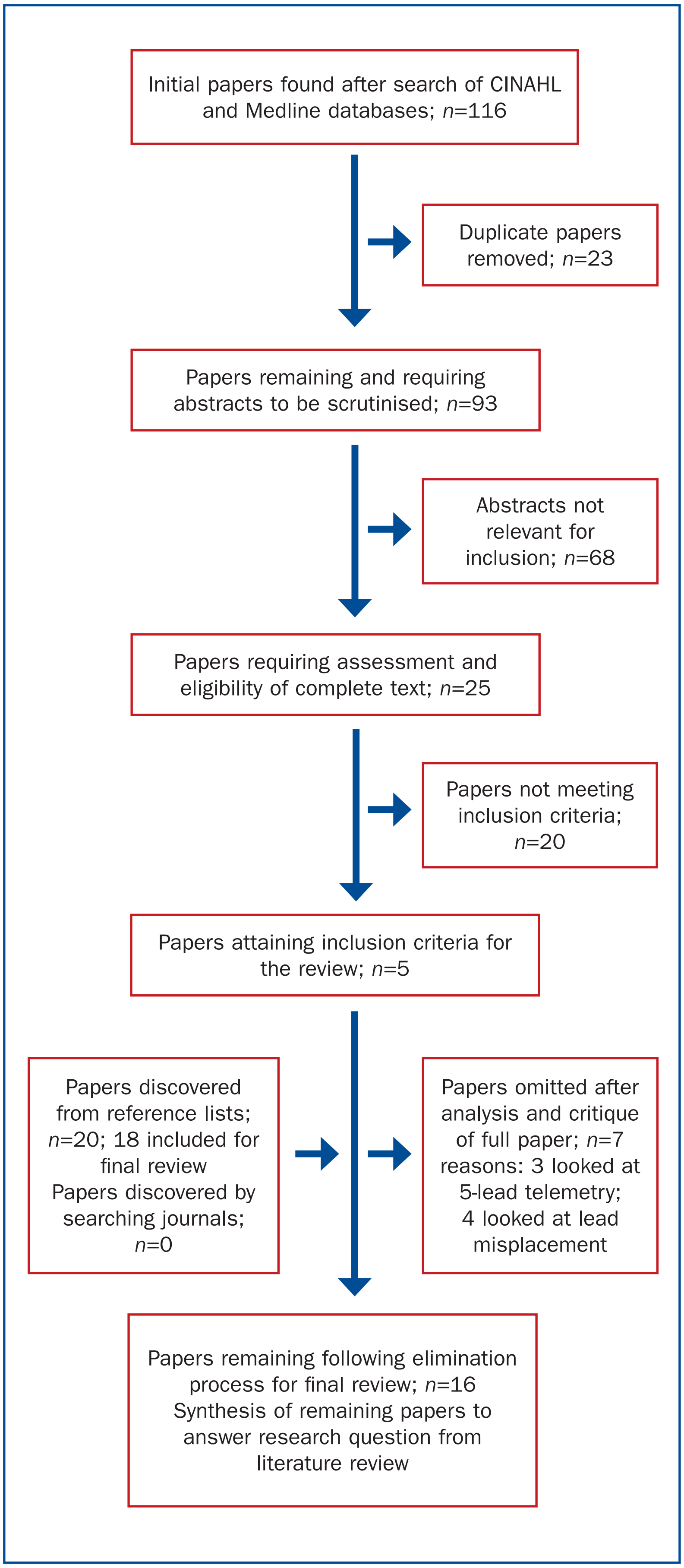

Figure 1. Flow chart showing study selection process for review inclusion

Investigation into this topic area is limited and the available evidence is inconsistent and contradictory. More research is therefore required.

Theme 3. Operator error

Operator error was found to be the most common cause of electrode misplacement (McCann et al, 2007; Rajaganeshan et al, 2008; Bond et al, 2016). Wenger and Kligfield (1996) found that 73% of precordial electrodes were more than 1.59 cm away from their correct locations and 36% were more than 3 cm from the correct location. Additionally, research by McCann et al (2007) found that clinicians' EP differed greatly; however, only three department clinicians were included in their study, which made the sample size too small to generalise the outcomes (Polit and Beck, 2013).

One reason for the V1 being placed too high is that cardiologists use the second intercostal space when listening for heart sounds (Rajaganeshan et al, 2008). Additionally, ECG training for some doctors consists of observing nurses acquiring a STLER (Rajaganeshan et al, 2008). Doctors may also be out of practice; it is uncommon for them to acquire a STLER in a hospital environment as nurses and support workers mainly perform this task (Lloyd, 2008).

Additionally, the work environment in which the procedures were undertaken has an effect; nurses and doctors may have a greater amount of work to perform (Rudiger et al, 2007) and may feel that accurate placement was too time consuming (Wirt et al, 2014). In a study comparing disciplines, technicians were the most accurate (Rajaganeshan et al, 2008) as most of their work centred on obtaining and interpreting cardiac rhythms. They are generally more adept at EP, with it being a focal point of their training (Rajaganeshan et al, 2008). In contrast, in a study by Bond et al (2016), no technician succeeded in placing all the electrodes accurately; however, these results could be biased, as poor performances by the technicians would promote use of the CardioQuick Patch product, which could have benefited the researchers financially. Additionally, the small sample size meant that the performance of each operator affected the results by 5%.

Nonetheless, other findings from Bond et al (2016) are consistent with several of those in the present review. They substantiate the claim that V1 is the most commonly misplaced electrode (Wenger and Kligfield, 1996; Rajaganeshan et al, 2008; Bond et al, 2102; Richley et al, 2013; Martinez et al, 2015) and reflect the views that electrodes misplaced because of operator error have the potential to affect morbidity and mortality rates.

Theme 4. Impact on diagnosis and management

Misplaced electrodes could lead to over- or underdiagnosis of MI and other cardiac-related illness (McCann et al, 2007; Rajaganeshan et al, 2008; Bond et al, 2016). This association between misplaced electrodes and morphology changes in the STLER is an important factor that has been widely investigated.

Kania et al (2014) question whether morphology changes because of electrode misplacement have any bearing on a clinician's diagnosis. However, the validity of their study results can be questioned because it includes only men, so is not representative of the population (Hartung and Touchette, 2009; Barker et al, 2016).

An overwhelming number of studies in the review do, however, conclude that morphology changes identified from the precordial electrodes are sufficient to alter the interpretation of the ECG (Wenger and Kligfield, 1996; McCann et al, 2007; Rajaganeshan et al, 2008; Bond et al, 2012; Richley et al, 2013; Bond et al, 2016). It can be argued that these alterations in morphology are more than an increase or attenuation in voltage amplitude and could lead to over- or underdiagnosis.

It is estimated that misplaced electrodes will alter the diagnosis of 17–24% of patients (Bond et al, 2012). The consequence of over- or underdiagnosis could be that a patient receives unnecessary interventions and medications and is admitted to hospital when this is not required (Øvretveit, 2009; Lehmann and Katona, 2012). Alternatively, the patient could miss out on lifesaving referrals, interventions and medications (McCann et al, 2007; Bond et al, 2016), with 11% of patients having an acute STEMI missed because electrodes are misplaced (Bond et al, 2012). An undiagnosed MI can lead to an increase in mortality from all causes (Dehghan et al, 2014).

A secondary potential consequence is further strain on the NHS during the current financial climate in the UK, where the NHS has been challenged to save £20 billion by improving efficiency and lowering costs (Appleby et al, 2014; NHS England, 2014). Financial resources are wasted, because of inadequate training (Wenger and Kligfield, 1996; Richley et al, 2013); this can lead to unnecessary referrals and interventions from misdiagnosis because health professionals misplace electrodes (Lehmann and Katona, 2012; Richley et al, 2013).

Theme 5. Training issues

Inadequate training was a significant factor in a study by Wolff et al (2012). This study consisted of 91 GP practices that acquired STLERs. The survey revealed that staff had low confidence in their ability to acquire STLERs accurately. Findings indicated that 28% of staff received no training; 62% were trained mainly in-house; and 22% were trained externally. More than 40% of staff said they were not assessed during their training and only 18% had accessed refresher training.

This is further supported by Richley et al (2013), who acknowledged however that their sample size was small and their participants were not randomly selected. They found that, before training, 40 of the 54 ECG operators questioned were confident in their ability to identify the exact location for the six precordial electrodes, but only three of the 40 operators identified V1 and V5 correctly. After training, 50 of 54 ECG operators responded, stating they now knew where to correctly place the electrodes.

SCST guidelines recommend that all ECG operators should be suitably trained and assessed, and periodical reviews performed to maintain skills in acquiring a STLER (Campbell et al, 2017). Thaler et al (2010) showed that high-quality training minimises errors when acquiring a STLER. At the same time, refresher training was shown to have a significant positive effect on competence; this suggests that ongoing training and lifelong learning is important and should be incorporated into tasks associated with patient care. As a result, health professionals should not perform tasks with a cursory attitude (Lloyd, 2008). If they are not trained and assessed adequately, they may approach tasks too casually (Lloyd, 2008), wrongly believing they are competent (Richley et al, 2013). Their practice should be based on evidence (Greenhalgh, 2014) and assessed regularly.

The studies by Wolff et al (2012) and Richley et al (2013) concentrated on nurses and HCAs in primary care but could be applied to secondary and tertiary care, as research shows that nurses in these environments misplace electrodes as well (McCann et al, 2007; Rudiger et al, 2007; Rajaganeshan et al, 2008; Martinez et al, 2015). Research by Rajaganeshan et al (2008) found that more than 50% of nurses misplaced electrodes, which is consistent with the findings of Martinez et al (2015), who showed that more than 60% of nurses misplaced electrodes. In addition, Martinez et al (2015) demonstrated that, after nurses received refresher training, their EP accuracy increased by 40%. Similarly, Richley et al (2013) found that, after training, confidence in recording an ECG rose by over 35%; participants who said they knew where the precordial chest leads should be placed had an increase in confidence from 75% before training to 100% after.

Consequently, more research is required into the standard of training operators receive, as the implications of misplaced electrodes have been shown to have a significant impact on patient care.

Discussion

The findings of the current review demonstrate that EP accuracy when acquiring a STLER varies from 16–90% and has been historically poor for more than 20 years (Wenger and Kligfield, 1996; Rajaganeshan et al, 2008; Martinez et al, 2015). The evidence, based on findings from the literature, indicates that many STLERs are of an inferior quality (BCS and SCST, 2015; Richley, 2016). Given that more than a million EGCs are recorded every day (Pullan et al, 2005), a significant number of STLERs per year could be inaccurate. This could alter the diagnosis of 17–24% of patients (Bond et al, 2012).

These inaccurate STLERs could potentially result in delays in lifesaving interventions and operations (Lehmann and Katona, 2012). They could also lead to inaccurate treatment plans because of over- or underdiagnosis (McCann et al, 2007; Kania et al, 2014), as well as the associated financial waste from unnecessary hospitalisation, medication, cardiac catheterisation and other interventions, which also carry risks to the patient, increasing morbidity and mortality rates (McCann et al, 2007; Lehmann and Katona, 2012; Bond et al, 2016).

Furthermore, the literature strongly highlights the need for training (Wolff et al, 2012; Richley et al, 2013). Inferior quality STLERs in secondary care and primary care result in errors (BCS and SCST, 2015), which have occurred over the past 20 years (Wenger and Kligfield, 1996; Rajaganeshan et al, 2008; Richley et al, 2013; Bond et al, 2016). There is a minimal amount of research evidencing the training received by ECG operators. However, the available research highlights disparities in the standard of training delivered, with some operators receiving no education while others receive in-house training; fewer than one in five operators had accessed refresher training. This is in stark contrast to the SCST guidelines (Campbell et al, 2017), which recommend that an ECG operator should be competent; possess a relevant qualification in STLER; and access periodical refresher training.

This disparity in training shows the need for hospital trusts to evaluate the training dispensed to staff and to implement a standardised education programme, as electrode accuracy improves substantially after training (Thaler et al, 2010; Richley et al, 2013; Martinez et al, 2014). Training should include locating anatomical landmarks to help accurate placement when confronted with patients who are obese or who have a substantial amount of breast tissue, as these anatomical differences are another reason for electrode misplacement (Macfarlane et al, 2003; McCann et al, 2007; Harrigan et al, 2012).

Furthermore, the evidence on placing electrodes over or under the breast on women is inconsistent and contradictory. It is recommended that further research is carried out in this area (Kligfield et al, 2007; Campbell et al, 2017). Furthermore, if this were to result in guidelines changing and stipulating that electrodes should be placed over the breast, supplementary research would need to be performed to ascertain that breast implants do not have a detrimental effect on the morphology reproduced on a STLER.

Conclusion and recommendations

Because training is inadequate, there is a need for robust, high-quality training and regular refresher training (Martinez et al, 2015; Richley, 2016), especially for nursing staff who play a major role in ECG acquirement (Khunti, 2014). Inadequate training can result in an inaccurate diagnosis and subsequent poor and ineffective management of patients (Jevon, 2010; Richley, 2016). Therefore, it is advised that all organisations take ownership regarding quality and governance as they do with basic life support and manual handling courses, and implement an appropriate, standardised, mandatory training package that includes assessment, certification and continuous training. Furthermore, this could be implemented in large hospitals, using the skills of a cardiac technician who could educate a staff member from each ward/area in EP and assessment skills. This staff member could possibly become an ECG link nurse, with the responsibility of cascading information and performing training, assessments and refresher courses. Additionally, ECG operators should access refresher training periodically (BCS and SCST, 2015) to minimise mistakes (Rudiger et al, 2007; Thaler et al, 2010).

A reusable learning object (RLO) maintained by the cardiac technician team could be used for refresher courses. Although RLOs can be used for teaching, EP placement has been shown to be more accurate when taught person-to-person compared with using computer-based simulation (Dolan et al, 2015). However, when an operator has an initial person-to-person training session and assessment when gaining accreditation, and receives further monitoring and guidance by an ECG link nurse to eradicate poor practice, a classroom teaching session or RLO would be suitable for refresher training. BJCN

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Key Points

- Of all electrodes, precordial electrodes were the ones found to be most often misplaced
- Misplacement of electrodes was linked to operator error
- Anatomical differences can mean that electrodes are misplaced
- Misplaced electrodes can cause over- or underdiagnosis
- Inadequate training affects accuracy. There is no compulsory, standardised, training requirement for ECG operators
- There is a lack of ownership over the monitoring standards of operators' competency and the quality of STLER produced

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CPD Reflection Questions

- Have you been placing ECG electrodes correctly and would you feel confident to competently place ECG electrodes correctly now?
- Did you realise the guidelines recommended training, certification and refresher courses. Would you still be happy to perform this task without proper training and certification? Have your HCAs had proper training and certification and would you still be happy to delegate this task to them?
- Did you realise that it was a requirement of the guidelines to document on the ECG recording if electrodes were not in the correct position, e.g. if dressings were in the way after surgery to the upper torso. Have you been documenting that electrodes were not correctly placed because of the dressing, for example, and will your practice change now?

Appendix 1. Data extraction table for literature search

Author, date	Design	Method	Possible reasons for misplacements	Misplaced electrode (Most common listed first)	Consequence(s) of misplaced electrode(s)	Results	Suggestions and recommendation
Bond et al, 2012	Ireland, UK Retrospective, RCT, blinded	Two technicians interpreted 75 ECG recordings with correct and incorrect EP	Operator error	V2; V4; V1	Over- or underdiagnosis	11% of patients had acute MI missed 17%–24% different diagnostic interpretation	Education Electrode misplacement simulator
Bond et al, 2016	Ireland, UK RCT	20 technicians acquired a STLER	Operator error	V1; V3; V2; V6	Effect on interpretation. Over- or underdiagnosis	No technicians scored 100% on EP; CardioQuick patch faster to place and improved accuracy	Education regarding ECG acquisition. Using a CardioQuick patch
Colaco et al, 2000	Glasgow, UK Prospective cohort study	One practitioner STLER of V3–V6 on and under the breast on 84 women	Adhering to guidelines to go under breast	Only took into account V3; V4; V5; V6	Conflicting results suggest EP over/under breast not reason for rise in poor R-wave progression	V3 on breast significantly lower R-wave amplitude. V5 and V6 on breast higher R wave. Electrodes up to 3 ICSs below standard due to breast tissue	Further research into electrode position on women with large mass of breast tissue
Derkenne et al, 2017	Emergency care unit in France, case study	Emergency team and nurse's placement of V3 to V5 on a woman with large amount of breast tissue	Different interpretations of EP guidelines	V3; V4; V5	Morphology depends on EP over/under breast. Affects interpretation and diagnosis	Electrodes under breast hid the presence of ST elevation. ST elevation was seen only when electrodes were over the breast	Repeat STLER if major inconsistencies between symptoms and recordings. Place electrodes over breast. Refresher training
Jowett et al, 2005	Medical and surgical wards in UK Prospective cohort study	Nurse acquired STLER from 100 patients using combinations of standard and non-standard limb EP	Non-standardised was easier, quicker and reduced artefact	Only took into account RA; LA; LL; RL	Effect on interpretation	Limb electrodes on torso significantly altered 36% of STLER.	Place electrodes in recommended positions, not on torso. Deviations should be documented on STLER
Kania et al, 2014	Hospital in Vienna, Austria	Does not stipulate who placed electrodes on to 60 patients	Anatomical differences; breast tissue; operator error	V2; V3; V1; V4	Morphology changes. Questions over whether changes affect diagnosis	Morphology changes in V1–V4 and no changes in V5 and V6	Highlights EP methods from Kerwin et al; Herman et al; Soliman
Lehmann and Katona, 2012	Michigan (USA) Prospective cohort study	Cardiologist and investigator	Operator error	Only took into account V1; V2	False interpretation of Brugada syndrome; ischemia; infarction. Unnecessary interventions, medication; morbidity	90% accuracy with hand to neck manoeuvre	Hand to neck manoeuvre
Martinez et al, 2015	Hospital emergency department in France, RCT	Thirty nurses	Operator error because of no refresher training	V6; V1; V2; V5	Affect interpretation, especially in repeat ECGs. Over- or underdiagnosis	33% accuracy before training and 73% after ECG training	Education, refresher training, consisting of short course regarding ECG acquisition

Appendix 1. Data extraction table for literature search (continued)

Author, date	Design	Method	Reasons	Misplaced electrode	Consequence(s)	Results	Suggestions and recommendation
McCann et al, 2007	Hospital ED, Australia Blinded, prospective observational convenience sample	One advanced trainee in emergency medicine and two senior emergency nurses checked ED nurses' EP	Operator error identifying anatomical positions, even experts. Patient factors	V5; V6	Over- or underdiagnosis	219 (23.7%) precordial EPs out of 924 paired measurements differed by more than 25 mm	Leave chest electrodes on or mark with permanent marker during hospital stay
Macfarlane et al, 2003	Glasgow, UK Prospective cohort study	One practitioner. STLER of V3–V6 on and under breasts of 84 women	Adhering to guidelines to go under breast	Looked only at V3; V4; V5; V6	Minimal difference in amplitude on breast; v3 and V4 <4% and V5 and V6 <13.5%	Decrease in voltage/morphology size on V3 and V4 when over the breast, and an increase on V5 and V6 on STLERs	Further research into electrode position on women with large mass of breast tissue
Rajaganesh-an et al, 2008	Six hospitals, mainly Greater London. Cohort study	Ten technicians, 37 nurses 20 cardiologists, 52 physicians	Operator error. Doctor's training is often observing nurses	V1; V2	Significant morphology changes. Over- or underdiagnosis	V1 correctly selected by 90% of technicians, 49% of nurses, 31% of physicians and 16% of cardiologists	Education regarding ECG acquisition and a suitable environment
Rautaharju et al, 1998	Used ECGs from ARIC and NHANES 3	ECGs of 6814 women were compared to check for EP	Adhering to guidelines to go under breast	Mainly discuss V3; V4; V5; V6	No significant change on V3. Significant decrease in R-wave amplitude V4 and V5; <1% of variation due to breast tissue	Breast tissue has a minimal impact on ECG amplitudes	Place electrodes over breast
Richley et al, 2013	GP practice staff, England Questionnaire	21 HCAs, 27 practice nurses, 4 nurse practitioners, 2 GPs	Operator error Insufficient training	V1; V5	Significant morphology changes. Over or under diagnosis	Training improved confidence in EP accuracy	Education regarding ECG acquisition
Rudiger et al, 2007	Hospital in Zurich Blinded cohort study	Technicians, physicians, nurses recorded 838 ECGs from 568 patients	Nurses and physicians' high workload. Increase of error in acute hospital	Not stated	Morphology changes	99% EP accuracy by technicians and 96% by nurses and physicians	Education regarding ECG acquisition. Standardise equipment and procedure
Wenger and Kligfield, 1996	New York, US	30 technicians at 11 hospitals	Anatomical differences/ breast tissue/ operator error	V1; V2; V6	Misdiagnosis	36% of precordial electrodes were placed >3 cm away from correct location. Technicians were 8%–94% accurate	Template or mark with permanent marker during hospital stay
Wolff et al, 2012	91 GP practices, England Postal survey	91 ECG operators, mainly nurses and support workers	Operator error	Not stated	Misdiagnosis and increased hospital referrals	Low staff confidence in acquiring STLER accurately because of poor training and assessment	Use SCST guidelines to create an ECG course

RCT: randomised controlled trial; HCA: healthcare assistant; MI: myocardial infarction; ECG: electrocardiograph; ED: emergency department; EP: electrode placement; SCST: Society for Cardiological Science and Technologies; STLER: standard 12-lead ECG recording; ICS: intercostal space; ARIC: Atherosclerosis Research in Community Study; NHANES 3: National Centre for Health Statistics; RA: Right arm limb lead; LA: Left arm limb lead; LL: Left leg limb lead; RL: Right leg limb lead.