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RESEARCH REPORT

ASSESSING THE ACCURACY OF ECG CHEST ELECTRODE PLACEMENT BY EMS AND CLINICAL PERSONNEL USING TWO EVALUATION METHODS

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ABSTRACT

Background and purpose: A valid 12-lead electrocardiogram (ECG) depends on correct acquisition technique, particularly on the accurate location of precordial (chest) electrodes. The emergency medical services (EMS) segment of the care continuum is under-represented in previous clinically oriented studies of electrode placement. This study sought to assess the accuracy of chest electrode placement by EMS and clinical personnel in one geographic area, to identify patterns of misplacement to inform future training and continuing education, and to compare two methods of assessing electrode placement.

Methods: This prospective observational study recruited a convenience sample of EMS and clinical personnel. Participants placed simulated electrodes on a CPR-style manikin and completed a questionnaire about their training and experience. A subset also marked electrode locations on a printed diagram of the ribcage. Digitized placement data and questionnaire responses were analysed statistically.

Results: Findings from 149 participants showed misplacement patterns consistent with prior studies, with 41.6% rated as "acceptable" and 34.2% placing ≤ 3 electrodes acceptably. Correctness of electrode placement was comparable between EMS and clinical participants. More correct electrode placement correlated with classroom vs. on-the-job training, frequent vs. infrequent practice, and greater self-confidence. The diagram data collection method proved not equivalent to, and probably less reliable than, the hands-on manikin method for assessing placement skills.

Conclusions: Significant variation in ECG chest electrode placement by EMS personnel was comparable to that previously reported for clinical personnel, suggesting that existing concerns about placement errors by clinical personnel may apply equally to EMS personnel. More frequent practice and classroom-based initial ECG training were associated with significantly greater placement accuracy. Participants used diverse strategies to identify electrode locations. Further research is warranted to clarify optimal strategies for placing chest electrodes, especially on diverse body types. Sound initial ECG training and continuing education are necessary to reinforce high-quality ECG skills.

INTRODUCTION

The 12-lead electrocardiogram (ECG) is firmly established as a valuable and widely used diagnostic test (Bickerton & Pooler, 2019; Kligfield et al., 2007). National (U.S.) surveys estimate that nearly 27 million ECGs were acquired in ambulatory care visits to physicians' offices in 2018 and nearly 34 million ECGs in emergency departments (ED) in 2019 (Cairns & Kang, 2019; Santo & Okeyode, 2018). Corresponding inpatient hospital estimates are not available, but it is possible to assume that the annual volume of inpatient ECGs is comparable to either of the outpatient estimates or to both combined. In 2022, emergency medical service (EMS) personnel in the U.S. acquired more than 6.5 million ECGs (12-, 15-, and 18-lead) outside of healthcare facilities (National Emergency Medical Services Information System, n.d.). Thus, approximately 95-129 million ECGs are acquired in the U.S. each year, more or less one for every three inhabitants (U.S. Census Bureau, n.d.).

Potentially life-changing treatment decisions may be made on the basis of an ECG tracing. Thus, every ECG must reflect the patient's condition as accurately as possible. Validity of the 12-lead ECG depends on the correct acquisition technique and particularly on the accurate placement of precordial (chest) electrodes. Small deviations in electrode placement can significantly alter the waveforms recorded, potentially impacting the provider's interpretation of the ECG (Bond et al., 2012; Harrigan et al., 2012; Kania et al., 2014; Rosen et al., 2014; Rudiger et al., 2006). Misplaced electrodes can lead to false-positive interpretations that can generate needless anxiety, inconvenience, exposure to procedural risk, and expense (Abobaker & Rana, 2021; Drew, 2008; Ilg & Lehman, 2012; Rehman & Rehman, 2020; Toosi & Sochanski, 2008; Walsh, 2018). Less commonly, but more concerning, they also can mask pathological signals, potentially allowing serious conditions to go undetected and untreated (Derkenne et al., 2017). Conflicting results due to inconsistent ECG acquisition technique can create confusion and increase the risk of error when a patient moves between or within care settings (Drew, 2007). Acquiring 12-lead ECGs with precision across the continuum of care, supported by sound initial training and continuing education, is essential to safe and effective patient care (Hoffman, 2008).

Several studies have assessed 12-lead ECG chest electrode placement among physicians, registered nurses (RNs), and technicians in clinical settings (Aydemir, 2021; Medani et al., 2018; Rajaganeshan et al., 2008), and one recent study has focused on EMS personnel (Gregory et al., 2021). Results are concerning, suggesting that a large share of 12-lead ECGs are acquired incorrectly and thus are potentially misleading. The present study sought to assess the accuracy of chest electrode placement among EMS and clinical practitioners in the authors' geographic area; to inform future training and continuing education by identifying patterns of misplacement; and to compare two methods of assessing electrode placement.

MATERIALS AND METHODS

A convenience sample was recruited from EMS services after obtaining ethical approval for this prospective observational study from the Institutional Review Board (IRB #1471953-1). A cohort of clinical personnel was also enrolled for comparison. EMS personnel were paramedics and advanced emergency medical technicians (EMT-A). Clinical personnel were RNs and patient care technicians whose duties included the acquisition of 12-lead ECGs. Physicians were not included in this study because they rarely are personally involved in acquiring 12-lead ECGs in the United States. We focused on the standard 12-lead ECG using chest leads V_1-V_6. Extended-lead ECGs were beyond the scope of this study.

Data collection was conducted privately for each participant. After obtaining informed consent, the researcher (ELC) asked every second participant to mark electrode locations on a printed diagram of the ribcage (Figure 1). This method was included to compare results with prior studies using that methodology. Then, each participant was asked to place six simulated electrodes on a plastic transparency taped to the chest of a CPR-style manikin (Figure 2). This method is substantially similar to the method validated by Medani et al. (2018), modified to facilitate quick data collection and to preserve original data for further analysis. Two conditions precluded employing a live human model, extended data collection over many months and data collection at numerous sites.

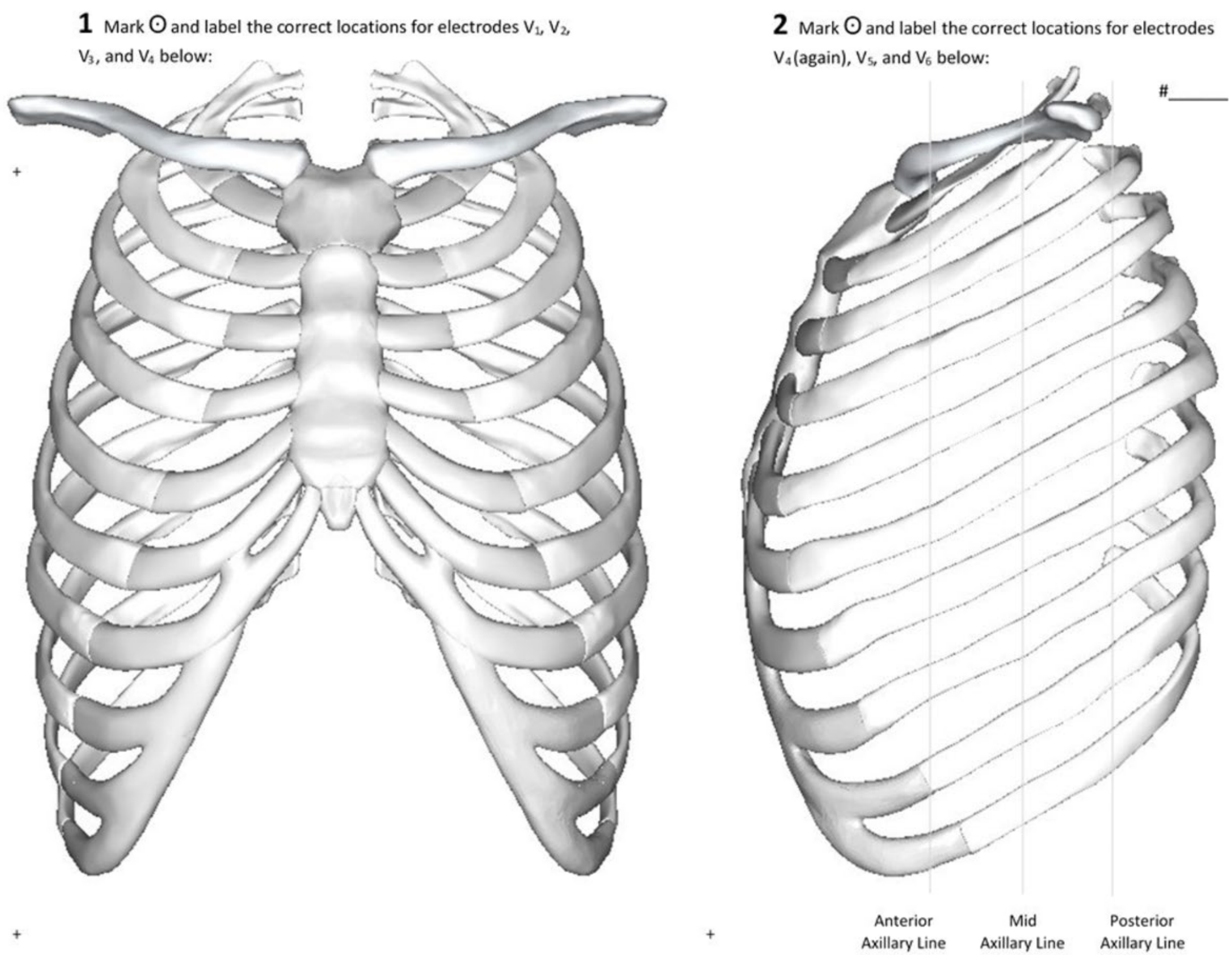

Figure 1. Printed diagram of the ribcage used for diagram data collection. Created using Anatomography, https://lifesciencedb.jp/bp3d.

After each participant finished placing electrodes, the locations of three registration points on the chest were marked on the transparency to establish standard axes for plotting the (x,y) coordinates of the electrodes. Following electrode placement, all participants completed a questionnaire (Appendix A). One final question was posed orally, and the response was summarized and encoded by the researcher on the questionnaire sheet: "We are interested in how people find the starting point for locating the chest electrodes. What physical landmark do you locate first?"

The rib diagrams and the transparencies were scanned, the (x,y) coordinates of electrode locations were digitized using *Graph Grabber* v2.0.2 (Quintessa Software Ltd., Henley-on-Thames, UK, https://www.quintessa.org), and the data were uploaded into Excel®. Questionnaire responses also were entered into Excel®.

Data collection began in November 2019 and concluded in December 2021, with a hiatus from March 2020 to June 2021 due to the COVID-19 pandemic. All participants used the same manikin and identical materials. The first author (ELC) collected and reduced the data.

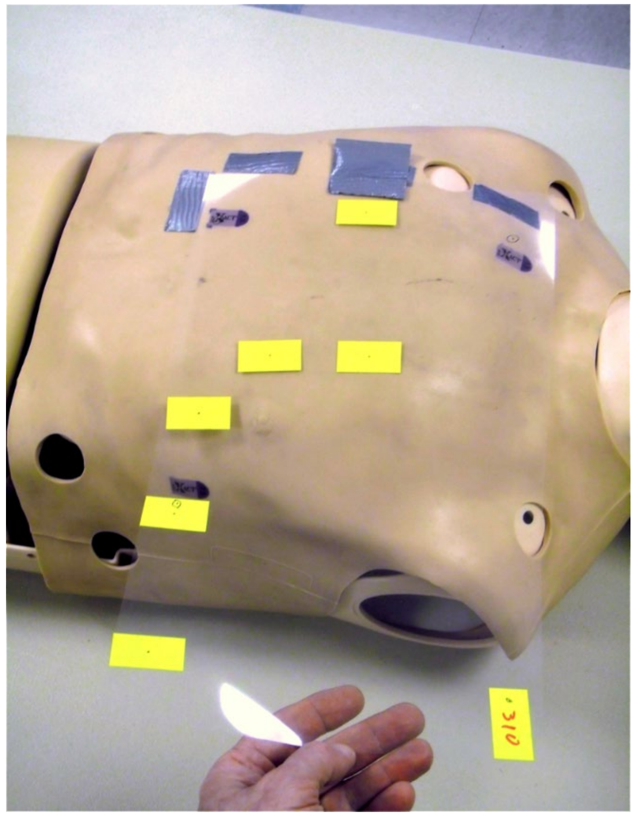

Figure 2. The manikin with a completed transparency showing simulated electrodes placed by a study participant.

DATA ANALYSIS

Ideal electrode locations were determined following AHA guidelines (Kligfield et al., 2007). To assess placement accuracy, a tolerance radius centered on the ideal location of each electrode was established for the two data collection methods (Table 1). Tolerances were based on the detailed assessment of the effects of electrode misplacement on ECG waveform morphology by Kania et al. (2014). A placement was considered acceptable if it lay within the tolerance radius for that electrode. Distances from ideal locations were calculated individually for each electrode, and aggregate error distances were calculated for electrode groups V_1-V_4 and V_1-V_6 (V_{all}). In addition, each participant's overall performance was coded as "acceptable" or "unacceptable" based on whether three or more of the electrodes V_1-V_4 lay within their respective tolerance radii. We concentrated on electrodes V_1-V_4 because the accuracy of the ECG depends most sensitively on correct placement of those four electrodes (Bond et al., 2012; Kania et al., 2014; Rudiger et al., 2007).

Method	V_1	V_2	V_3	V_4	V_5	V_6
Diagram	13	13	13	17	22	22
Manikin	30	30	30	40	60	60

Table 1. Tolerance radius (mm) for each electrode.

Descriptive and non-parametric statistics were calculated in Excel®, and mean aggregate electrode placement errors were analysed for variance with respect to questionnaire responses (ANOVA with Tukey comparisons) using *R* (R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org).

RESULTS

A total of 149 participants completed the study. EMS data (n = 99) were collected during 27 visits to 14 sites representing six municipal fire departments, two hospital-affiliated EMS services, and one independent community EMS service located in one northeastern US state. Clinical data (n = 50) were gathered during 10 data collection sessions at the two campuses of the first author's hospital organization, a 150-bed medical and surgical hospital and a 40-bed inpatient mental health and outpatient surgical hospital, each location having a comprehensive ED. The study questionnaire and tabulated responses (Appendices A and B) describe the study participants.

Two-thirds of the study sample worked in EMS roles and one-third in clinical roles: RNs, certified nursing assistants (CNA), ED technicians, respiratory technicians, and inpatient psychiatric technicians. Half of the participants were paramedics; the other half were EMT-As, RNs, and clinical technicians. Nearly all ECGs are acquired by CNAs and ED technicians at the studied hospitals; very few full-time ECG technicians are employed, and none participated in the study.

See table 2 for ANOVA analysis of electrode placement errors for selected electrode groups. Only variables for which significant interactions were found are shown in the table.

Significant interactions appeared between questionnaire responses and placement errors, most often with electrodes V_4 and V_6 and least often with electrodes V_1, V_2, and V_5. Table 2 presents ANOVA results that achieved statistical significance for electrode groups V_1-V_4 and V_{all}.

Figures 3 and 4, respectively, present scatterplots of the placements of chest electrodes on the printed diagram of the ribcage (n = 67) and on the manikin (n = 149). Crosses in the figures indicate the ideal locations of the electrodes, and in Figure 4, solid circles mark the mean placements of the electrodes. The proportions

Variables	Mean Aggregate Errors	
	Electrodes V_1-V_4	All Electrodes
Frequency of Practice	≥ 5x/wk (113) > < 5x/mo (161) **p = 0.008**	≥ 5x/wk (180) > < 5x/mo (252) **p = 0.0009** ≥ 5x/wk (204) > < 5x/mo (252) p = 0.027
Initial Training: Where?	Academic (109) > Hospital (145) p = 0.013 Academic (109) > Fire Department (160) **p = 0.003**	Academic (185) > Fire Department (247) **p = 0.004**
Initial Training Format?	Classroom (146) > OJT (119) p = 0.047	[n.s.]
Recent Refresher: None	Too new (103) > Never (167) **p = 0.002**	Too new (161) > Never (262) **p = 0.002**
How Confident?	Very (118) > Somewhat (147) **p = 0.009**	[n.s.]
The mean aggregate error in mm (see text) for each participant group appears in parentheses. The notation " 5x/wk (180) > < 5x/wk (252)" indicates participants who reported acquiring five or more ECGs per week on average performed better (i.e., had a smaller mean aggregate placement error) than those reporting fewer than five ECGs per month. Bold font indicates p 0.01. n.s., no significant differences were found. OJT, on-the-job training.		

Table 2. ANOVA analysis of electrode placement errors for selected electrode groups.

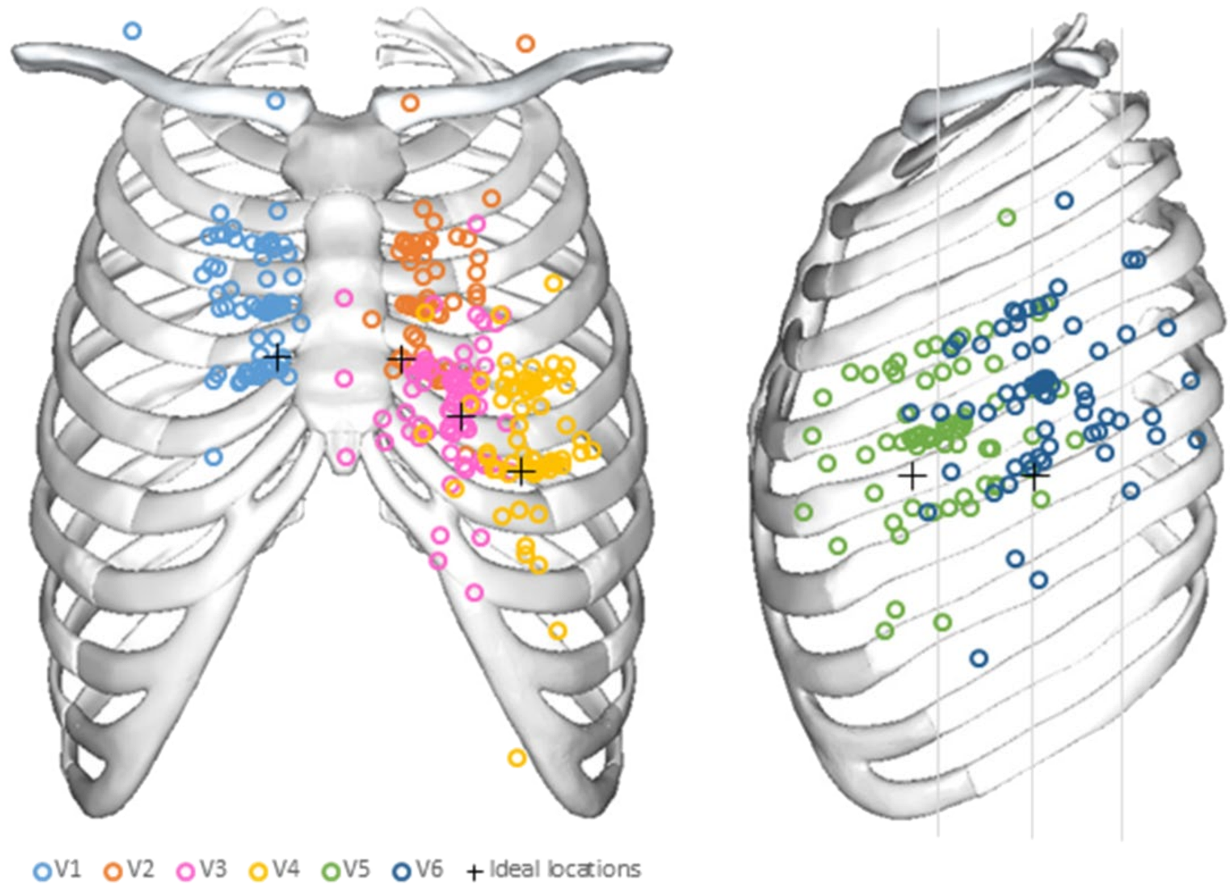

Figure 3. Scatterplot of diagram electrode placements superimposed on the diagram used by participants (n = 69). Crosses mark ideal locations of V_1-V_6 (left-right). Vertical lines on the lateral view mark the anterior, mid-, and posterior axillary lines (left-right).

of the two scatterplots differ because of differences between the printed diagram and the 3-dimensional manikin.

Overall, 41.6% of participants (n = 62) met the above-described acceptability criterion on the manikin; 21.5% (n = 32) placed five or more electrodes within tolerance; and 34.2% (n = 51) placed three or fewer electrodes within tolerance. The ANOVA analysis revealed no consistent differences in mean aggregate placement error related to the level of training, work role, or length of experience. The mean aggregate placement error for EMS practitioners was smaller than that for clinical practitioners in leads V_1-V_4 (127 mm vs. 144 mm, $p = 0.092$), and it and was approximately equal across all leads (207 mm vs. 205 mm, $p = 0.8529$). Nearly all (95%) placed electrodes V_1 and V_2 either both correctly or both incorrectly.

More than two-thirds of participants reported acquiring an average of at least five ECGs per month, or more than one per week (Appendix B). Almost one-third reported infrequent practice, fewer than once per week on average. Participants who reported acquiring five or more ECGs per week (V_1-V_4, $p = 0.008$; V_{all}, $p = 0.0009$) and those reporting five or more ECGs per month (V_{all}, $p = 0.027$) performed significantly better than those who reported fewer than five per month (Table 2).

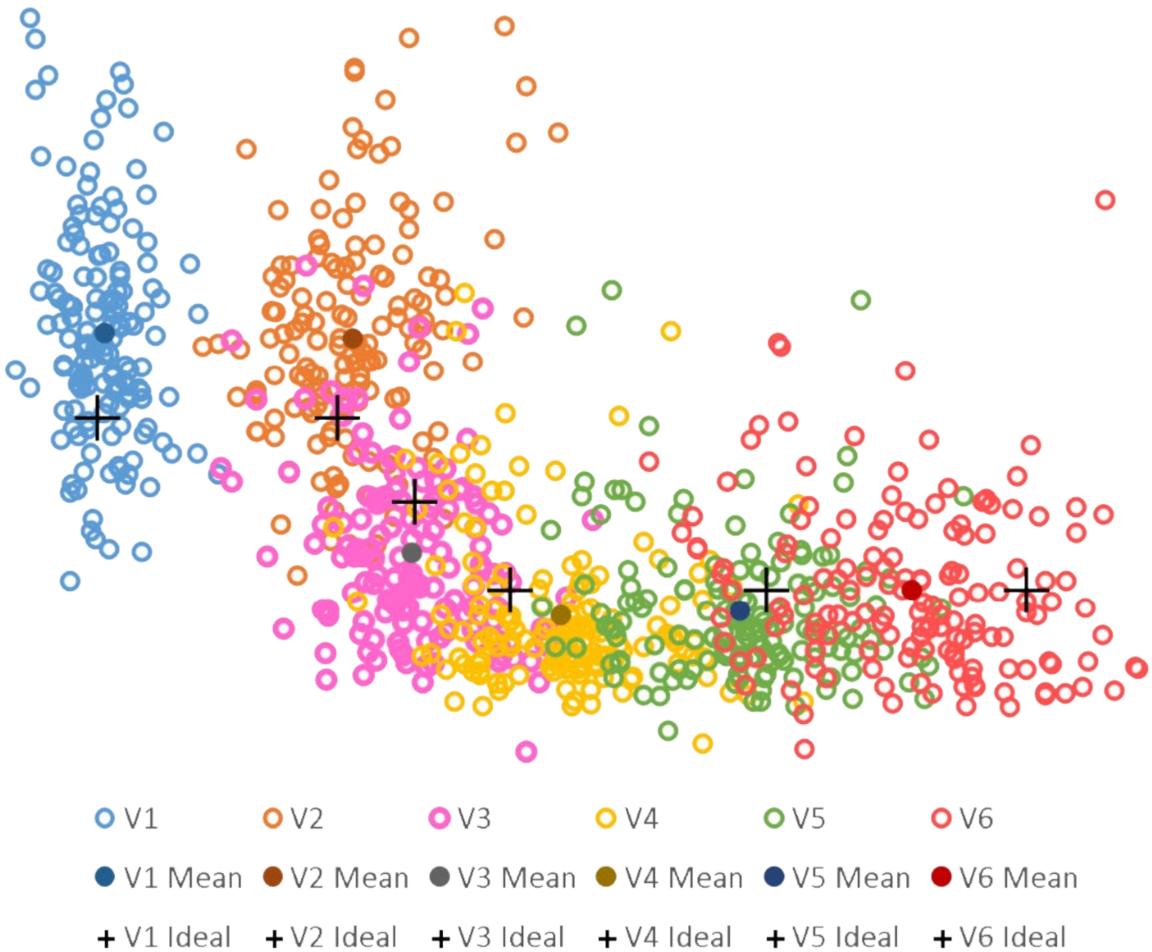

Figure 4. Scatterplot of manikin electrode placements (n = 149). Crosses mark ideal locations of V_1-V_6 (left-right), and solid circles mark the mean electrode placements.

Approximately 40% reported receiving initial ECG training from an academic organization (i.e., university, college, community college, or technical school) (Appendix B). Those participants performed significantly better than individuals trained in hospital (V_1-V_4, p = 0.013) or fire department (V_1-V_4, p = 0.003, V_{all}, p = 0.004) settings. This source of initial training was the most widespread difference we observed, achieving significance on all electrodes and groups but one. Similarly, those who reported classroom-based initial training performed significantly better (V_1-V_4, p = 0.047) than participants who reported on-the-job training (Table 2).

More than 90% of participants reported receiving their most recent refresher training through their workplaces (Appendix B). Differences in source, timing, and format of refresher training were not reflected in participants' electrode placement performance. However, among those who reported having received no refresher training, respondents whose initial training was within the past six months (i.e., too recently to require refresher training) performed significantly better (V_1-V_4, p = 0.002) than those with more experience but no refresher training.

According to our survey, participants who reported being "very confident" of their electrode placement skills performed significantly better than those who were "somewhat confident" (V_1-V_4, p = 0.009). No significant difference in performance appeared between those who did and those who did not report being responsible for training others on ECG technique. However, the self-identified instructors were more confident of their skills than non-instructors (66% vs. 45% indicated "very confident", Mann-Whitney test, p = 0.050) and reported somewhat more frequent practice (45% vs. 29% indicated ≥ 5 ECGs/week, p = 0.080). Instructors and non-instructors claimed approximately equivalent years of experience (both groups, median time since initial training = 5 to 10 years, p = 0.739).

The clavicle (44% of responses) and the nipple line (14%) were the physical landmarks cited most frequently as primary reference points for placing the chest electrodes (Appendix B). The first rib and the sternal notch were each cited by 7%. No significant difference in performance was associated with the choice of landmark.

Acceptability results for the two data collection methods were concordant (i.e., characterized as either "acceptable" or "unacceptable" by both methods) for 60% of the participants who used both methods (n = 67). Cohen's kappa for the two methods was κ = 0.308.

DISCUSSION

Classroom vs. on-the-job training and frequent vs. infrequent practice were associated with significantly smaller errors in electrode placement. The latter finding is consistent with the observation by McManus et al. (2004) that firefighter-paramedics assigned to busier stations performed better on ECG rhythm interpretation; together, they suggest that thresholds may exist below which practice becomes too infrequent to establish or maintain skills. The connection between greater self-confidence in placement skills and smaller placement errors seems to reflect participants' objective self-awareness of skills.

No specialized ECG technicians participated in this study. We would anticipate smaller error rates among specialized personnel for whom acquiring ECGs is a primary focus of their training and work, as found by Rajeganeshan et al. (2008). The fact remains, however, that specialist personnel are not available in all clinical settings — and rarely if ever in the EMS setting — so non-specialists necessarily acquire, and will continue to acquire, an unknown but probably large number of clinical ECGs as part of their overall duties.

Placement Accuracy and Patterns of Electrode Placement Error

The mean aggregate placement error among EMS personnel on the more sensitive leads V_1-V_4 was somewhat smaller than that for clinical personnel in this study. However, the standard deviation in the EMS group was greater, which suggests that while most EMS personnel placed the electrodes slightly more accurately than their clinical counterparts, some placed electrodes farther outside the acceptable range. The difference was not statistically significant (127 mm vs. 144 mm, p = 0.092), indicating that EMS personnel performed approximately equivalently to the clinical personnel we studied. Therefore, concerns that have been expressed here and elsewhere (Aydemir, 2021; Bickerton & Pooler, 2019; Garcia, 2015; García-Niebla et al., 2009; Kligfield et al., 2007; Medani et al., 2018; Rajaganeshan et al., 2008) regarding ECG electrode placement errors by clinical personnel appear to apply equally to the EMS personnel we studied. Gregory et al. (2021)

reached a similar conclusion regarding EMS personnel in the United Kingdom.

The scatterplots (Figures 3 and 4) indicate that mean electrode placements were generally close to acceptable, mostly within approximately one intercostal distance. However, the individual placements varied widely, with many lying far outside their acceptable ranges. Thus, the validity of ECGs acquired using those placements would be questionable.

Wide dispersion of electrode placements around approximately correct means suggested that there were few consistent patterns of directional displacement (i.e., significant individual placement errors in all directions mostly cancelled one another). A conspicuous exception is that V_1 and V_2 tended to be placed approximately one intercostal space (ICS) above their standard locations, which is consistent with previous findings (Aydemir, 2021; Gregory et al., 2021; Kligfield et al., 2007; Medani et al., 2018; Rajaganeshan et al., 2008). Contrary to earlier results, mean placements of electrodes V_3-V_6 in this study were either close to (manikin) or above (diagram) standard locations. In our study, placements of V_1 and V_2 were more dispersed vertically than laterally and were concentrated near the sternum, implying a good understanding of correct placement at the sternal border but less satisfactory identification of the correct (4th) ICS. These electrodes were misplaced equally often by all groups. Participants tended to associate the placement of electrodes V_1 and V_2 closely with one another, locating them either both correctly, or more often both incorrectly, in 95% of cases.

Linear groupings coinciding with ICSs in the diagram data implied a general understanding that certain electrodes are to be placed in ICSs. Most participants (46 of 67, 69% by visual inspection) placed electrodes V_4-V_6 along the 5th (or another) ICS on the diagram, but corresponding placements on the manikin tended to be anatomically horizontal (33 of 149, 22%, followed an ICS). That difference suggests that participants may have been misled by the ICSs on the graphic image, but that in practice they place electrodes more in line with AHA guidelines that V_5 and V_6 be placed in the horizontal plane defined by V_4 (Kligfield et al., 2007).

The absence of linear groupings in the manikin data also could have arisen from difficulty in palpating ribs on the manikin. However, many participants placed V_1, V_2, and V_4 in the wrong ICSs on the diagram where the correct ICSs could readily be located by sight. Figures 3 and 4 show that placements on the diagram are dispersed at least as widely as those on the manikin. Thus, general uncertainty about correct electrode locations apparently played a greater role in the broad dispersion of electrode placements observed in the manikin data than did difficulty identifying specific physical landmarks on the manikin.

Comparison of Data Collection Methods

Clear differences exist in electrode placements between the diagram and manikin data collection methods (Figures 3 and 4). Rajaganeshan et al. (2008) did not report whether they validated their diagram-based data collection method by having a cohort of participants also place electrodes on a live human model as Medani et al. (2018) did for their manikin-based data collection method. In the present study, several participants indicated informally that they were more comfortable working with the manikin than with the diagram because the manikin provided a more realistic and more familiar approximation of real-life practice. Visual inspection found that performance on eight of the 67 diagrams was very erratic, some to the point of being difficult to interpret, yet the manikin placements by seven of the same eight participants were at least close to acceptable.

In characterizing participants' overall performance as either "acceptable" or "unacceptable", the two methods were concordant (i.e., either "acceptable" or "unacceptable" according to both methods) for 60% of the 67 participants who used both methods. Cohen's kappa, $\kappa = 0.308$, indicated fair to minimal agreement between the two methods, depending on one's interpretation of the kappa statistic (McHugh, 2012). Because our manikin data collection method was substantially similar to the method validated by Medani et al. (2018), we regard it as preferable to the diagram method evaluated in this study.

Preferred Physical Reference Landmarks

Responses to the question about the primary reference point for placing chest electrodes were enlightening. They ranged from systematic placement strategies leading to textbook-correct results, to equally methodical approaches leading to incorrect results, to "I know I'm supposed to count ribs, but I usually just eyeball it." Some attributed their use of short-cut methods to time pressures inherent in EMS practice that are less prevalent in clinical settings. A few reported using separate strategies for female vs. male or obese vs. non-obese patients. After having made significant placement errors on the manikin, several used correct terminology (e.g., "4th intercostal space", "mid-clavicular line") and even described the placement process flawlessly. This suggests a disconnect between training and practice as reported by Gianetta et al. (2020) and Aydemir (2021) and underscores the importance of substantive follow-up to initial training.

In our study, the most commonly reported landmark was the clavicle (44% of participants). Only 6% cited the sternal angle (i.e., the angle of Louis) as a reference point for locating V_1 and V_2, as recommended by numerous textbooks and peer-reviewed articles (García-Niebla et al., 2009; Garcia, 2015; Goldberger et al., 2023; Brady et al., 2019; Campbell et al., 2017; Longo et al., 2017; Rautaharju, 2008). We concur with this recommendation, as the sternal angle unambiguously guides the practitioner to the second rib and thus to the second ICS, from which the fourth ICS can readily be located.

Interestingly, we found no significant differences in mean placement errors among participants employing various physical landmarks as their primary reference points, but these results raised one thought-provoking question. Participants referring to the nipple line, generally regarded as an unreliable reference point (e.g., García-Niebla, 2009; Goldberger et al., 2023; Crawford & Doherty, 2010), demonstrated the smallest mean and median placement errors across all electrodes but one and across all electrode groups. Perhaps these participants had developed an intuitive sense of correct electrode placement through long experience (e.g., one articulated this landmark as "where the nipple line ought to be"). However, their median time since initial ECG training equaled that of the overall study sample. This observation lacked statistical significance, but it increased our curiosity regarding strategies for identifying correct electrode locations.

Training Considerations

The diverse placement strategies and outcomes reported here and elsewhere in the literature indicate a need for more uniform initial training and continuing education in ECG technique for both EMS and clinical personnel (Bickerton & Pooler, 2019; Gregory et al., 2021). Wolff et al. (2012) and Rautaharju (2008) found that sources of ECG training, supervision, and quality assurance for non-specialist clinical personnel who acquired ECGs in clinical settings were informal and unclear. Hayden and Barney (2018) wrote that no minimum standard exists for ECG competency for EMS practitioners. EMS curriculum guidelines give considerable curricular autonomy to individual training programs and EMS services (National Highway Traffic Safety Administration, 2021), with responsibility for the content of ECG training borne by the physician medical directors of individual programs and services. Given this study's findings, we agree with Hayden and Barney's proposal that instruction in the mechanics of ECG acquisition and in recognition of a few key ECG findings constitute "an obvious starting point" toward establishing a minimum ECG skills competency standard for EMS practitioners.

Today, the Internet provides easy access to resources of diverse quality and reliability. Bond et al. (2014) evaluated 42 diagrams illustrating ECG electrode placement obtained from online sources. They found that the accuracy and the overall utility of the diagrams were not suitable to guide clinicians in correctly acquiring 12-lead ECGs. In 2017, Walsh et al. reported that expert reviewers judged 13 of 22 chest electrode placement illustrations obtained from online sources to be too inaccurate for instructional use. Furthermore, Hoffman (2007) noted significant electrode placement errors in a diagram printed on an ECG electrode package. These observations highlight the importance of critically assessing potential learning and performance evaluation resources obtained from online sources by ECG instructors and practitioners alike.

Although 41% of participants in the present study reported receiving their initial ECG training through an academic institution, 90% stated fire departments, hospitals, or EMS services provided their most recent refresher training. A similar rate of electrode placement errors by self-identified instructors and non-instructors suggests that incorrect practices are being perpetuated through formal training and informal on-the-job coaching. We agree with the literature that proper ECG practice requires sound initial training and substantive continuing education with frequent reference to and reinforcement of established practice standards. Workplace administrators should ensure that their educators have sufficient time and access to resources to prepare and provide high-quality continuing education. Medani et al. (2018) is an interesting example of a study that not only identified this need but acted to address it with a peer-led education program that demonstrated promising improvements in ECG electrode placement among clinical staff.

LIMITATIONS

Eligible ECG practitioners in our sample were self-selected, which could have introduced unknown bias into the findings. A systematic, stratified sampling technique, though more challenging to achieve, would have provided a more objective cross-sectional assessment. Likewise, sources and formats of training were self-reported, and the terms were not defined on the questionnaire and might not have been understood consistently. Therefore, our findings regarding training should be interpreted with this in mind.

The sample size in this study is a limitation, but it still exceeds those in previous studies (Aydemir, 2021; Gregory et al., 2021; Medani et al., 2018; Rajeganeshan et al., 2008). A larger sample of up to 400 subjects was projected in our initial IRB proposal. However, the COVID-19 pandemic suspended data collection for 16 months. After data collection resumed, some interested EMS services were still unable to participate due to ongoing safety policies that prevented the researcher from visiting their facilities.

The study focused on EMS services in one predominantly rural and small-city geographic area and on clinical personnel in a single hospital organization. We believe that the studied samples are broadly representative of corresponding populations elsewhere. However, scopes of practice (which define the categories of personnel who acquire ECGs) and policies, traditions, and available training resources can be expected to vary among regions and organizations, potentially affecting the applicability of our findings.

The manikin used in this study was not ideal, as indicated when participants were asked, "Did the hands-on electrode placement task allow you to demonstrate accurately where you would have placed the electrodes on a living patient?" (Appendix A). Slightly more than half (58%) responded "yes, completely"; thus, 42% were less than completely satisfied that this approach would accurately reflect their performance. Of those responding other than "yes, completely," 44% commented that the manikin differed significantly from a living patient, and a further 37% reported difficulty locating physical landmarks such as ribs and clavicles on the manikin. We acknowledge that this limitation may account for some of the variation observed in electrode placement. However, we did not find a statistically significant relationship between responses to this question and the accuracy of electrode placement. As noted above, V_1, V_2, and V_4 placements were dispersed at least as widely on the diagram as on the manikin. We believe that difficulty identifying physical landmarks on the manikin was not the primary source of the observed dispersion of electrode placements.

Several participants noted that the manikin did not reflect the variety of body types (e.g., obese patients and female patients) that they encountered in practice, and some commented that their ECG technique varied according to the physical characteristics of the patient. Others took exception to the choice of a default male body type for the study. While physical variability constitutes an acknowledged challenge in maintaining consistency in ECG practice (Bickerton & Pooler, 2019; Harrigan et al., 2012; Kligfield et al., 2007; Macfarlane et al., 2003; McCann et al., 2007; Walsh, 2018), the goal of this study was to assess electrode placement performance on a standardized model. While it is of great practical and clinical impact, addressing the effect of varied body types on the accuracy of ECG electrode placement was beyond the scope of this study and constitutes an important opportunity for further research.

CONCLUSIONS

We observed significant variability in the accuracy of chest electrode placement for 12-lead ECG by EMS personnel, comparable to that observed in previous studies and within this study among clinical personnel. Existing concerns regarding ECG electrode placement by clinical personnel and the subsequent risk of error as patients move along the continuum of care appear to apply equally to EMS personnel.

Initial ECG training from academic organizations vs. workplace-based training was associated with more accurate electrode placement. More frequent practice was also associated with better accuracy, as was greater confidence in the practitioner's own skills. The rate of placement errors among participants identifying as ECG instructors or trainers was comparable to the overall error rate, raising concerns about the quality of instruction they provide. A paper diagram data collection method proved not to be concordant with, and probably less reliable than, a hands-on manikin method for assessing placement skills. Further research is warranted to clarify optimal strategies for locating chest electrodes, especially on diverse body types. Our findings indicate that there is an urgent need for sound initial ECG training and continuing education with careful attention to established practice guidelines.

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APPENDIX A. QUESTIONNAIRE

ECG Electrode Placement Survey

Survey #___________

1. Did the hands-on electrode placement task allow you to demonstrate accurately where you would have placed the electrodes on a living patient?

- ☐ Yes, completely
- ☐ Yes, but only partly (why?_______________)
- ☐ Yes, mostly (why?________________)
- ☐ No (why?_____________________________)

2. What is your most advanced level of training in health care?

- ☐ PA/NP
- ☐ Basic EMT
- ☐ Registered Nurse
- ☐ Medical Assistant/LPN/CNA/ED Technician
- ☐ Paramedic
- ☐ Dedicated ECG Technician
- ☐ Advanced EMT

3. In what capacity do you most often acquire 12-lead EGSs?

- ☐ PA/NP
- ☐ Advanced EMT
- ☐ Registered Nurse
- ☐ Medical Assistant/LPN/CNA/ED Technician
- ☐ Paramedic
- ☐ Dedicated ECG Technician

4. On average, how frequently do you personally acquire 12-lead ECGs?

- ☐ 5 or more per week
- ☐ fewer than 1 per month
- ☐ 5 or more per month
- ☐ fewer than 1 per year
- ☐ fewer than 5 per month

5. In what setting do you most often acquire 12-lead EGSs?

- ☐ hospital (inpatient, emergency department, ambulatory surgery, etc.)
- ☐ clinic or other outpatient medical facility
- ☐ EMS
- ☐ other ________________________________

6. Your ***initial*** 12-lead ECG training ***(mark one in each column)***:

Where:	***When:***	***Format:***
☐ military service	☐ 6 months ago or less	☐ classroom course for academic credit
☐ hospital or other health care institution	☐ more than 6 months ago	☐ classroom training program for certification or licensure, but not for academic credit
☐ university, college, community college, technical school	☐ more than 1 year ago	☐ on-the-job training
☐ fire department	☐ more than 5 years ago	
☐ non-fire department EMS	☐ more than 10 years ago	

7. Your ***most recent*** 12-lead ECG training or review:

☐ none since initial training; OR ***(mark one in each column)***:

Where:

- ☐ military service
- ☐ hospital or other health care institution
- ☐ university, college, community college, technical school
- ☐ fire department
- ☐ non-fire department EMS

When:

- ☐ 6 months ago or less
- ☐ more than 6 months ago
- ☐ more than 1 year ago
- ☐ more than 5 years ago
- ☐ more than 10 years ago

Format:

- ☐ classroom course for academic credit
- ☐ classroom training, not for academic credit
- ☐ skills fair or formal on-the-job review session

8. Are you responsible for instructing or training others in 12-lead ECG technique? ***Mark all that apply.***

- ☐ yes: classroom course for academic credit
- ☐ yes: training program for certification or licensure, but not for academic credit
- ☐ yes: formal on-the-job training
- ☐ no

9. How confident are you that you acquire 12-lead ECGs correctly?

- ☐ very confident
- ☐ somewhat confident
- ☐ not very confident

Thank you for participating

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APPENDIX B. QUESTIONNAIRE RESPONSES

Variables	All		EMS		Clinical	
	n	%	n	%	n	%
Level of Training						
RN	26	17%	2	2%	24	48%
EMT-P	74	50%	74	76%	0	0%
EMT-A	24	16%	22	22%	2	4%
EMT-B	1	1%	0	0%	1	2%
ED Technician	23	15%	0	0%	23	46%
Other (PhD)	1	1%	0	0%	1	2%
Role						
RN	24	16%	1	1%	23	47%
EMT-P	77	52%	77	77%	-	---
EMT-A	22	15%	22	22%	-	---
ED Technician	26	17%	-	---	26	53%
Frequency ECG Practice						
5 / week	50	34%	31	32%	19	37%
< 5 / week	54	36%	43	44%	11	22%
< 5 / month	27	18%	17	17%	10	20%
< 1 / month	11	7%	5	5%	6	12%
< 1 / year	7	5%	2	2%	5	10%
Setting of Practice						
EMS	98	66%	-	---	-	---
Clinical	51	34%	-	---	-	---
Initial ECG Training: Where?						
Military	2	1%	1	2%	1	1%
Hospital or similar	40	27%	3	7%	37	39%
Academic institution	61	41%	7	15%	54	57%
Fire department	21	14%	20	43%	1	1%
Non-fire department EMS	17	11%	15	33%	2	2%
Initial ECG Training: When?						
≤ 6 months ago	11	7%	2	2%	9	19%
6 months – 1 year	6	4%	1	1%	5	10%
1 year – 5 years	38	26%	22	22%	16	33%
5 years – 10 years	27	18%	23	23%	4	8%
≥ 10 years	64	43%	50	51%	14	29%
Initial ECG Training: Format?						
Classroom, academic credit	27	18%	22	24%	5	11%
Classroom, not for credit	62	42%	57	63%	5	11%
On the job training	48	32%	12	13%	36	78%
Latest ECG refresher: Where?						
Military	2	2%	1	1%	1	3%
Hospital or similar	38	32%	7	8%	31	94%
Academic institution	11	9%	11	13%	0	0%
Fire department	57	48%	57	66%	0	0%
Non-fire department EMS	12	10%	11	13%	1	3%

Variables	All		EMS		Clinical	
	n	%	n	%	n	%
Latest ECG refresher: When?						
Too new	12	8%	2	2%	10	20%
Never	13	9%	6	6%	7	14%
≤ 6 months ago	45	30%	34	36%	11	22%
6 months – 1 year	27	18%	19	20%	8	16%
1 year – 5 years	37	25%	25	27%	12	24%
5 years – 10 years	7	5%	5	5%	2	4%
≥ 10 years	4	3%	3	3%	1	2%
Latest ECG refresher: Format?						
Classroom, academic credit	23	15%	18	24%	5	13%
Classroom, not for credit	38	26%	29	39%	9	24%
On the job training	51	34%	27	36%	24	63%
Train others in ECG technique?						
Yes	44	30%	23	23%	21	41%
No	105	70%	75	77%	30	59%
How confident in ECG skills?						
Very confident	76	51%	57	58%	19	38%
Somewhat confident	68	46%	39	40%	29	58%
Not very confident	4	3%	2	2%	2	4%
Reference point for placing chest electrodes						
Sternal notch	7	7%	4	10%	3	7%
Clavicle	47	44%	17	43%	30	70%
Sternal angle	6	6%	3	8%	3	7%
First rib	8	8%	7	18%	1	2%
Nipple line	15	14%	9	23%	6	14%
Other	22	21%	15	38%	7	16%
None	1	1%	1	3%	0	0%

Abbreviations: RN, registered nurse; EMT, Emergency Medical Technician; EMT-P, paramedic; EMT-A, advanced EMT; EMT-B, basic EMT; ED, emergency department.