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Is computer-assisted instruction more effective than other educational methods in achieving ECG competence amongst medical students and residents? A systematic review and meta-analysis

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ABSTRACT

Objectives It remains unclear whether computer-assisted instruction (CAI) is more effective than other teaching methods in acquiring and retaining ECG competence among medical students and residents.

Design This systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines.

Data sources Electronic literature searches of PubMed, databases via EBSCOhost, Scopus, Web of Science, Google Scholar and grey literature were conducted on 28 November 2017. We subsequently reviewed the citation indexes for articles identified by the search.

Eligibility criteria Studies were included if a comparative research design was used to evaluate the efficacy of CAI versus other methods of ECG instruction, as determined by the acquisition and/or retention of ECG competence of medical students and/or residents.

Data extraction and synthesis Two reviewers independently extracted data from all eligible studies and assessed the risk of bias. After duplicates were removed, 559 papers were screened. Thirteen studies met the eligibility criteria. Eight studies reported sufficient data to be included in the meta-analysis.

Results In all studies, CAI was compared with face-to-face ECG instruction. There was a wide range of computer-assisted and face-to-face teaching methods. Overall, the meta-analysis found no significant difference in acquired ECG competence between those who received computer-assisted or face-to-face instruction. However, subanalyses showed that CAI in a blended learning context was better than face-to-face teaching alone, especially if trainees had unlimited access to teaching materials and/or deliberate practice with feedback. There was no conclusive evidence that CAI was better than face-to-face teaching for longer-term retention of ECG competence.

Conclusion CAI was not better than face-to-face ECG teaching. However, this meta-analysis was constrained by significant heterogeneity amongst studies. Nevertheless, the finding that blended learning is more effective than face-to-face ECG teaching is important in the era of increased implementation of e-learning.

PROSPERO registration number CRD42017067054.

Strengths and limitations of this study

- ► To the best of our knowledge, this is the first systematic review and meta-analysis comparing the efficacy of computer-assisted instruction to other methods of ECG instruction among medical students and residents.
- ► Systematic reviews provide robust evidence because they follow a rigorous method of search, selection and appraisal of articles.
- ► We used the Medical Education Research Study Quality Instrument (MERSQI) to assess the quality of studies included in this systematic review.
- ► The interpretation of the meta-analysis results is constrained by significant heterogeneity among the studies.
- ► This systematic review with its meta-analysis and subanalyses identified valuable information about the educational approaches and types of computer-assisted learning material that were beneficial in acquiring ECG competence.

INTRODUCTION

The ECG is an indispensable diagnostic modality in cardiac disease.[1 2] Although knowledge of, and skills in ECG analysis and interpretation, hereafter referred to as ECG competence, are desired learning outcomes of undergraduate and postgraduate medical training programmes, there is ongoing concern that graduating medical trainees lack adequate ECG competence.[3–12] Many reasons account for this observation. First, electrocardiography is a difficult subject to

teach and to learn.[13 14] Second, although clinical exposure is important to gain experience in ECG analysis and interpretation,[15] experiential learning alone does not guarantee ECG competence unless it is supplemented by structured teaching.[16] Third, medical knowledge is ever-expanding,[17] and there is limited time allocated to the teaching of electrocardiography in medical curricula.[18–22] Alternative methods of instruction are therefore being sought to improve ECG training.

Technology-enhanced methods of instruction are increasingly being implemented in the training of healthcare professionals.[23–25] It remains important to review whether these novel teaching and learning methods are effective.[26] Previous studies have shown that students' knowledge of, and skills in the analysis and interpretation of ECGs improve with computer-assisted instruction (CAI).[27–34] However, these studies did not compare CAI to other methods of instruction and thus it cannot be concluded that CAI is better than traditional methods of ECG teaching.

To the best of our knowledge, there is no published systematic review comparing the efficacy of CAI with other methods of ECG instruction for training medical students and residents. Systematic reviews are important in the era of best evidence health professions education,[35] because they follow a rigorous process of searching, selecting and appraising eligible articles.[36 37] Reviewer bias is limited by applying strict criteria when appraising the articles and summarising the strengths and weaknesses of the studies evaluated.[36–38]

Objectives

The objectives of this systematic review were to:

- establish whether CAI (on its own or in a blended learning setting) achieves better acquisition of ECG competence among medical students and residents than other methods of ECG instruction do;
- establish whether CAI (on its own or in a blended learning setting) achieves better retention of ECG competence among medical students and residents than other methods of ECG instruction do;
- establish whether there is a difference in the effectiveness of computer-assisted ECG instruction between medical students and residents enrolled for specialty training;
- identify the types of learning material and/or activities that are used in computer-assisted ECG instruction, and to establish which CAI material and/or activities are associated with better outcomes;
- identify the educational approaches used in computer-assisted ECG instruction, and to establish which of these are associated with better outcomes;
- identify learning theories that may underpin computer-assisted ECG instruction.

METHODS

A protocol was developed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) guidelines[39] and registered with the International Prospective Register of Systematic Reviews (PROSPERO) on 6 July 2017 with registration number CRD42017067054.[40]

Search strategy

By using the search strategy described in the protocol,[40] and shown in online supplementary file 1, we searched for relevant studies on 28 November 2017 using the following electronic databases: PubMed, EBSCOhost (which searched Academic Search Premier, CINAHL, PsycINFO, Education Resources Information Center, Africa-Wide Information, Teacher Reference Center), Scopus, Web of Science and Google Scholar. Citation indexes and reference lists were reviewed, and a grey literature search was also conducted.

Eligibility criteria

As summarised in table 1, all studies that compared the efficacy of CAI with other methods of ECG instruction were eligible for inclusion in this review. Studies were excluded if the teaching methods were not exclusively used to teach ECGs, or if the subject of teaching was not the conventional 12-lead ECG. We included studies in which the participants were medical students and/or residents enrolled for specialty training. Studies were excluded if the data for medical students or residents could not be separately identified from students other than medical students, healthcare professionals who were not medical doctors or qualified doctors who were not in training. We excluded studies that did not assess ECG knowledge and analysis and interpretation skills (ECG competence). There were no language or geographical restrictions. All eligible articles published before 1 July 2017 were included.[40]

Study selection

Two reviewers (CAV and RSM) independently screened all the articles identified by the search. All titles and abstracts were screened for eligibility and full-text articles of all studies potentially meeting inclusion criteria were retrieved. Both reviewers (CAV and RSM) individually evaluated the full text articles using a predesigned form evaluating each study's eligibility. Where there was no consensus, the reviewers (CAV and RSM) discussed uncertainties pertaining to inclusion eligibility and a third reviewer (VCB) acted as an adjudicator.

Data abstraction

Two reviewers (CAV and RSM) independently extracted data from all eligible studies using a standardised electronic data abstraction form hosted on Research Electronic Data Capture (REDCap),[41] which was subsequently crosschecked (CAV and RSM). Data extraction included study design, study duration, study population, ECGs used during teaching, teaching methods (CAI and non-CAI methods), type of digital learning material, educational approaches, learning theories underpinning instructional methods (using a classification proposed

Table 1 Eligibility criteria

Inclusion criteria	Exclusion criteria
Population	
► Medical students; or ► Residents enrolled for specialty training in for example, cardiology, internal medicine, emergency medicine, family medicine, anaesthetics or paediatrics	► Students other than medical students; or ► Healthcare professionals who are not medical doctors
Intervention	
► Online or offline computer-assisted instruction used to teach the analysis and interpretation of ECGs	► Computer-assisted instruction not included as teaching modality in study ► Teaching modalities were not primarily and solely used to teach ECGs ► The subject of teaching was not the conventional 12-lead ECG
Comparator	
► Any comparative ECG teaching method, not making use of computer-assisted instruction	► Absent or inadequately described comparator or control group
Outcome	
Educational intervention's effectiveness: ► Acquisition of ECG competence, or ► Retention of ECG competence, or ► Level of Kirkpatrick outcomes	► There is no objective outcome measured (ie, no testing of ECG competence)
Study	
Any comparative research design: ► Randomised controlled trial, or ► Cohort study, or ► Case-control study, or ► Before-and-after study, or ► Cross-sectional research	Any non-comparative research design: ► Audit, or ► Case-series, or ► Historical narrative, or ► Survey based

by Taylor).[42] ECG competencies measured, testing times and results, as well as the validity and reliability of results with psychometric properties of the assessment tools (eg, Cronbach's α coefficient) where reported.

In the event of missing or unreported data, corresponding authors were contacted. Following two email messages, a delay of 6 weeks was allowed to receive a response.

Quality of included studies and risk of bias assessment

The Medical Education Research Study Quality Instrument (MERSQI) was used to assess the quality of studies included in this systematic review. The MERSQI is a validated quality assessment tool used in health professions education to evaluate the quality of experimental, quasi-experimental and observational studies.[36 43]

As recommended by the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA),[44] two reviewers (CAV and RSM) independently assessed each included study for risk of selection, performance, attrition, detection and/or reporting bias.

Data synthesis

Tests scores (pre-intervention test, post-intervention test and delayed post-intervention test) reported in the studies were used as objective measures of teaching method effectiveness.[34 40 45] Where the mean or SD results were not reported, these were requested from the authors or, in the absence of a reply, calculated using the formula of Wan *et al*.[46] The mean and SD results for the CAI and non-CAI groups in each study were converted to a standardised mean difference (effect size, Cohen's *d*).[47–49] Random-effects models were used to pool weighted effect sizes for all studies, as well as for the planned subanalyses. Planned subanalyses were conducted based on the level of training of participants (students or residents), the different educational approaches reported in the studies (eg, blended learning or not, massed or distributed instruction, restricted or unrestricted access to CAI, online or offline use of CAI), as well as learning materials (eg, real patient ECGs, case scenarios, images, animations) and learning activities (eg, online chat rooms, self-administered quizzes with automated feedback) used with CAI. The consistency in results was determined by visualising the forest plots and calculating the I^2 statistic.[50]Statistical analyses were performed on Stata (V.14.2, StataCorp, College Station, Texas, USA) and Review Manager (RevMan, V.5.3.5, Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014).

We analysed studies for their educational impact using the modified version of the Kirkpatrick framework.[35 51–53]

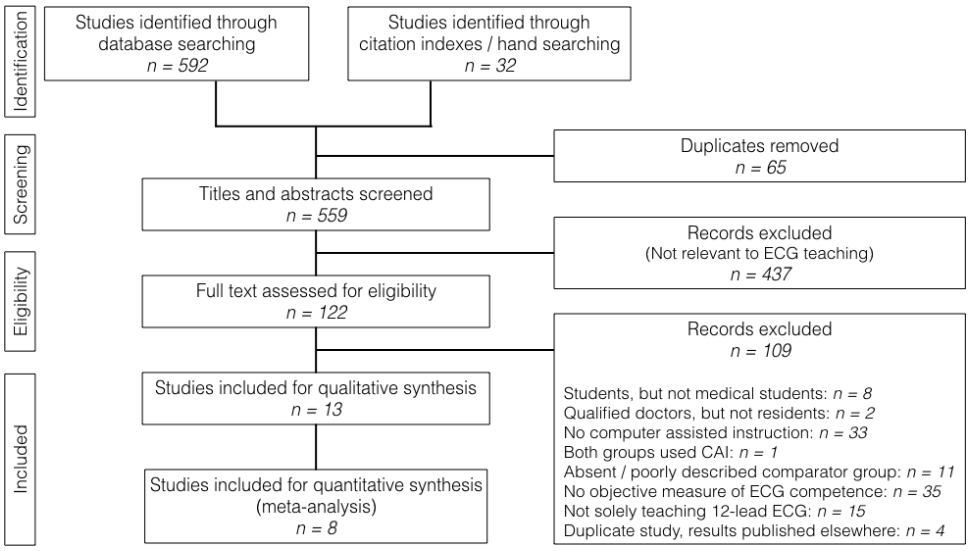

Figure 1 Trial flow. CAI, computer-assisted instruction.

The modified Kirkpatrick model is a widely used method of appraising the outcome of educational interventions by measuring participants' perceptions of (reactions to) the learning experience (level 1), modification of participants' perceptions of the intervention (level 2a), modification of their knowledge and/or skills (level 2b), transfer of learning to the workplace (level 3), change in organisational practice (level 4a) and benefits to patients (level 4b).

Patient and public involvement

There were no patients or public involved in this systematic review and meta-analysis.

RESULTS

Trial flow

Our search strategy identified 592 papers, that is, 129 articles in PubMed, 349 in EBSCOhost, 65 in Scopus and 49 in Web of Science. We identified an additional 32 papers by reviewing the citation indexes and reference lists of the identified articles and grey literature. After 65 duplicate publications were removed, another 437 articles were excluded by screening their titles and abstracts. From the remaining 122 articles that were assessed in full text, thirteen articles met the predefined eligibility criteria for this systematic review. The reasons for exclusion are shown in figure 1. Eight studies contained sufficient data (mean scores, SD and number of participants reported for each cohort) to be included in the meta-analysis.

Study characteristics

Table 2 summarises the characteristics of the nine randomised control trials and four prospective cohort studies that were included in this systematic review. Nine studies were conducted at a single centre, three studies at two centres and one study at more than two centres. Four studies were conducted in the USA,[54–57] three in the UK,[58–60] two in France[61 62] and one each in China,[63] Iran,[64] India[65] and Sweden.[66] All the studies were published in English and included 1242 students and 86 residents in total. Of the thirteen studies, eleven focused on undergraduate students,[54–58 60 61 63–66] one on residents[62] and one on both students and residents.[59]

As shown in online supplementary file 2, the earliest study on the use of computer-assisted ECG instruction was published in 1965,[60] followed by two studies in the mid 80s.[55 56] Most of the studies were published in the last decade,[54 57–59 61–66] the majority of which used online CAI (web-based instruction).[54 58 61–64 66]

Study quality

A detailed summary of the quality of the included studies as measured by the MERSQI tool is contained in online supplementary file 3. The mean MERSQI total score of all included studies was 12.73 (SD 1.76). The studies scored well in the domains that assessed the type of data and data analysis. All studies had objective outcome assessments and twelve of the thirteen studies reported appropriate analyses, which extended beyond descriptive analysis. Studies scored poorly in the sampling domain: more than two-thirds of studies were conducted at a single centre and a third had a response rate of either less than 50% or did not report their response rate.

Risk of bias

As elaborated in table 3, and summarised in online supplementary file 3, there was selection bias and/or performance bias in nine studies. Three studies had attrition bias and one had reporting bias.

Educational approaches

In all studies, CAI was compared with face-to-face teaching (refer to glossary for definitions). However, CAI and face-to-face teaching were delivered in variable formats. CAI formed part of a blended learning strategy in four studies (online supplementary file 4).[54 57 63 66] In one of these studies, blended learning was applied in a

Table 2 Characteristics of included studies in this systematic review

Study characteristic	All		Students		Residents	
	N studies	N participants	N studies	N participants	N studies	N participants
All studies that met eligibility criteria						
All studies included	13	1328	12	1242	2	86
Study design						
Randomised control trial	9	950	8	864	2	86
Prospective cohort study	4	378	4	378	0	0
Face-to-face teaching compared with						
Blended learning (CAI with face-to-face teaching)	4	457	4	457	0	0
CAI alone	9	871	8	785	2	86
Frequency of exposure to teaching method						
Massed instruction	3	267	3	220	1	47
Distributed instruction	9	861	8	822	1	39
Unknown	1	200	1	200	0	0
Computer-assisted instruction						
Online	7	658	6	619	1	39
Offline	5	470	5	423	1	47
Not specified	1	200	1	200	0	0
Learning material as presented by CAI						
Real patient 12-lead ECGs	10	982	9	896	2	86
Case scenarios	4	378	3	339	1	39
Text	8	908	8	861	1	47
Images	2	110	2	110	0	0
Animations	3	253	3	206	1	47
Self-administered assessment with feedback	8	637	7	598	1	39
Chat rooms	2	279	2	279	0	0
Unspecified	2	307	2	307	0	0
ECGs taught						
Basic principles	8	718	7	632	2	86
Normal ECG	5	707	5	660	1	47
Bradyarrhythmias	5	579	4	493	2	86
Tachyarrhythmias	5	579	4	493	2	86

Continued

Table 2 Continued

Study characteristic	All		Students		Residents	
	N studies	N participants	N studies	N participants	N studies	N participants
Arrhythmias (unspecified)	2	288	2	288	0	0
Chamber enlargement	5	637	5	590	1	47
Acute coronary syndromes	7	867	6	781	2	86
Pericarditis	3	288	3	288	0	0
Metabolic abnormalities	7	867	6	781	2	86
Drug effects	2	264	2	264	0	0
Not specified	4	362	4	362	0	0
Testing ECG knowledge and/or competence						
Pre-test*	6	718	5	679	1	39
Post-test†	13	1328	12	1242	2	86
Delayed post-test‡	1	168	1	121	1	47
Method of testing						
Multiple choice questions	5	544	4	458	2	86
Short answer questions	5	639	5	639	0	0
Not specified	3	310	3	310	0	0
The modified Kirkpatrick's framework for the evaluation of educational interventions						
Level 1§	8	864	8	817	1	47
Level 2a¶	3	398	3	351	1	47
Level 2b**	13	1328	12	1242	2	86

*Assessment of the baseline ECG knowledge and/or competence before the educational intervention has taken place;
†Assessment of the acquisition of ECG knowledge and/or competence after the educational intervention has taken place;
‡Assessment of the retention of ECG knowledge and/or competence by means of a repeat assessment after the educational intervention, without any further instruction since the acquisition of knowledge was assessed;
§Level 1: Participants reactions;
¶Level 2a: Changes in attitudes and perceptions;
**Level 2b: Acquisition of knowledge and skills
CAI, computer-assisted instruction; N, number.

Table 3 Summary of the study design, assessment of knowledge and outcomes of the included studies

Author (country) *Journal* Year	Study design, participants, response rate	Prior ECG exposure / training	Assessment of ECG knowledge: CAI ▶ Score of assessment(s) ▶ When assessment(s) took place	Assessment of ECG knowledge: Comparator method ▶ Score of assessment(s) ▶ When assessment(s) took place, not assessed	Quality assessment ▶ MERSQI score ▶ Risk of bias ▶ Validity and reliability where reported by authors	Outcomes ▶ Findings summarised ▶ Kirkpatrick's framework for evaluation of educational intervention
Barthelemy *et al* [62] (France) *Eur J Emerg Med* 2017	Randomised control trial on **residents** rotating in the emergency department of four university hospitals randomised to either ▶ four months access to an *'e-learning course'* (19 residents), or ▶ two *'lectures'* of 180 min each (20 residents) 100% response rate	Not reported	Pre-test (baseline knowledge) **Median 42.1% (IQR 34.8–49.4)** Assessed before CAI Post-test (acquisition of knowledge) **Median 59.5% (IQR 51.8–67.1)** Assessed four months after baseline test, two weeks after last CAI Delayed post-test (retention of knowledge) Not assessed	**Median 37.5% (IQR 30.7–44.2)** (p=0.42 compared with CAI) Assessed before lectures **Median 51% (IQR 42.4–59.6)** (p=0.12 compared with CAI) Assessed four months after baseline test, three months after last lecture Not assessed	MERSQI score 15.5 Risk of bias: comparison group had last lecture three months prior to acquisition of knowledge test, whereas CAI group had access to e-learning up to two weeks prior to acquisition of knowledge test	Significant improvement from pre-test to post-test in both groups. However, no statistically significant difference between CAI and lectures. Benefits of e-learning are that it allows for practice with feedback and asynchronous learning. Kirkpatrick ▶ Level 2b
Rui *et al* [63] (China) *BMC Med Educ* 2017	Randomised control trial with 181 junior **medical students** from a single centre. Randomised to either ▶ *'Flipped classroom method'* (prior to lecture students watched online video, read a textbook and PowerPoint courseware, and completed a pre-assignment) exposure time of 42.33±22.19 min before lectures, three lectures of 135 min and 56.5±46.8 min after lectures (90 students) ▶ *'Lecture-based learning'*, with exposure time of 30.55±10.15 min before lectures, three lectures of 125 min and 54.62±31.77 min after lectures (91 students) 100% response rate	None	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 87.2% (SD 10.1)** Assessed 1 week after last instruction Delayed post-test (retention of knowledge) Not assessed	Not assessed **Mean 80.3% (SD 10.1)** (p<0.001 compared with flipped classroom) Assessed 1 week after last instruction Not assessed	MERSQI score 14.5 Though no pre-test was done, groups were similar with regards to scores in core course grade point averages. It needs to be pointed out that it may be the method of flipped classroom that is more effective, not necessarily the CAI itself. However, the flipped classroom method does use an online platform for study material prior to lectures.	Flipped classroom (including online learning) was more effective than lecture-based learning alone. However, the flipped classroom method requires more time for preparation for both lecturer and student. Kirkpatrick ▶ Level 1 ▶ Level 2b
Chudgar *et al* [54] (USA) *J Electrocardiol* 2016	Prospective cohort study with second year **medical students** from a single centre during their internal medicine clerkship. ▶ The group exposed to CAI had access to an online *'ECG teaching module'* (ECGTM) for full academic year (101 students) ▶ The comparator group only attended face-to-face teaching that forms part of medical clerkship (90 students) 83% response rate in CAI group, response rate in comparator group not reported.	All students attended an interactive *'workshop'* on how to perform and interpret an ECG and *'didactic lecture'* with ECGs and clinical scenarios a week prior to the clerkship.	Pre-test (baseline knowledge) **Median 57.5% (IQR 40–60)** Assessed at start of clerkship Post-test (acquisition of knowledge) **Median 70% (IQR 60–80)** Assessed at end of clerkship Delayed post-test (retention of knowledge) **Median 92% (IQR 80–96)** Assessed at end of academic year	Not reported Not reported **Median 76% (IQR 68–84)** (p<0.001 compared with CAI) Assessed at end of academic year	MERSQI score 11.5 There was continued use of the CAI after the clerkship, which could have impacted on the end of year results. Also, the summative assessment at the end of the academic year might have had an impact on end of year results being better than post-clerkship results.	CAI group performed significantly better in end of year test, as compared with comparator group. CAI demonstrated a significant improvement from the start to the end of clerkship (p<0.001). However, no comparison with control group for these measurements. Kirkpatrick ▶ Level 1 ▶ Level 2a ▶ Level 2b

Continued

Table 3 Continued

Author (country) *Journal* Year	Study design, participants, response rate	Prior ECG exposure / training	Assessment of ECG knowledge: CAI ▶ Score of assessment(s) ▶ When assessment(s) took place	Assessment of ECG knowledge: Comparator method ▶ Score of assessment(s) ▶ When assessment(s) took place, not assessed	Quality assessment ▶ MERSQI score ▶ Risk of bias ▶ Validity and reliability where reported by authors	Outcomes ▶ Findings summarised ▶ Kirkpatrick's framework for evaluation of educational intervention
Davies *et al*[58] (UK) *Clin Teach* 2016	Randomised control trial with second year **medical students** from one centre. Randomised to either ▶ '*E-learning module*', exposure time not reported (18 students), or ▶ '*Near-peer teaching*', two immediately consecutive 30 min *'face-to-face tutorials'* (21 students) Of the 55 medical students invited, 39 consented to take part in study. 100% response rate of consented students.	Not reported	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 74% (SD 11.6)** Assessed 2 hours after e-learning Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 84% (SD 6.6)** (p=0.002 compared with CAI) Assessed 2 hours after near-peer teaching Delayed post-test (retention of knowledge) Not assessed	MERSQI score 15.5 Risk of selection bias (ECG knowledge not assessed at study entry to determine whether to groups had similar baseline knowledge) Assessment was based on curriculum, and was compared with previous examinations for validity and reliability.	Both e-learning and near-pear teaching effective, but near-pear teaching reported as more effective. However, since no pre-test was done to prove that groups were equal, it cannot be concluded that near-pear teaching is superior. Kirkpatrick ▶ Level 1 ▶ Level 2a ▶ Level 2b
Fent *et al*[59] (UK) *J Electrocardiol* 2016	Randomised control trial with third, fourth and fifth year **medical students**, as well as first year **residents** from two centres. Randomised to either ▶ 45 min CAI, *'ECG simulator teaching'* (67 students, 18 residents), ▶ 45 min *'tutorial'* in *'small group teaching'* format (54 students, 29 residents) 100% response rate for acquisition of knowledge test, but only 14% response rate for retention of knowledge test	Students had no formal ECG training in the same academic year of study; residents had variable prior ECG experience.	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 66.2% (SD 17.3)** Assessed on same day as CAI Delayed post-test (retention of knowledge) **Mean 53.0% (SD 17.7)** Assessed 3 months later	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 70.7% (SD 18.8)** (p=0.12 compared with CAI) Assessed on same day as small group teaching Delayed post-test (retention of knowledge) **Mean 57.9% (SD 21.5)** (p=0.55 compared with CAI) Assessed 3 months later	MERSQI score 13, up to acquisition of knowledge test (but 12 if considering drop-out rate for retention of knowledge test) Ratio of student to resident not the same in the two groups; more residents in the comparator group. Retention of knowledge test only written by 14% of participants.	No difference between CAI and small group teaching for acquisition or retention of ECG competence. However, the ratio of students to residents was not the same for the two groups. Only 14% of participants completed the retention of knowledge assessment. Kirkpatrick ▶ Level 1 ▶ Level 2a ▶ Level 2b
Montassier *et al*[61] (France) *Eur J Emerg Med* 2016	Prospective, randomised, controlled, non-inferiority study, with fifth year **medical students** from one centre. Randomised to either ▶ 6 weeks access to *'e-learning course'*, median 180 min (49 students), or ▶ Single *'lecture'* of 180 min (49 students) Response rate not reported.	Students attended ECG lectures in their second and fourth year of study	Pre-test (baseline knowledge) **Median 45% (IQR 30–60)** Assessed at start of study Post-test (acquisition of knowledge) **Mean 76% (SD not reported)** Assessed 2 weeks after last CAI exposure Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) **Median 45% (IQR 30–60)** (p=0.9 compared with CAI) Assessed at start of study Post-test (acquisition of knowledge) **Mean 75% (SD not reported)** Assessed 2 weeks after last CAI exposure Delayed post-test (retention of knowledge) Not assessed	MERSQI score 13.5 Though response rate not reported, groups were equal in size. CAI group had access to e-learning up to two weeks before assessment, whereas lecture group had single lecture three weeks prior to assessment.	Web-based learning non-inferior to lectures. Kirkpatrick ▶ Level 1 ▶ Level 2b

Continued

Table 3 Continued

Author (country) *Journal* Year	Study design, participants, response rate	Prior ECG exposure / training	Assessment of ECG knowledge: CAI ▶ Score of assessment(s) ▶ When assessment(s) took place	Assessment of ECG knowledge: Comparator method ▶ Score of assessment(s) ▶ When assessment(s) took place, not assessed	Quality assessment ▶ MERSQI score ▶ Risk of bias ▶ Validity and reliability where reported by authors	Outcomes ▶ Findings summarised ▶ Kirkpatrick's framework for evaluation of educational intervention
Sonali *et al*[65] (India) *Res J Pharm Biol Chem Sci* 2014	Randomised control trial with second year **medical students** from a single centre. Randomised to either ▶ *'computer-assisted learning'* (100 students) ▶ *'traditional blackboard teaching'* (100 students) Response rate not reported	Not reported	Pre-test (baseline knowledge) **Mean 41.44% (SD 10.9)** Not reported when assessed Post-test (acquisition of knowledge) **Mean 70.81% (SD 13.95)** Not reported when assessed Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) **Mean 35.91% (SD 13.95)** Not reported when assessed Post-test (acquisition of knowledge) **Mean 62.15% (SD 14.75)** Not reported when assessed Delayed post-test (retention of knowledge) Not assessed	MERSQI score 11.5 Exposure times, learning material, topics and response rate not reported.	Both CAI and lecture are effective ways of teaching. In this study, CAI was more effective than blackboard teaching. Kirkpatrick ▶ Level 2b
Akbarzadeh *et al*[64] (Iran) *Research & Development in Medical Education* 2012	Prospective cohort study with **medical students**, at a single centre. Exposed to either ▶ 1 hour *'web-based multimedia education'* (30 students, of which 15 were junior and 15 were senior), or ▶ 1 hour *'classroom-based learning'* (30 students, of which 15 were junior and 15 were senior) Response rate not reported.	Not reported	Pre-test (baseline knowledge) **Mean 18% (SD not reported) in junior students** **Mean 25% (SD not reported) in senior students** Not reported when assessed Post-test (acquisition of knowledge) **Mean 72% (SD not reported) overall** Assessed on same day as CAI Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) Not reported Post-test (acquisition of knowledge) **Mean 71% (SD not reported) overall** Assessed on same day as lectures Delayed post-test (retention of knowledge) Not assessed	MERSQI score 9.5 Baseline knowledge not reported for comparator group. Acquisition of knowledge test on same day as tuition.	Web-based learning as effective as small group teaching. Kirkpatrick ▶ Level 1 ▶ Level 2b
Nilsson *et al*[66] (Sweden) *BMC Med Educ* 2008	Prospective cohort study with **medical students** from the sixth semester from two centres. Participants were exposed to either ▶ 5 months' access to *'web-based programme'* (20 students) ▶ 3.5 days of *'conventional teaching'* during the physiology course, which included ECG training (30 students) 85% response rate in CAI group and 83% in the comparator group.	All participants had a 15 hours ECG course in semester prior to study	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 60.63% (SD 13.69)** Assessed at the end of the semester Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 50.63% (SD 15.44)** (p=0.03 compared with CAI) Assessed at the end of the semester Delayed post-test (retention of knowledge) Not assessed	MERSQI score 12 Risk of selection bias (no baseline knowledge test to compare groups). Risk of performance bias (not specified whether CAI and face-to-face teaching groups were taught same curriculum).	CAI in combination of lecture is better than lectures alone. Students had positive attitude towards web-based learning. Kirkpatrick ▶ Level 1 ▶ Level 2b

Continued

Table 3 Continued

Author (country) *Journal* Year	Study design, participants, response rate	Prior ECG exposure / training	Assessment of ECG knowledge: CAI ▶ Score of assessment(s) ▶ When assessment(s) took place	Assessment of ECG knowledge: Comparator method ▶ Score of assessment(s) ▶ When assessment(s) took place, not assessed	Quality assessment ▶ MERSQI score ▶ Risk of bias ▶ Validity and reliability where reported by authors	Outcomes ▶ Findings summarised ▶ Kirkpatrick's framework for evaluation of educational intervention
Patuwo *et al*[57] (USA) *Comput Cardiol* 2007	Randomised control trial with 35 **medical students** from one centre during a summer medical education programme. All participants received 30 min *'oral instruction'* prior to be randomised to either ▶ 15 min using ECGSIM software, or ▶ No further instruction The number of participants in each group and response rate are not reported.	No prior ECG training	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 19.4% (SD 4.2)** Assessed on same day as CAI Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 6.4% (SD 3.6)** (p=0.002 compared with CAI) Assessed on same day as teaching Delayed post-test (retention of knowledge) Not assessed	MERSQI 11.5 The study only assessed participants' ability to calculate the QRS axis. Reporting bias (number of participants not reported). Risk of selection bias (no pre-test or other measure to compare the two groups prior to exposure to intervention).	Blended learning superior to lecture alone. However, exposure to CAI was only 15 min. Kirkpatrick ▶ Level 2b
Fincher *et al*[56] (USA) *South Med J* 1988	Randomised control trial with junior **medical students** from one centre during their Internal Medicine Clerkship. Randomised to either ▶ *'computer-assisted learning'* with workbook, exposure time not reported (42 students) ▶ 6-weekly 1 hour *'seminars'*, without workbook (41 students) 55% response rate for CAI group, 80% response rate for small group teaching group	Not reported	Pre-test (baseline knowledge) **Mean 8.5% (SD not reported)** Assessed at start of study Post-test (acquisition of knowledge) **Mean 65.8% (SD not reported)** Assessed at end of 6 week rotation Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) **Mean 4.8% (SD not reported)** (P value reported as NS compared with CAI group) Assessed at start of study Post-test (acquisition of knowledge) **Mean 49.1% (SD not reported)** (p<0.05 as compared with CAI group) Assessed at end of 6 week rotation Delayed post-test (retention of knowledge) Not assessed	MERSQI score 14 Higher dropout rate in CAI group could imply that more dedicated student remained in study, which could affect results. Validity of tests were verified. Reliability of second test reported as 0.84.	CAI had better results than tutorials, however, risk of attrition bias must be considered. Better attendance of lectures than CAI (students might feel obliged to attend lectures, whereas less so when doing CAI on their own). Kirkpatrick ▶ Level 2b
Fincher *et al*[55] (USA) *J Med Educ* 1987	Randomised control trial with third year **medical students** from one centre during their Internal Medicine Clerkship. Randomised to either ▶ Having access to an *'interactive computer programme'*, exposure time not reported (55 students) ▶ 6 weekly 1 hour *'seminars'* (52 students) 67% response rate for CAI group, 65% response rate for small group teaching group	Not reported	Pre-test (baseline knowledge) **Mean 17.6% (SD not reported)** Assessed at start of study Post-test (acquisition of knowledge) **Mean 46.1% (SD not reported)** Assessed at end of 6 week rotation Delayed post-test (retention of knowledge) Not assessed	Pre-test (baseline knowledge) **Mean 14.2% (SD not reported)** (P value not reported) Assessed at start of study Post-test (acquisition of knowledge) **Mean 39.2% (SD not reported)** (p=0.79 compared with CAI group) Assessed at end of 6 week rotation Delayed post-test (retention of knowledge) Not assessed	MERSQI score 12.5 Risk of performance bias (most of the students did not complete the CAI modules).	Seminars are not more effective than CAI, however most of the students did not complete the CAI modules. Kirkpatrick ▶ Level 2b

Continued

Table 3 Continued

Author (country) *Journal* Year	Study design, participants, response rate	Prior ECG exposure / training	Assessment of ECG knowledge: CAI ▶ Score of assessment(s) ▶ When assessment(s) took place	Assessment of ECG knowledge: Comparator method ▶ Score of assessment(s) ▶ When assessment(s) took place, not assessed	Quality assessment ▶ MERSQI score ▶ Risk of bias ▶ Validity and reliability where reported by authors	Outcomes ▶ Findings summarised ▶ Kirkpatrick's framework for evaluation of educational intervention
Owen *et al* [60] (UK) *Postgrad Med J* 1965	Prospective cohort study with fifth year **medical students** from a single centre Randomised to either ▶ CAI, with *'Grundytutor teaching machine'* at medical school), mean exposure time of 14.3 hours (SD 5.82), (36 students) ▶ *'Lectures'*, total lecture time 11.7 hours, (41 students) 100% response rate	The authors report that none of participants had much ECG training prior to study	Pre-test (baseline knowledge) Not assessed Post-test (acquisition of knowledge) **Mean 86% (SD 19.1)** 1 week after completing course Delayed post-test (retention of knowledge) Not assessed	 Not assessed **Mean 84.2% (SD 23.3)** 1 week after completing course Not assessed	MERSQI score 12 Although no pre-test, students in both groups had equal graded performance assessments The exact topics that were taught were not reported, but it was said to be the same in both groups. Tests were validated by qualified doctors.	Overall CAI was as effective as lectures However, subgroup analyses favoured CAI over lectures in academically weaker students and foreign students (who were not necessarily native English speakers). Kirkpatrick ▶ Level 1 ▶ Level 2b

CAI, computer-assisted instruction; MERSQI, Medical Education Research Study Quality Instrument.

'flipped classroom' approach, where CAI took place before classroom teaching.[63] Face-to-face teaching was facilitated by experienced lecturers or specialists in all the studies,[54–57 59–66] with the exception of one study in which near-peer teaching was used.[58]

The frequency of instruction in the studies was variable. In three of the thirteen studies, participants were exposed to a single learning event (massed instruction), whether assigned to CAI or face-to-face teaching, before ECG competence was assessed.[58 59 64]

Learning materials and activities

A range of learning materials were used in CAI (table 2). In most studies, the digital learning material consisted of ECG tracings with accompanying text. In addition, in some studies CAI also included the use of multimedia in the form of diagrams and images[64] or animations.[57 59 66] As summarised in table 2, the curricular content varied across the studies and a wide range of ECG diagnoses were included.

Active learning (during which learners deliberately engaged with learning material)[67] formed an integral part of CAI, which used 'interactive software' in all the studies included in this review. In addition to engaging with the learning material, some studies also reported on the use of self-administered assessments with automated feedback,[54 56 58 60–62 64 66] online chat rooms[61 63] and interaction with lecturers and peers during 'flipped classroom' activities.[63] Six of the thirteen studies reported interaction between students and lecturers in the non-CAI group, for example, lecturers quizzed students or students asked questions during the face-to-face teaching activities (online supplementary file 5).[54 58 59 61 62 64] In the study where CAI was compared with near-peer face-to-face teaching, there was a strong emphasis on interaction between students and tutors in the face-to-face teaching group.[58]

Educational outcomes

The outcomes of the studies are summarised in table 3. Baseline ECG competence was assessed in six of the thirteen studies.[54–56 61 62 65] All studies tested ECG competence acquired after the educational intervention; only one study assessed the retention of ECG competence after a period of three months without further instruction since the acquisition of knowledge was tested.[59] Five studies used multiple choice questions to assess study participants' knowledge,[58 59 61 62 65] whereas another five used short answer questions marked by the course convenors.[54–56 60 63] Three studies did not report how ECG competence was assessed.

Using the Kirkpatrick model of evaluation of educational interventions, it was found that eight studies reported participants' reactions to CAI (Kirkpatrick level 1)[54 58–61 63 64 66] and three studies reported a change in trainees' attitudes and perceptions after exposure to CAI (Kirkpatrick level 2a).[54 58 59] All the studies reported on the acquisition and/or retention of ECG competence

(Kirkpatrick level 2b) since this was one of the eligibility criteria of this systematic review. None of the studies reported on outcomes at Kirkpatrick level 3 or 4.

Kirkpatrick level 1 and 2a outcomes were variable. Though some studies reported that students had a positive attitude towards web-based learning,[54 60 63 64 66] others reported less favourable attitudes towards CAI than lectures.[58 59 61] In one study, all the potential participants did not want to use the e-learning platform and so some potential participants were excluded from the particular study.[66] While three studies reported on students who felt that an improvement in their confidence was no better with CAI as compared with lectures,[58 59 61] other studies identified students who thought that CAI improved their confidence in ECG interpretation.[54 58 66] In general, students valued CAI approaches that included multimedia learning material,[59 64] and self-assessment tools.[66] In some studies they requested more visually-oriented learning material[59 64] and applications that had a facility or method for asking questions.[59] Kirkpatrick level 2b outcomes of the studies are summarised in table 3 and have already been described .

Learning theories

Learning theories that underpin education were infrequently mentioned or discussed in any detail. The most frequent reference to learning theories was to self-directed learning in CAI.[54 59 62 63 66] One study[66] referenced Kolb's description of experiential learning,[68] and another study mentioned 'cognitive learning' and 'collaborative learning'.[63] However, careful review of the papers included in this systematic review identified multiple examples of teaching and learning activities that were aligned with contemporary theories of learning. These are shown in table 4 using a simplified classification of learning theories described by Taylor.[42]

Quantitative data synthesis

Overall, we found that CAI was not better than face-to-face teaching for acquiring ECG competence (standardised mean difference (SMD)=0.32 (95% CI −0.09 to 0.74); eight studies, n=945; I^2=88.9%) (figure 2). However, there was inconsistency among the studies and effect sizes ranged from −1.08 to 1.09 (table 5). A positive effect size (ie, CAI was better than face-to-face teaching) was found in most studies, one of which showed a large effect size (>0.8)[54] and four a moderate effect size (>0.5).[62 63 65 66] However, in two studies[59 60] there was no significant difference between CAI and face-to-face teaching and one study showed that face-to-face teaching was better than CAI.[58]

Only one study assessed the effect of CAI on the retention of ECG competence.[59] While this study showed that there was no significant difference between the CAI and face-to-face teaching (SMD=−0.24 (95% CI −1.05 to 0.58)), the response rate was only 14% for the retention of knowledge test which was conducted three months after the educational intervention.

Medical students compared to residents

In the subanalysis comparing the acquisition of ECG competence with CAI and face-to-face teaching in undergraduate and postgraduate trainees separately (figure 3), there was a tendency to favour CAI over face-to-face teaching among both medical students (SMD=0.41 (95% CI −0.03 to 0.84); six studies, n=738; I^2=87%) and residents (SMD=0.64 (95% CI 0 to 1.28); one study, n=19). The single study assessed the retention of ECG competence combined medical students and residents.[59]

Educational approaches

A subanalysis found a large positive effect size when CAI formed part of a blended learning strategy as compared with face-to-face teaching (SMD=0.84 (95% CI 0.54 to 1.14); three studies, n=422; I^2=50%) (figure 3). This systematic review did not identify any studies that evaluated the retention of ECG analysis and interpretation skills after exposure to CAI in a blended learning programme.

In another subanalysis, studies using a distributed approach to ECG instruction (ie, more than one ECG training opportunity) showed that CAI was better than face-to-face teaching (SMD=0.65 (95% CI 0.31 to 1.00); five studies, n=538; I^2=70%). Review of these studies showed that the benefit of distributed instruction was only present in studies where CAI was part of a blended learning approach (SMD=0.84 (95% CI 0.54 to 1.14); three studies, n=422; I^2=50%; vs SMD=0.31 (95% CI −0.21 to 0.84); two studies, n=116; I^2=46%). There was no statistically significant difference between CAI and face-to-face teaching when massed instruction strategies were used (ie, a single session of ECG teaching) (figure 3).

Although there was no difference between online and offline CAI, four studies showed that CAI was better than face-to-face teaching when students had unlimited access (ie, 24 hours a day, 7 days a week) to CAI learning materials (SMD=0.82 (95% CI 0.57 to 1.07); four studies, n=461; I^2=32%). This benefit, as shown in a subanalysis, was not apparent when access to CAI learning materials was limited (SMD=−0.34 (95% CI −0.86 to 0.18); three studies, n=284; I^2=74%).

In the study that used reminder emails to encourage the use of CAI, there was a large effect size in favour of CAI (1.09 (95% CI 0.79 to 1.4)).[54]

Learning activities and materials used in CAI

Subanalyses showed that CAI was better than face-to-face teaching when ECGs were accompanied by case scenarios (SMD=0.90 (95% CI 0.59 to 1.21); three studies, n=280; I^2=24%) and if images were used to explain impulse conduction (SMD=1.09 (95% CI 0.79 to 1.40); one study, n=191). Studies in which CAI included self-administered assessments with automated feedback showed better ECG knowledge acquisition than face-to-face teaching (SMD=0.64 (95% CI 0.14 to 1.13); four studies, n=357; I^2=77%) (figure 3). This effect size was larger in studies where self-administered assessment with automated feedback formed part of a blended learning approach

Table 4 Learning theories, based on a classification by Taylor[42] that underpinned computer-assisted and face-to-face ECG instruction in the included studies

Learning theories	Examples of instructional methods demonstrating the application of contemporary learning theories	
	CAI	**Face-to-face teaching**
Instrumental learning theories		
► **Cognitivism** (ie, *acquiring knowledge*, learning with demonstrations and explanations, understanding concepts)[42 96 106]	► Used multimedia, including animations, audio and video clips used to demonstrate and explain difficult concepts.[59 64 66]	► Face-to-face teaching allowed for demonstrations and explanations.[65]
► **Constructivism*** (ie, *creating meaning* by building personal interpretations of the world based on individual experiences and interactions)	► Application of knowledge to interpret an ECG and make a diagnosis. ► Used a flipped classroom method that allowed for studying material by means of CAI before applying new knowledge in classroom teaching activities.[63]	► Application of knowledge to interpret an ECG and make a diagnosis.
Humanistic learning theories		
► **Andragogy** (ie, adult learning driven by internal and external motivation)[107 108]	► Used a summative assessment after learning intervention (external motivation).[54] ► Used reminder e-mails used to encourage use of e-learning modules (external motivation).[54]	► Used a summative assessment after learning intervention (external motivation).[54]
► **Self-directed learning** (ie, independent, self-regulated learning, learner plans and monitors own learning)[109 110]	► Facilitated independent study.[55] ► Provided unlimited access; studying can occur at any place at any time[54 58 59 62 64] ► Allowed for repetition and revision of learning material, at student's own pace.[54 60 64 65]	► Note-taking in lectures and self-study of notes afterwards.[59]
Social learning theories		
► **Collaborative learning** (ie, interaction with peers and tutors)[111 112]	► Chat rooms allowed for interaction with the lecturer and/or other participants.[61 63] ► Blended learning strategies allowed for interaction with lecturer during face-to-face teaching sessions in addition to CAI.[54 57 63 66]	► Responding directly to learners' questions during lecture or tutorial.[55 58 59 61 62]
► **Contextual learning** (ie, case scenarios, multiple examples with different perspectives)[113 114]	► Provided case scenarios, making learning relevant and placing the learning in context.[54 61 62 66] ► Provided different examples of same diagnosis.[54]	► Provided case scenarios, made learning relevant and placed the learning in context.[54 61 62 66] ► Provided different examples of same diagnosis.[54]
Reflective models		
► **Reflection** (ie, deliberate practice with feedback)	► Self-administered quizzes with feedback (self-evaluation) help to enhance learning by highlighting areas that the student needs to focus on.[54 61 62 66]	

*Constructivism is considered a branch of cognitive learning, but is distinguished by a focus on actively creating meaning rather than merely acquiring knowledge.[96]
CAI, computer-assisted instruction.

(SMD=0.95 (95% CI 0.57 to 1.34); two studies, n=241; I^2=38%). CAI was better than face-to-face teaching when students had access to online chat rooms to discuss the study material (SMD=0.68 (95% CI 0.38 to 0.98); one study, n=181) (figure 3).

DISCUSSION

This systematic review and meta-analysis set out to determine whether CAI is more effective than other methods of teaching electrocardiography knowledge and analysis and interpretation skills to undergraduate and postgraduate medical trainees. All the studies included in this systematic review and meta-analysis compared CAI to face-to-face teaching. Based on the overall results of the review there is currently insufficient evidence to favour CAI over face-to-face ECG instruction. Though there was significant heterogeneity in the studies included in the meta-analysis, subanalyses of the different learning materials and educational approaches were less heterogenous. We found that CAI was better than face-to-face teaching when used in a blended learning approach. Studies also favoured computer-assisted distributed instruction with unrestricted access to learning materials; the use of case scenarios to contextualise ECG interpretation with images to explain concepts and interactive learning activities, including chat rooms, and self-assessment with automated

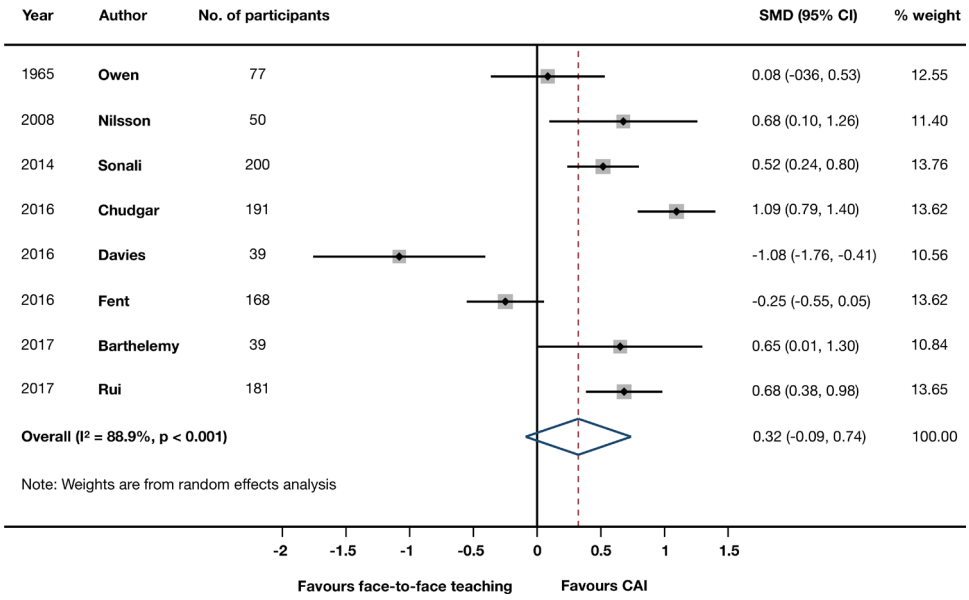

Figure 2 Overall effect of teaching methods on the acquisition of ECG knowledge and analysis and interpretation skills. CAI, computer-assisted instruction; SMD, standardised mean difference.

feedback. While contemporary learning theories were not explicitly articulated in most studies, there were many examples of computer-assisted instruction strategies and activities that were aligned with these theories.

Although self-directed, computer-assisted learning may seem attractive to busy clinicians with limited time for teaching,[55 61] our systematic review and meta-analysis did not find sufficient evidence to recommend that computer-assisted ECG instruction should replace face-to-face teaching. Rather, we found that computer-assisted ECG instruction was more effective than face-to-face teaching when it formed part of a blended learning strategy. This is in keeping with the literature which shows that CAI should be used as an adjunct to face-to-face teaching in order to enhance ECG training.[56 61 69] Our findings are also in keeping with the results of a recent meta-analysis published in the health professions education literature, which showed that blended learning was better than face-to-face teaching alone.[70] However, as with other systematic reviews and meta-analyses that assessed the efficacy of blended learning in the training of healthcare professionals,[71 72] our analyses were also limited by a small number of studies, incomplete reporting of results and significant heterogeneity among the studies.

Table 5 Acquired and retained ECG competence according to educational approaches used in the included studies

		Educational approaches/CAI strategies				Outcome (SMD (95% CI))	
Author	Year	Blended learning*	Massed instruction†	Unrestricted access‡	Deliberate practice§	Acquisition of knowledge	Retention of knowledge
Studies favouring CAI							
Chudgar[54]	2016	X		X	X	1.09 (0.79 to 1.4)	
Nilsson[66]	2008	X		X	X	0.68 (0.1 to 1.26)	
Rui[63]	2017	X		X		0.68 (0.38 to 0.98)	
Barthelemy[62]	2017			X	X	0.65 (0.01 to 1.3)	
Sonali[65]	2014					0.52 (0.24 to 0.80)	
No statistical difference							
Owen[60]	1965				X	0.08 (–0.36 to 0.53)	
Fent[59]	2016		X			–0.25 (–0.55 to 0.05)	–0.24 (–1.05 to 0.58)
Study favouring face-to-face teaching							
Davies[58]	2016		X			–1.08 (–1.76 to –0.41)	

*CAI formed part of a blended learning strategy (CAI combined with face-to-face teaching)
†Learners were exposed to a single teaching opportunity
‡Unrestricted access to CAI during study period
§CAI facilitated self-administered assessments with feedback
CAI, computer-assisted instruction; SMD, standardised mean difference.

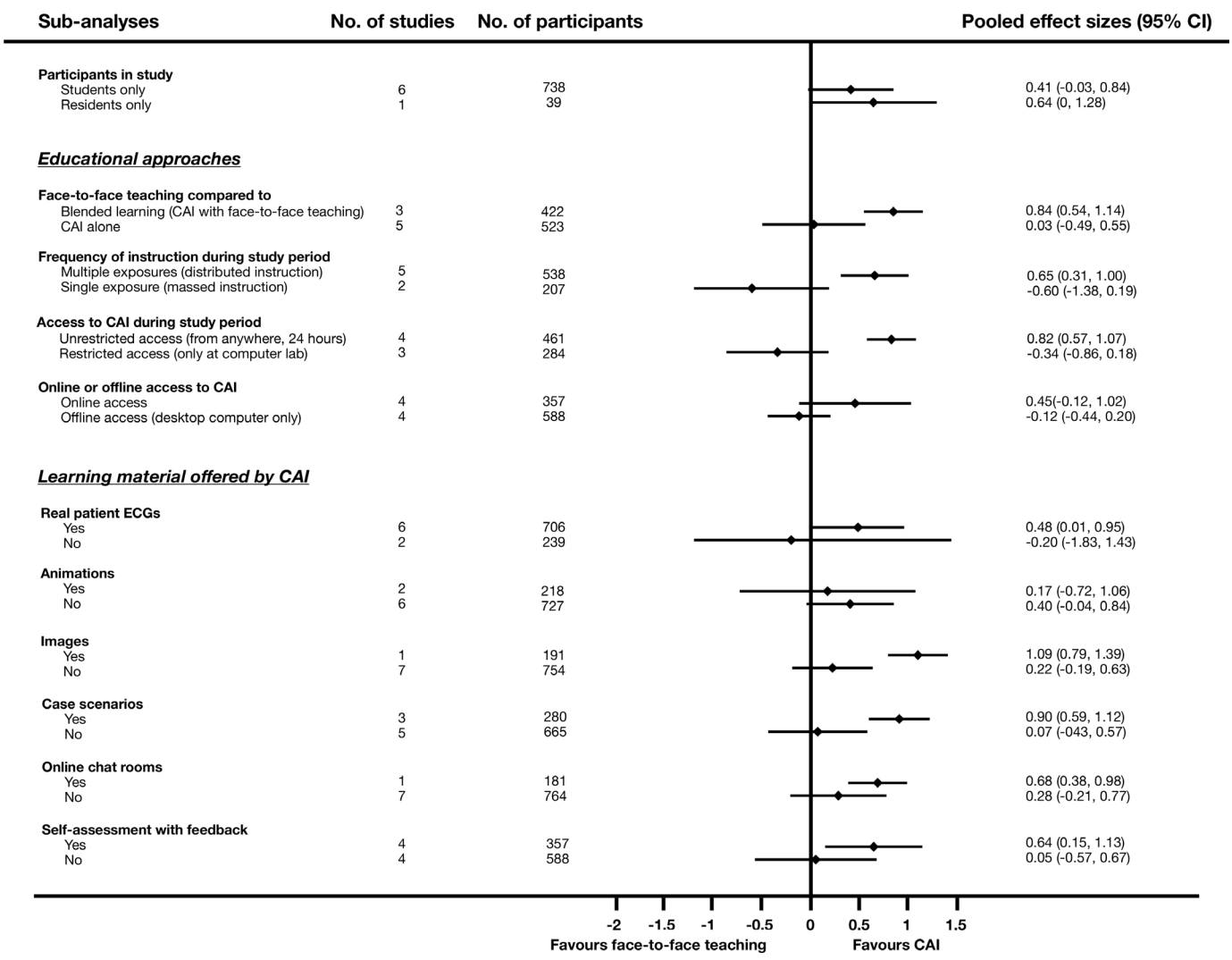

Figure 3 Pooled effect sizes according to level of training of participants, educational approaches and CAI learning materials used in the studies. CAI, computer-assisted instruction.

One of the studies included in this review demonstrated the successful use of CAI in a flipped classroom strategy for teaching ECG analysis and interpretation skills.[63] Although the flipped classroom method required more preparation time, for both lecturers and students, trainees were more proactive in discussions with their peers and their lecturers during the face-to-face teaching time, resulting in better post-intervention test scores than traditional face-to-face teaching.[73] Since it is accepted that ECG competence is difficult to acquire,[13 14] the successful use of a flipped classroom approach is encouraging because this method allows for engagement with the learning material prior to face-to-face interaction with teachers when difficult concepts can be discussed and misunderstandings resolved.

When evaluating the educational effect of teaching and learning methods, it is critical to review access and frequency of exposure to the learning materials. In a subanalysis, students did not benefit from computer-assisted or face-to-face massed instruction (single educational event). As has been previously found,[74] CAI was only beneficial if students had multiple exposures to the learning activities and study materials (distributed instruction). In the setting of blended learning, CAI facilitates distributed instruction, because it can be used asynchronously, allowing for consolidation of knowledge acquired during face-to-face teaching.[24 34 61 75]

This review found that there was a significant benefit to students when they had unrestricted access to CAI learning materials. Although we did not show a difference in outcomes between online and offline CAI, the benefit of web-based learning is that it can be accessed whenever and wherever convenient.[24 34 61 75] However, the high cost of, and/or lack of access to computers with Internet facilities may be a barrier to web-based learning, particularly in developing countries.[24 64 76] Health professions educators, especially in resource-limited settings should therefore be cognisant of the availability of computers and students' access to the Internet when planning CAI with online requirements.

A key aspect of any method of instruction is the nature of the learning materials and activities included in the

programme. CAI has been shown to enhance the learning experience by using multimedia and interactive learning materials.[69] In this study we confirmed that visual material was highly valued by participants and a subanalysis showed specific benefit when using images in combination with the 12-lead ECG, for example to explain cardiac impulse conduction. The value of using images in medical education is that it helps to embed knowledge in long-term memory.[25] Although images are widely used to demonstrate concepts in medical education,[77] it has previously been shown to be of most value when accompanied by good explanations,[78 79] as was the case in the study by Nilsson *et al*.[66] In this study we also found that there were additional educational gains when computer-assisted ECG instruction made use of clinical scenarios.[54 61 62 66] This is in line with previous studies which have shown more accurate ECG analysis and interpretation when the clinical context was known.[80 81]

In this systematic review we found evidence that CAI was better than face-to-face teaching in studies in which the CAI included exercises of ECG analysis and interpretation that required deliberate practice with automated feedback. This finding is in keeping with studies which have shown that practice exercises followed by feedback facilitate high levels of interactivity with educational materials and significantly enhance learning.[61 82–84] In CAI there are opportunities for both self-reflection[85] and repetitive practice[86] because students can repeat the self-assessments, correct their errors and further improve their performance.[54 60–62 66 84]

The studies included in this review demonstrated variable outcomes using the Kirkpatrick framework of evaluation. Improvement of trainees' ECG knowledge and analysis and interpretation skills using either CAI and face-to-face instruction was an eligibility criterion for inclusion in the study. A few studies reported on the responses of participants to the methods of instruction used with no consistent preference for CAI. None of the studies evaluated CAI at the level of behavioural change (Kirkpatrick level 3), change in organisational practice (Kirkpatrick level 4a) or improved patient care (Kirkpatrick level 4b). This is consistent with studies showing that health professions education interventions rarely show impact at Kirkpatrick level 3 or 4.[87 88] Indeed it is a widely recognised ongoing shortcoming of health professions education research. This systematic review endorses a plea in the literature for the evaluation of educational interventions at the level of impact on physician behaviour,[89 90] organisational practice[91 92] and patient care.[93–95]

While learning theories were not explicitly discussed in most of the studies in this review, there were multiple examples of educational strategies that are aligned with contemporary learning theories.[96] However, as this review shows, studies describing and evaluating educational interventions continue to be conducted without a firm rationale imbedded in contemporary learning theories. This highlights a significant ongoing shortcoming of health professions education research.[97–99]

CAI serves as a good example of self-directed learning, whereby students plan and conduct their own learning.[42] While face-to-face teaching time is limited,[100] CAI allows for flexibility in learning – students can adjust the pace of their learning and spend as much time as they need to assimilate new knowledge. While face-to-face teaching is ideal for promoting collaborative learning by allowing interaction between peers and tutors,[55 58 59 61 62] it is also possible in CAI when chat rooms were available[61 63] or when CAI forms part of a blended learning programme.[54 57 63 66]

In this review we found that participants valued learning with demonstrations and explanations (cognitivism).[96] CAI-based learning opportunities had the advantage of offering multimedia learning resources, which enrich the educational content by means of animations, audio and video clips.[69]

The flipped classroom method of teaching ECGs, as described in one study included in this review,[63] serves as an excellent example of a learning process which focuses on actively creating meaning rather than merely acquiring knowledge (constructivism).[96] In a flipped classroom approach, students used CAI to familiarise themselves with educational content, and expand their learning by using the time in class to discuss concepts that they did not understand.[101] It seems that this could be a useful approach for electrocardiography, which is considered a difficult subject to teach and to learn.[13 14]

Because CAI does not require attendance of class, external motivation in the form of reminder emails or summative assessments might be needed to encourage students to use the e-learning modules. In the study that made use of such external motivation strategies, CAI showed a large positive effect size.[54]

Though variably applied in the studies in this review, contextualisation was possible in both CAI and face-to-face teaching settings.[54 61 62 66] Where CAI made use of patient scenarios, there was a larger benefit in acquiring ECG competence.

Reflective learning is possible with CAI when self-administered quizzes with automated feedback are used. Learning is facilitated because knowledge and/or skills gaps are highlighted.[54 61 62 66]

Strengths and limitations

The strength of this study is that it was conducted as a systematic review using a comprehensive search strategy and detailed data extraction method. However, the inferences that can be made from this systematic review and its meta-analysis are limited by high levels of bias and the heterogeneity of the included studies. There was significant variability in study design, the format, delivery and exposure time of the teaching intervention (CAI) and control (face-to-face teaching) and the topics taught and assessed.[57] Many studies also did not include a baseline test of ECG knowledge and/or analysis and interpretation skills prior to the educational intervention and did not report all their data. Nevertheless, the mean MERSQI score of the studies included in this review was similar

to MERSQI scores reported in other systematic reviews in medical education.[23 102–104] In fact, 9 of the 13 studies in this review had a high MERSQI score (ie ≥12).[105] Furthermore, most of the studies included in this systematic review were performed in well-resourced countries and the generalisability of these findings to resource-constrained settings is therefore not known.

Implications for practice and future research

Owing to the heterogenous nature of the studies included in this review it was not possible to provide conclusive evidence that CAI is better than face-to-face teaching of ECG knowledge and analysis and interpretation skills. However, CAI was better than face-to-face teaching in a blended learning setting where students had unrestricted access to the learning materials and opportunities for self-assessment with automated feedback.

There are currently many aspects of CAI that need to be further explored. These include a more detailed evaluation of the efficacy of this medium of instruction in postgraduate education and its impact on the long-term retention of ECG competence in both undergraduate and postgraduate trainees. Studies are also needed to better understand the impact of CAI on clinician behaviour (ECG analysis and interpretation practices in clinical settings), changes in organisational practice and patient care.

CONCLUSION

Owing to the mixed findings of the studies included in this systematic review, there is currently insufficient evidence to favour the use of computer-assisted ECG instruction. However, CAI can be used to enhance face-to-face teaching in a blended learning setting. CAI was found to be more beneficial than face-to-face teaching when students had unrestricted access to learning materials and opportunities for self-assessment with automated feedback.

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