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Atrial fibrillation detection using single lead portable electrocardiographic monitoring: a systematic review and meta-analysis

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ABSTRACT

Objectives Recent technology advances have allowed for heart rhythm monitoring using single-lead ECG monitoring devices, which can be used for early diagnosis of atrial fibrillation (AF). We sought to investigate the AF detection rate using portable ECG devices compared with Holter monitoring.

Setting, participants and outcome measures We searched the Medline, Embase and Scopus databases (conducted on 8 May 2017) using search terms related to AF screening and included studies with adults aged >18 years using portable ECG devices or Holter monitoring for AF detection. We excluded studies using implantable loop recorders and pacemakers. Using a random-effects model we calculated the overall AF detection rate. Meta-regression analysis was performed to explore potential sources for heterogeneity. Quality of reporting was assessed using the tool developed by Downs and Black.

Results Portable ECG monitoring was used in 18 studies (n=117 436) and Holter monitoring was used in 36 studies (n=8498). The AF detection rate using portable ECG monitoring was 1.7% (95% CI 1.4 to 2.1), with significant heterogeneity between studies (p<0.001). There was a moderate linear relationship between total monitoring time and AF detection rate (r=0.65, p=0.003), and meta-regression identified total monitoring time (p=0.005) and body mass index (p=0.01) as potential contributors to heterogeneity. The detection rate (4.8%, 95% CI 3.6% to 6.0%) in eight studies (n=10 199), which performed multiple ECG recordings was comparable to that with 24 hours Holter (4.6%, 95% CI 3.5% to 5.7%). Intermittent recordings for 19 min total produced similar AF detection to 24 hours Holter monitoring.

Conclusion Portable ECG devices may offer an efficient screening option for AF compared with 24 hours Holter monitoring.

PROSPERO registration number CRD42017061021.

Strengths and limitations of this study

- First systematic review comparing single-lead ECG monitoring with 24 hours Holter monitoring for atrial fibrillation (AF) detection.
- Comprehensive literature search and specific inclusion criteria allowing for large patient numbers.
- Heterogeneity among individual studies with regard to patient population, AF definitions and monitoring time.
- Poor reporting of CHA_2DS_2-VASC scores among individual studies.
- Patient compliance unable to be accounted for in this meta-analysis.

Atrial fibrillation (AF) is a leading cause of stroke and heart failure worldwide, and is associated with increased all-cause mortality[1 2] as well as substantial financial cost.[3 4] The prevalence of AF increases with age, exceeding >15% for those aged 85 years and older.[5] The epidemics of obesity, diabetes mellitus and metabolic syndrome have also been associated with the increasing prevalence of AF.[6–8] Up to 20% of patients with stroke have underlying AF, and detection allows the initiation of anticoagulation, which is associated with a significant reduction in stroke recurrence.[9]

Early diagnosis of AF may have several benefits, including individualised lifestyle intervention[10] and anticoagulation, and may be associated with a reduction in complications and healthcare costs. The importance of early diagnosis has been recognised in recent guidelines from the European Society of Cardiology, which recommended opportunistic screening using pulse palpation and 12-lead ECG.[11] However, screening for AF is challenging for several reasons; many patients are asymptomatic or may have atypical symptoms. There are a variety of monitoring techniques available, all of which vary in diagnostic accuracy and sensitivity, and there is no accepted reference standard. Subclinical AF is associated with an increased risk of stroke, cardiovascular disease and all-cause mortality,[12] although there is controversy surrounding the significance of brief paroxysms of AF and the potential benefit of

anticoagulant therapy. Implantable devices are expensive, and not cost-effective for mass screening, and the use of external devices for long periods of monitoring require electrodes, which may be poorly tolerated by patients.

Recent advances in technology have allowed for the development of single-lead portable ECG monitoring devices. Multiple devices are available, all using multiple points of finger contact to create a single-lead ECG trace. The in-built memory of these devices allows for single or multiple time-point screening. Interpretation from a cardiologist or by automated algorithms has achieved high sensitivity and specificity for AF detection.[13–15] Although they have not been incorporated into the latest AF guidelines, the accuracy, ease of use and potential cost-effectiveness of these devices may lead to them having an important role in AF screening. This paper describes a systematic review of the published literature to investigate the overall AF detection rate using portable ECG devices compared with traditional Holter monitoring.

METHODS

Search strategy

We conducted our systematic review and meta-analysis using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guideline (PRISMA).[16] We searched the Medline, Scopus and Embase databases using key terms including 'atrial fibrillation/AF and screening/monitoring and electrocardiographic/Holter monitoring', which were mapped to subject headings. We also searched the reference lists to identify other potential articles. The search was limited to adult human subjects aged >18 years and limited to the English language (see search strategy for Medline database in online supplementary material 1). The study was prospectively registered on the PROSPERO database on 22 April 2017 (CRD42017061021), and the search was conducted on 8 May 2017.

Study selection

Titles and abstracts of studies identified from the search were reviewed by two independent reviewers (SR and DDS). Studies which had a primary aim of AF detection in adult participants were included. We included all cohorts including community screening, those with risk factors and recent stroke. The screening methods included portable single-lead ECG devices or continuous (Holter) monitoring (up to 1 week). We included studies which used single-lead ECG devices for single episode screening or multiple intermittent screening periods. We included conference abstracts if demographic and outcome data were available. We excluded studies if participants were aged <18 years or if other forms of monitoring were used (pacemaker, implantable loop recorders, event recorders, monitoring patches and inpatient telemetry). We also excluded studies where AF detection was not the primary aim.

The primary outcome of interest was the detection rate of new AF using either single-lead intermittent or continuous monitoring. Our secondary objective was to determine the optimal time of intermittent monitoring, which produced equivalent AF detection to continuous monitoring.

Data collection

Full-text manuscripts of studies fitting the inclusion criteria were obtained. Quality of reporting and risk of bias was assessed using the tool developed by Downs and Black.[17] A standardised data-extraction form was used by the reviewers, which included information about the patient demographics, comorbidities, screening strategy, patients with known AF and overall new AF detection rate. Where data were not reported, we attempted to contact the primary authors of the study. Any disagreements between the two reviewers were resolved by consensus or by consulting a third reviewer (THM).

Statistical analysis

The cumulative AF detection rate for continuous and intermittent monitoring and the 95% CI was calculated using a random-effects model. The results were displayed as a forest plot and heterogeneity among the studies was assessed using the I^2 statistic. A subgroup analysis was performed by comparing the cumulative detection rate of single-lead ECG studies, which performed multiple timepoint recordings with 24 hours Holter monitoring studies. Linear regression analysis was used to determine the association between the total monitoring time and AF detection using single-lead ECG devices. This formula was used to determine the monitoring time using single-lead ECG devices to approximate the overall AF detection rate using 24 hours continuous monitoring. Univariate meta-regression analysis was performed to assess the influence of various clinical and screening factors with AF detection. Publication bias was assessed using a funnel plot and the Egger test. Statistical analysis was performed using Stata V.13 (StataCorp, College Station, Texas, USA) with two-tailed p values <0.05 used to denote statistical significance.

Patient and public involvement

Patients were not involved in this review.

RESULTS

Study characteristics

The PRISMA flow chart of our included studies is shown in figure 1 and the search strategy in online supplementary table 1. Our initial search strategy identified 5427 studies, with another 26 identified through other sources. After removing duplicate records, 4122 studies were left. After screening those using the inclusion/exclusion criteria, we identified 111 full-text studies for detailed review, which excluded 59 studies, leaving 52 full-text studies for inclusion in the meta-analysis (see online supplementary

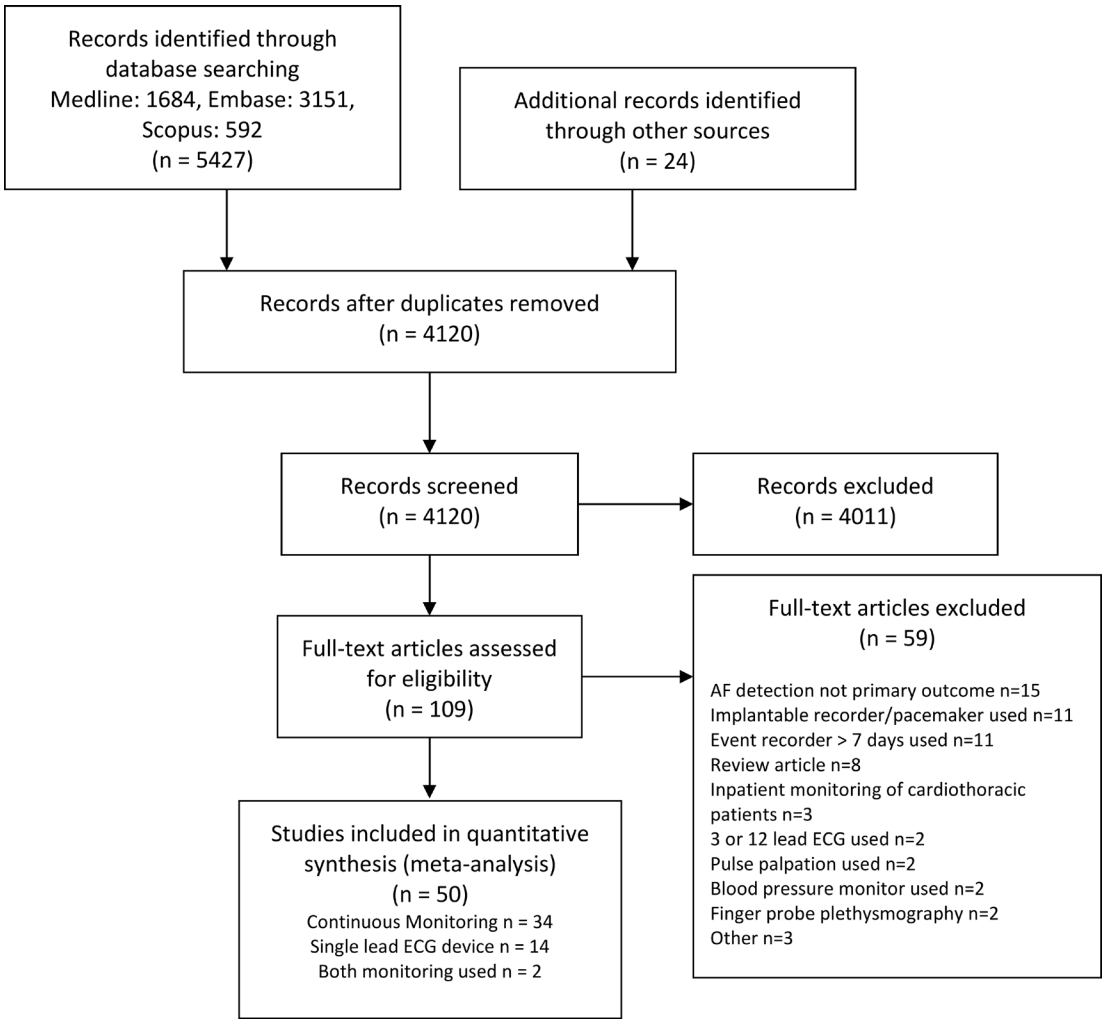

Figure 1 Overview of inclusion and exclusion of studies based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow chart.

table 2 for excluded studies). Of the 52 studies included, 34 used continuous (Holter) monitoring (n=8154),[18–51] 16 studies (n=117 092) used single-lead portable ECG monitoring[14 15 52–65] and 2 studies (n=344) used both continuous and intermittent single-lead monitoring for AF detection in a head-to-head comparison.[66 67]

The baseline characteristics of the individual studies is presented in table 1. There was a considerable range in age (54–76 years), and gender (male 29%–77%) between studies. As many studies chose healthy volunteers and other studies focused on patients poststroke or those with AF risk factors, there was significant variation in comorbidities such as diabetes, hypertension and obesity. Stroke risk determined by the CHADS or CHA_2DS_2-VASC score was reported in only 14/52 studies (27%). Of the 52 studies, 36 (69%) were conducted in Europe, 8 (15%) in Asia, 5 (10%) in North America and 3 (6%) in Australia. Nine studies (17%) were retrospective, the remainder all being prospective cohort or randomised controlled trials.

Of the 18 studies using single-lead ECG devices, 10 studies (56%) used a single 10–60 s recording for AF detection while 8 studies (44%) used multiple readings over a 1-week to 52-week period. There were five portable ECG devices used (table 1). Sixteen studies (89%) used healthy participants with risk factors.[14 15 52–61 63–65 67] Two studies assessed patients following stroke or transient ischaemic attack (TIA).[62 66]

Of the 36 studies using continuous (Holter) monitoring, 27 studies (75%) used 24 hours continuous monitoring,[18–23 25–28 33–36 38 39 41–45 47–50 66 67] 4 studies (11%) used 1-week monitoring,[30–32 51] 2 studies (6%) used 48 hours monitoring,[37 46] 2 studies (6%) used 72 hours monitoring[24 29] and 1 study (3%) used 96 hours monitoring.[40]

Overall AF detection

The combined AF detection rate using single-lead ECG monitoring (n=117 436 from 18 studies) was 1.7% (95% CI 1.4% to 2.1%). The cumulative AF detection rate using continuous (Holter) monitoring (n=8498 from 36 studies) was 5.5% (95% CI 4.4% to 6.6%). There was significant heterogeneity between studies (I^2=94% for single-lead ECG monitoring, 87% for Holter monitoring). The overall new AF detection rate is presented in figure 2.

Table 1 Summary of included trials investigating AF detection using single-lead ECG devices or Holter monitoring

Study	n	Country	Type of patients used	Device used	Duration of recording (s)	Frequency of recording/ day	Total monitoring (days)	Mean/ median age (years)	Male (%)	BMI (kg/ m^2)	HTN (%)	DM (%)	IHD (%)	Previous diagnosis of AF (%)	HF (%)	Previous stroke (%)	Mean/ median CHADS/ CHA_2DS_2-VASC	Definition of AF	New AF (n)	New AF rate (%)
Lowres *et al*[52]	1000	Australia	Community pharmacy screening	Alive Cor	60	1	0	76	44	NR	62	23	16	10.4	3	7	3.3	Cardiologist interpretation	15	1.5
Svennberg *et al*[53]	7173	Sweden	Community screening (aged 75–76 years)	Zenicor	30	2	14	75	46	25.9	50	11	9.2	9.2	3.4	9	3.4	30 s irregular rhythm without P waves or 2× episodes between 10 and 29 s	218	3
Proietti *et al*[54]	65 747	Belgium	Belgian Heart Week screening	Omron Heartscan HCG-801	30	1	0	58	41	NR	36	21	23	0.5	20	20	2	Irregular R-R interval, no distinct P waves, variable atrial cycle length	603	1.1
Kaasenbrood *et al*[55]	3269	Holland	Influenza vaccination—opportunistic screening	MyDiagnostik	60	1	0	64.1	49	NR	NR	NR	NR	2.6	NR	NR	NR	Cardiologist interpretation×2	37	1.1
Engdahl *et al*[56]	848	Sweden	Community screening (aged 75–76 years) in Halmstad, Sweden	Zenicor	30	2	14	75	43	NR	53	11	NR	9.6	4	10	1.9	30 s duration of irregular rhythm or ≥2 episodes of 10 s or more	40	4.7
Hendrikx *et al*[57]	928	Sweden	GP practices	Zenicor	10	2	28	69.8	50	NR	90.3	31.6	19.8	0	3.7	8.6	2	10 s irregular rhythm without P waves	35	3.8
Hendrikx *et al*[67]	95	Sweden	Referred for presyncope/ palpitations	Zenicor	30	2	28	54.1	44	NR	28.4	1.1	8.4	0	0	6.3	1	30 s irregular rhythm without P waves	9	9.5
Chan *et al*[15]	1013	Hong Kong	Patients aged ≥65 years with HTN or diabetes	Alive Cor	60	1	0	68.4	47	NR	90.4	36.6	16.2	2.2	4.4	10.5	3	Cardiologist interpretation	5	0.5
Doliwa Sobocinski *et al*[66]	249	Sweden	Patients post-TIA/ stroke	Zenicor	10	2	30	72	57	NR	65	16	20	0	4	25	3	Irregular rhythm of minimum 10 s without visible P waves	15	6
Doliwa Sobocinski P *et al*[14]	606	Sweden	Community event	Zenicor	10	1	0	NR	64	NR	NR	NR	NR	NR	NR	NR	NR	Irregular rhythm without visible P waves	6	1
Ramkumar *et al*[60]	204	Australia	Community aged ≥65 years with one or more risk factor for HF	Remon RM-100	60	5	7	70.1	51	29.1	72.1	56.4	5.9	0	0	NR	3	30 s duration of irregular rhythm with absent P waves	20	9.8
Hendrikx *et al*[58]	201	Sweden	Patients referred to respiratory clinics with suspicion of obstructive sleep apnoea	Zenicor	30	2	14	56	69	30	51	10	9.2	0	4.6	3.1	NR	Irregular supraventricular extra systoles in series for 30 s	13	6.5
Claes *et al*[61]	10 758	Belgium	Community heart rhythm screening programme through medical centres	Omron HeartScan HCG-801	30	1	0	59	38	NR	30.6	8.6	12.2	7.2	7.2	5.4	1	Irregular RR intervals, absence of P waves and variable atrial cycle length (when visible)	167	1.6

Continued

Table 1 Continued

Study	n	Country	Type of patients used	Device used	Duration of recording (s)	Frequency of recording/ day	Total monitoring (days)	Mean/ median age (years)	Male (%)	BMI (kg/ m^2)	HTN (%)	DM (%)	IHD (%)	Previous diagnosis of AF (%)	HF (%)	Previous stroke (%)	Mean/ median CHADS/ CHA_2DS_2-VASC	Definition of AF	New AF (n)	New AF rate (%)
Samol *et al*[62]	132	Germany	Large proportion poststroke/TIA. Also recruited from diabetes, HTN and dyslipidemia clinics	Omron HeartScan HCG-801	30	1	0	64	58	NR	67	27	NR	0	3	49	NR	Cardiologist Interpretation×2	7	5.3
Battipaglia *et al*[63]	855	UK	Community shopping centre screening	MyDiagnostik	15	1	0	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	7	0.8
Chan and Choy[59]	13122	Hong Kong	Nationwide community screening programme	Alive Cor	30	1	0	64.7	29	23.7	38.2	14.8	2.2	0	0.7	2.8	NR	Software algorithm definition with minimum of 30 s	101	0.8
Chan *et al*[65]	10735	Hong Kong	Nationwide community screening programme	Alive Cor	30	1	0	NR	NR	NR	NR	NR	NR	1.2	NR	NR	NR	Cardiologist interpretation (≥30s)	74	0.7
Halcox *et al*[64]	501	UK	Community based with individuals aged >65 years with CHA2DS2-VASC score≥2	Alive Cor	30	2× per week	365	72.6	48	NR	54	26	14	0	1.0	7.0	3.0	30 s duration of an irregular rhythm without P waves	19	3.8
Gladstone *et al*[18]	277	Canada	Patients admitted with cryptogenic stroke	Holter	Continuous	Continuous	1	73.2	56	NR	67	19.3	14.7	0	7	12.6	NR	30 s or longer duration of irregular rhythm	9	3.2
Barthélémy *et al*[19]	60	France	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	64.4	55	NR	50	17	NR	0	NR	27	NR	Fibrillatory waves associated with irregular ventricular response ratio at least 30 s duration	8	13.3
Jabaudon *et al*[20]	149	Switzerland	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	66.9	68	NR	58	16.7	16.8	4.7	NR	16.8	NR	NR	7	4.7
Koudstaal *et al*[21]	100	Holland	Retrospective study of 100 patients admitted with stroke/TIA	Holter	Continuous	Continuous	1	60.9	74	NR	NR	NR	41	NR	NR	NR	NR	NR	5	5
Hornig *et al*[22]	268	Germany	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	59.1	61	NR	43.7	34	NR	NR	14.9	45	NR	NR	10	3.3
Rizos *et al*[23]	496	Germany	Patients admitted with stroke/TIA	Holter	Continuous	Continuous	1	69	62	NR	78.8	24.6	NR	NR	NR	22.2	3	Cardiologist interpretation (≥30s)	14	2.8
Schuchert *et al*[24]	82	Germany	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	3	59.7	57	NR	36.5	NR	17.1	NR	NR	NR	NR	Small irregular baseline undulations of variable amplitudes and morphology at a rate >350/min with an irregular ventiruclar response for at least 1 min	5	6

Continued

Table 1 Continued

Study	n	Country	Type of patients used	Device used	Duration of recording (s)	Frequency of recording/ day	Total monitoring (days)	Mean/ median age (years)	Male (%)	BMI (kg/ m^2)	HTN (%)	DM (%)	IHD (%)	Previous diagnosis of AF (%)	HF (%)	Previous stroke (%)	Mean/ median CHADS/ CHA_2DS_2-VASC	Definition of AF	New AF (n)	New AF rate (%)
Schaer *et al*[25]	241	Switzerland	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	68.7	59	NR	76	25	41	7	NR	4.6	NR	NR	0	0
Schaer *et al*[26]	425	Switzerland	Retrospective review of patients poststroke/ TIA with Holter monitoring	Holter	Continuous	Continuous	1	67.4	61	NR	NR	NR	NR	NR	NR	1.2	NR	Self-terminating sequence of >30 s of irregular RR intervals and the presence of fibrillatory P waves	9	2.1
Shafqat *et al*[27]	465	Pakistan	Retrospective review of consecutive patients admitted with stroke/TIA	Holter	Continuous	Continuous	1	66.8	56	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	2.4
Lazzaro *et al*[28]	133	USA	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	63.1	50	NR	70	29.3	18.8	0	NR	2.3	NR	Supraventricular tachyarrhythmia characterised by uncoordinated atrial activation with fibrillatory waves varying in amplitude, shape and timing, replacing consistent P waves and with a duration >30 s	8	6
Grond *et al*[29]	1135	Germany	Patients admitted in seven German centres with stroke/TIA	Holter	Continuous	Continuous	3	67	55	27.4		20.4	7.3	0	5.8	17.4	NR	≥1 period of >30 s duration of an absolute arrhythmia without detectable P waves and without a pattern more consistent with an alternate diagnosis	49	4.3
Stahrenberg *et al*[30]	224	Germany	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	7	68	58	27.6	72.9	22.3	14.8	0	5.2	16.2	NR	2x Cardiologist interpretation of software algorithm detection of events	28	12.5
Ritter *et al*[31]	60	Germany	Patients admitted with cryptogenic stroke	Holter	Continuous	Continuous	7	61.8	57	NR	70	11.7	13.3	NR	0	NR	4	Cardiologist interpretation (>30 s)	1	1.7
Higgins *et al*[32]	50	Scotland	Patients admitted with stroke/TIA	Holter	Continuous	Continuous	7	67.1	48	NR	56	8	16	0	NR	NR	NR	Cardiologist interpretation (>30 s)	4	8
Hendrikx *et al*[67]	95	Sweden	Patients investigated for palpitations and presyncope	Holter	Continuous	Continuous	1	54.1	42	NR	28.4	1.1	8.4	0	0	6.3	1	30 s irregular rhythm without P waves	2	2.1

Continued

Table 1 Continued

Study	n	Country	Type of patients used	Device used	Duration of recording (s)	Frequency of recording/ day	Total monitoring (days)	Mean/ median age (years)	Male (%)	BMI (kg/ m^2)	HTN (%)	DM (%)	IHD (%)	Previous diagnosis of AF (%)	HF (%)	Previous stroke (%)	Mean/ median CHADS/ CHA_2DS_2-VASC	Definition of AF	New AF (n)	New AF rate (%)
Thakkar and Bagarhatta[33]	52	India	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	59.5	77	NR	51.9	23.1	15.4	0	1.7	7.7	NR	30 s irregular rhythm without P waves	3	5.8
Wachter *et al*[34]	198	Germany	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	73.2	62	NR	80.7	26.4	9.1	0	4.6	21.7	4.8	>30 s rhythm with irregular RR intervals and the presence of fibrillatory P waves	9	5
Gumbinger *et al*[35]	192	Germany	Patients admitted with stroke/TIA	Holter	Continuous	Continuous	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	2	1
Alhadramy *et al*[36]	426	Canada	Retrospective review of patients poststroke/ TIA with Holter monitoring	Holter	Continuous	Continuous	1	64.9	48	NR	58.2	14.1	14.1	0	1.6	6.3	NR	Irregular ventricular response in the absence of p waves or with fibrillatory waves	11	2.5
Doliwa Sobocinski *et al*[66]	249	Sweden	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	72	57	NR	65	16	20	0	4	25	3	Irregular rhythm of minimum 10 s without visible P waves	5	2
Dangayach *et al*[37]	51	USA	Retrospective audit of patients admitted with cryptogenic stroke	Holter	Continuous	Continuous	2	58.2	43	NR	35.3	16	15.7	7.4	NR	NR	NR	NR	15	29.4
Gunalp *et al*[38]	26	Turkey	Patients admitted with ischaemic stroke	Holter	Continuous	Continuous	1	66	69	NR	61	26	31	NR	NR	NR	NR	NR	11	42.3
Fonseca *et al*[39]	80	Portugal	Patients admitted with cryptogenic stroke	Holter	Continuous	Continuous	1	69.3	53	NR	71.3	28.8	11.3	NR	NR	22.5	NR	NR	17	21
Manina *et al*[40]	114	Italy	Patients admitted with cryptogenic stroke	Holter	Continuous	Continuous	4	63.1	NR	NR	52.6	9.6	NR	NR	NR	NR	NR	Irregular ventricular response in the absence of P waves or with fibrillatory waves	29	25.4
Tagawa *et al*[41]	308	Japan	Consecutive patients admitted with ischaemic stroke	Holter	Continuous	Continuous	1	72.6	60	NR	70.1	25.3	NR	20.4	NR	NR	NR	Small irregular baseline undulations of variable amplitude and morphology at a rate of 300–350/ min associated with irregular ventricular response	26	8.4
Shibazaki *et al*[42]	536	Japan	Consecutive patients admitted with ischaemic stroke	Holter	Continuous	Continuous	1	72.4	64	NR	65.9	25.7	9.8	NR	0.3	NR	NR	NR	12	2.2
Vandebroucke and Thijs[43]	136	Belgium	Retrospective audit of patients admitted with ischaemic stroke	Holter	Continuous	Continuous	1	68	52	NR	NR	NR	NR	NR	NR	NR	NR	NR	7	5.1

Continued

Table 1 Continued

Study	n	Country	Type of patients used	Device used	Duration of recording (s)	Frequency of recording/ day	Total monitoring (days)	Mean/ median age (years)	Male (%)	BMI (kg/ m^2)	HTN (%)	DM (%)	IHD (%)	Previous diagnosis of AF (%)	HF (%)	Previous stroke (%)	Mean/ median CHADS/ CHA_2DS_2-VASC	Definition of AF	New AF (n)	New AF rate (%)
Yodogawa *et al*[44]	68	Japan	Consecutive patients admitted with ischaemic stroke	Holter	Continuous	Continuous	1	69.9	54	NR	66.2	14.7	NR	NR	NR	NR	NR	Irregular and uncoordinated atrial electrical activity on surface ECG lasting >30 s	17	25
Atmuri *et al*[45]	140	Australia	Retrospective audit of patients admitted with ischaemic stroke/TIA	Holter	Continuous	Continuous	1	NR	NR	NR	65	20	37.1	18.6	NR	NR	NR	NR	12	8.6
Salvatori *et al*[46]	274	Italy	Cohort study of patients aged ≥65 years with HTN in multiple GP clinics	Holter	Continuous	Continuous	2	70	54	NR	100	15	9	7	4	2.2	NR	Cardiologist interpretation	4	1.5
Beaulieu-Boire *et al*[47]	284	Canada	Consecutive patients admitted with stroke/ TIA	Holter	Continuous	Continuous	1	70.6	52	NR	68.7	26.7	27.4	NR	2.2	22.3	NR	Cardiologist interpretation	18	6.3
Dogan *et al*[48]	400	Turkey	Retrospective review of patients admitted poststroke	Holter	Continuous	Continuous	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	40	10
Douen *et al*[49]	126	Canada	Retrospective review of patients admitted poststroke	Holter	Continuous	Continuous	1	NR	NR	NR	NR	NR	NR	7	NR	NR	NR	NR	9	7.1
Suissa *et al*[50]	354	France	Consecutive patients admitted with ischaemic stroke	Holter	Continuous	Continuous	1	62.4	57	NR	51.1	18.6	NR	0	NR	NR	NR	Cardiologist interpretation	2	0.6
Wohlfahrt *et al*[51]	224	Germany	Patients admitted with ischaemic stroke	Holter	Continuous	Continuous	7	68.5	59	NR	73.2	22.3	15.2	NR	5.4	24.1	NR	>30 s irregular rhythm	29	12.9

AF, atrial fibrillation; BMI, body mass index; DM, diabetes mellitus; GP, general practitioner; HF, heart failure; HTN, hypertension; IHD, ischaemic heart disease.

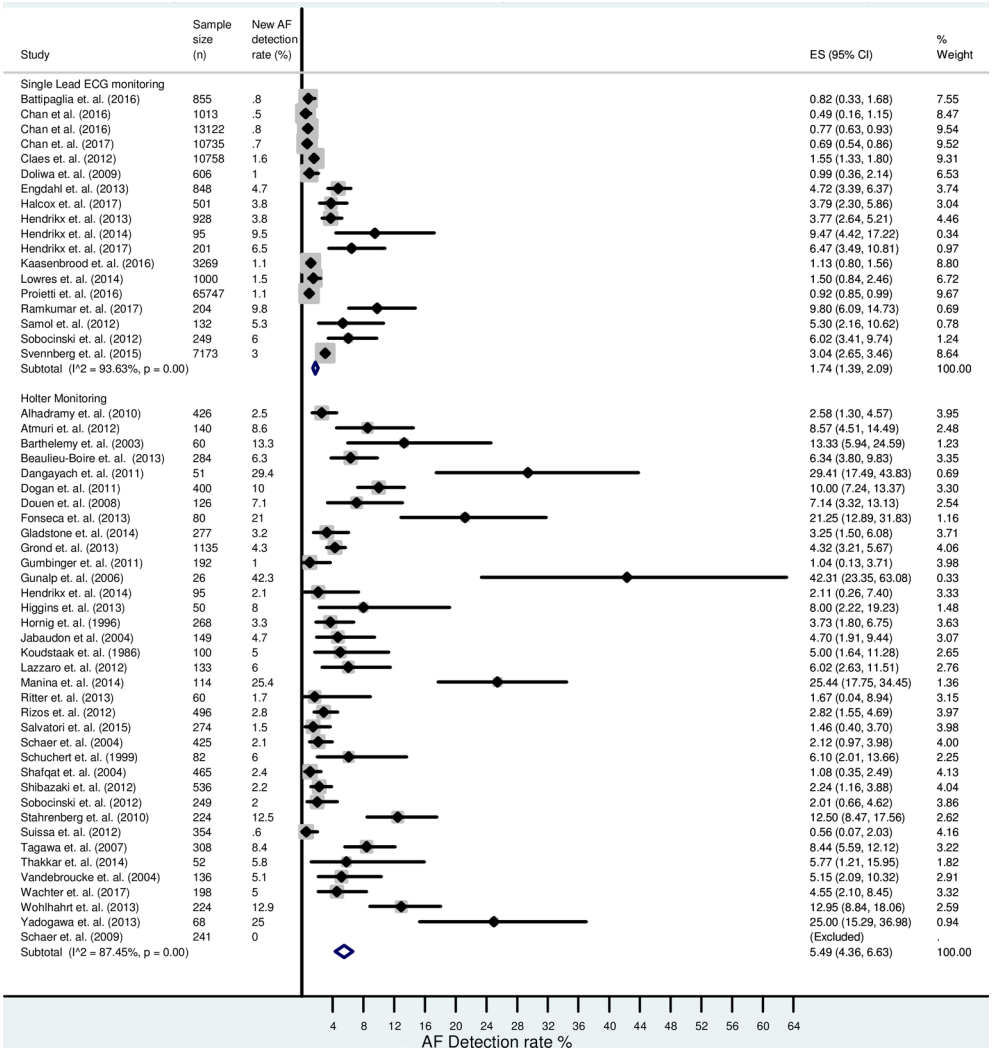

Figure 2 Forest plot showing the overall atrial fibrillation (AF) detection rate between single-lead ECG devices and Holter monitoring.

Comparison of multiple intermittent monitoring with 24 hours Holter

There was significant variation in the monitoring time using both single-lead and Holter monitoring, which contributed to the difference in the cumulative detection rate seen in figure 2. Figure 3 compares the detection rate of multiple intermittent single-lead recordings with 24 hours continuous monitoring, which is used routinely in clinical practice. There were eight studies (n=10 199, mean weighted age 68.8±8.4 years from six studies, 47% male from eight studies) that performed multiple intermittent single-lead ECG recordings and 27 studies (n=6284, mean weighted age 67.8±5.1 years from 23 studies, 58% male from 23 studies) that used 24 hours Holter monitoring. From the data available, the multiple intermittent ECG group had a lower AF risk to the 24 hours Holter group (hypertension 55% (n=8 studies) vs 65% (n=20 studies); diabetes mellitus 15% (n=8 studies) vs 22% (n=20 studies); heart failure 3.3% (n=8 studies) vs 3.9% (n=11 studies); ischaemic heart disease 11% (n=6 studies) vs 19% (n=15 studies) and previous stroke/TIA 9% (n=7 studies) vs 16% (n=15 studies)), respectively. The combined AF detection rate was 4.8% (95% CI 3.6% to 6.0%) using multiple intermittent ECG recordings. The cumulative AF detection rate using 24 hours Holter monitoring was 4.6% (95% CI 3.5% to 5.7%).

Association between monitoring time and AF detection

Using single-lead ECG devices, we found a moderate linear relationship between the total monitoring time and AF detection rate (β=0.13, R^2=0.42). Using this formula, we noted that approximately 19 min of total intermittent monitoring produced similar AF detection to 24 hours continuous monitoring (figure 4). The study by Halcox *et al* was an outlier, with a much lower AF detection rate than other studies (3.8% from 52 min of total monitoring) and this reduced the linear correlation between total monitoring time and AF detection rate.[64] Exclusion of these data led to a stronger linear relationship (β=0.26, R^2=0.80) and a much lower total intermittent monitoring time required (12 min) to produce a similar AF detection rate to 24 hours Holter monitoring.

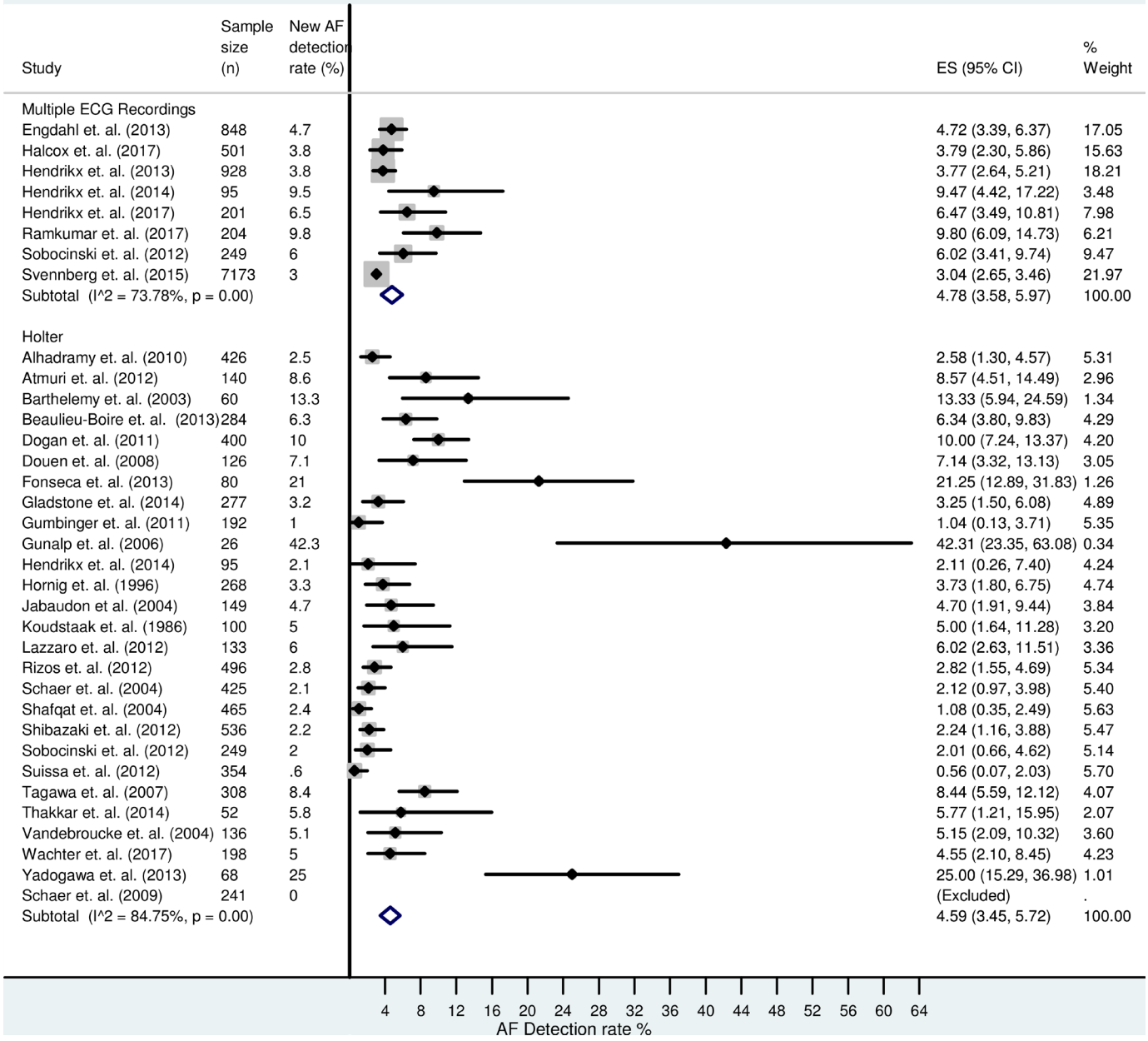

Figure 3 Forest plot comparing the atrial fibrillation (AF) detection rate between 24 hours Holter monitoring and performing multiple intermittent single-lead ECG recordings.

Meta-regression

Sources of heterogeneity in the 18 studies using single-lead ECG monitoring were investigated using meta-regression (table 2). Monitoring time per participant (β=0.11, 95% CI 0.04 to 0.18, p=0.005) and body mass index (β=1.1, 95% CI 0.58 to 1.5, p=0.01) were associated with AF detection.

Sensitivity analysis

A number of outlier studies were observed in the meta-analysis that could influence the cumulative AF detection rate.[37–40 44] Removal of these outlier studies resulted in a reduction in the overall AF detection rate in all Holter studies (table 3) and for 24 hours Holter studies (table 4). When these outlier studies were removed, the overall AF detection rate for 24 hours Holter was 3.86% (95% CI 2.88% to 4.83%), much lower than the detection rate by multiple intermittent ECG recordings using portable single lead devices (4.78%, 95% CI 3.58% to 5.97%). A cumulative meta-analysis (figure 5) did not show any significant variation in the AF detection rate over time using either Holter or single-lead ECG monitoring.

Publication bias

Publication bias was explored using a funnel plot of all included studies (see online supplementary figure 1). There was significant publication bias in both single-lead ECG device and Holter monitoring studies (Egger test, p=0.003 and p<0.001 respectively).

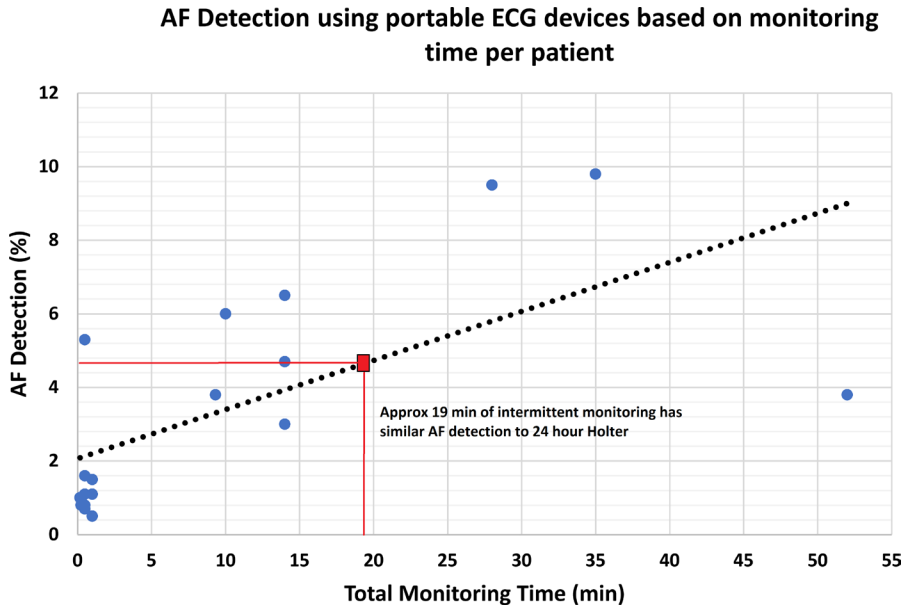

Figure 4 Graph showing the linear relationship between total monitoring time and atrial fibrillation (AF) detection rate in single-lead ECG devices.

Quality of studies

A summary of the quality analysis (see online supplementary table 3) showed that overall quality of reporting was moderate. All studies described the primary objective of the trial and included a summary of the main findings. Detailed comorbidities of the study participants were only adequately reported in 28/52 (54%), and limitations were discussed in 35/52 (67%) of studies. Most had a very selective patient population, 31/52 (60%) were poststroke/TIA cohorts.

DISCUSSION

Our study is the only systematic review that we are aware of that has studied the overall AF detection rate of single-lead portable ECG devices. The results of our systematic review suggest a linear relationship between monitoring time per patient and AF detection rate. Single timepoint screening has an approximate 1% AF detection rate, which can be increased to around 5% when multiple recordings are performed. We noted that approximately 19 min of intermittent monitoring produced similar detection rates to conventional 24 hours continuous Holter monitoring.

Early diagnosis of AF

AF creates a significant burden on both patients as well as the healthcare system. AF will continue to rise in incidence and the costs to the healthcare system will continue to increase, due to ageing, sedentariness and the prevalence of obesity and the metabolic syndrome.[3 68] Early diagnosis offers the possibility for early initiation of treatment, which may reduce the occurrence of the complications and may lead to reduced hospital admissions and associated healthcare costs. Early treatment for AF can be achieved in different ways. Patients with subclinical AF have an increased risk of stroke and cardiovascular

Table 2 Meta-regression analysis for atrial fibrillation (AF) detection (single-lead ECG studies)

Variable	Number of studies	β (95% CI)	P values
Age (years)	15	0.00 (–0.22 to 0.24)	0.95
Monitoring time per participant (min)	18	0.11 (0.04 to 0.18)	0.005
Body mass index (kg/m^2)	4	1.1 (0.58 to 1.5)	0.01
CHADS score (%)	11	–0.13 (–2.6 to 2.4)	0.91
Hypertension (%)	14	0.01 (–0.08 to 0.10)	0.75
Previous diagnosis of AF (%)	16	–0.13 (–0.50 to 0.24)	0.46
Ischaemic heart disease (%)	12	–0.10 (–0.42 to 0.21)	0.48
Previous stroke (%)	13	0.06 (–0.09 to 0.19)	0.45
Male gender	16	0.10 (–0.04 to 0.24)	0.16

Table 3 Outlier studies omitted (all Holter studies) to assess the change to the overall atrial fibrillation (AF) detection rate

Study omitted	Overall AF detection rate (%)	95% CI (%)
Dangayach *et al*[37]	5.27	4.17 to 6.38
Fonseca *et al*[39]	5.26	4.15 to 6.36
Gunalp *et al*[38]	5.32	4.21 to 6.42
Manina *et al*[40]	5.11	4.03 to 6.20
Yadogawa *et al* [44]	5.25	4.14 to 6.35
All studies excluded	4.31	3.36 to 5.26

Table 4 Outlier studies omitted (24 hours Holter) to assess the change to the overall atrial fibrillation (AF) detection rate

Study omitted	Overall AF detection rate (%)	95% CI (%)
Fonseca *et al*[39]	4.30	3.21 to 5.39
Gunalp *et al*[38]	4.39	3.30 to 5.47
Yadogawa *et al*[44]	4.30	3.22 to 5.38
All studies excluded	3.86	2.88 to 4.83

events, like those with established AF.[12 69] Anticoagulation may help reduce the incidence of stroke in this cohort.

The close relationship between metabolic syndrome and AF has encouraged research into the benefits of lifestyle intervention. Aggressive lifestyle intervention in patients with AF undergoing catheter ablation has been reported to lead to a reduction in symptom burden, improved quality of life and the need for repeat ablation procedures.[10] It remains to be tested whether initiation of

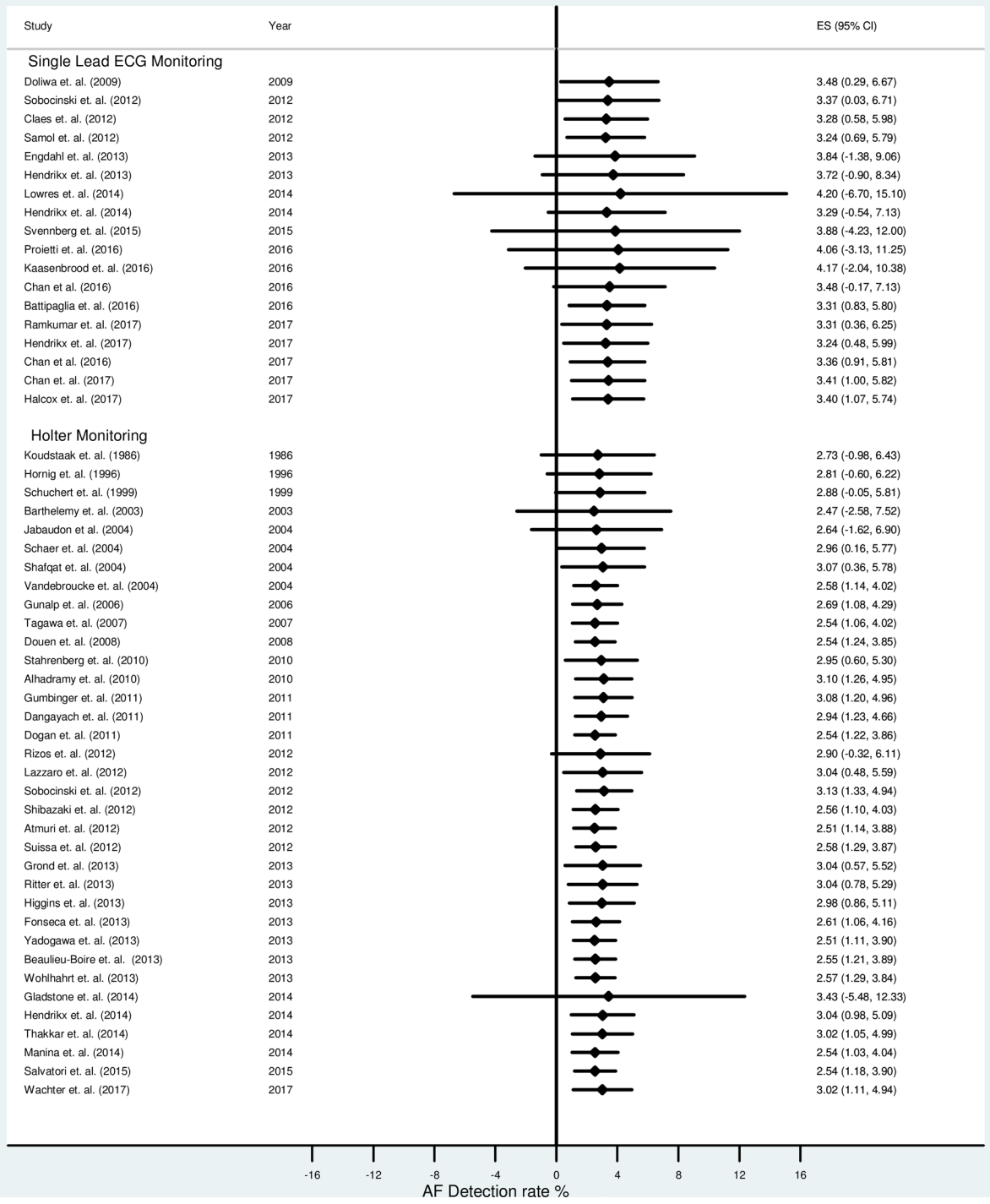

Figure 5 Cumulative meta-analysis showing minimal variation in atrial fibrillation (AF) detection over time using Holter and single-lead ECG devices.

lifestyle intervention and aggressive risk factor modification following the early diagnosis of AF may be associated with positive LA remodelling and reduction of disease progression. Such a process may lead to additional health benefits, including reduction in cardiovascular risk and improvement in exercise capacity.

AF screening and feasibility

AF is a leading cause of stroke and heart failure in the community. As well as an association with increased all-cause mortality, it is associated with reduced quality of life. The availability of preventive therapies, including anticoagulation, has led to increasing recognition of the importance of AF screening for early diagnosis. However, AF screening shares the limitations of screening with other diagnostic tests. The screening tool must have high sensitivity, and needs to be inexpensive and cost-effective. We also need to minimise and have a method of addressing false positives. Current guidelines recommend opportunistic screening using pulse palpation and 12-lead ECG.[11] In a previous systematic review, this was associated with a new AF detection rate of approximately 1%.[5] Pulse palpation may be non-specific in patients with other irregular rhythms such as ventricular ectopy, and 12-lead ECG is only able to capture a single timepoint for screening. There are multiple other methods for AF detection. Continuous Holter monitoring is probably the most commonly used in clinical practice, especially in stroke cohorts. It has the potential advantage of assessing heart rhythm throughout the day and may be useful in detecting nocturnal subclinical AF. However, the disadvantages include the cost of Holter monitoring (especially for mass screening), the inconvenience of leads and electrodes (which may affect compliance) and typical limitation to 1–2 days of capture (as extended periods are more cumbersome and less cost-effective). Other event recorders are again expensive and limited to symptomatic patients. Extended period monitoring using implantable devices have shown promise in the cryptogenic stroke population (where many have been diagnosed with paroxysmal AF),[70] but they are invasive and not feasible for mass screening.

Portable single-lead ECG devices permit multiple 30–60 s recordings to be captured, and downloaded to a computer. These devices have several potential advantages over Holter monitoring. They are leadless and require finger contact (and are hence easy to use and acceptable to patients). They have a high degree of sensitivity for identifying AF.[71–73] Most interface with a web-based cloud system where ECG rhythms can be wirelessly transferred to clinicians, allowing rapid analysis and diagnosis. The development of automated algorithms to detect AF is helpful for mass screening. In two small studies they have demonstrated superior AF detection compared with 24 hours Holter monitoring.[66 67] Although screening using these portable devices are currently not in the latest AF guidelines, they may offer a feasible option for mass screening. Screening using these devices has been demonstrated to be cost-effective.[74 75]

We noted a moderate linear association between monitoring time and AF detection rate. Single timepoint screening for 30–60 s achieved an overall detection rate of approximately 1%. This is no better than what has been reported using pulse palpation or 12-lead ECG, hence does not add any incremental benefit in screening programmes.[5] Multiple intermittent recordings improve AF detection; we found that at least 19 min of total monitoring should be performed to achieve detection rates similar to 24 Holter monitoring.

The linear relationship between monitoring time and AF detection rate (R^2=0.80) and the reproduction of AF detection rates of 24 hours Holter monitoring with only 12 min of intermittent monitoring was possible in our study only after exclusion of an outlier.[64] Despite the inclusion of elderly participants with at least one risk factor for AF, the use of a validated single-lead ECG device and a prolonged monitoring period, that study had a lower AF detection rate (3.8%) than the remaining studies, even using a shorter monitoring period.[53 56 57] Relatively low rates of adherence (only approximately 25% completed 2×30 s ECG recordings every week for the full year of monitoring) may be a potential explanation for the lower AF detection rate noted.[64]

Limitations

There are several challenges inherent in this meta-analysis of studies investigating AF detection. The most important is the target screening population. Most studies did not report the CHADS or CHA_2DS_2-VASC score, a history of previous stroke or other comorbidities. Consequently, it was difficult to ascertain if the risk profiles of patients in these studies were equivalent. Most Holter monitoring studies were performed in the stroke population—which is likely a population with higher AF risk than many studies using portable ECG devices, which recruited mainly healthy participants or those with AF risk factors from the community. The significant heterogeneity among both Holter and portable ECG device studies make it difficult to perform direct comparisons between both groups. The type/duration of monitoring and type of device used will also influence the overall AF detection rate and varied significantly between studies. There are several possible confounders which may not have been taken into account. The validity of the linear regression analysis comparing detection time and rate may be limited due to the significant differences in study population, study design and AF definitions. However, despite these limitations, the analysis may provide some important inferences into AF screening. Multiple intermittent ECG recordings achieved a similar AF detection rate to 24 hours Holter monitoring. This may suggest that in a similar cohort of patients with the same comorbidities,

single-lead intermittent monitoring may be superior for AF detection.

Compared with 24 hours continuous monitoring, single-lead portable ECG monitoring is more patient dependent. Good patient compliance is essential to obtain multiple readings across different timepoints which improves sensitivity. The analysis performed does not take into account patient compliance as this is difficult to assess and poorly reported across the individual studies. Most single-lead device manufacturers have proprietary automated AF detection algorithms, which were used for diagnosis. Not all of these algorithms have had rigorous testing and comparison to a reference standard. It is also difficult to distinguish AF from other supraventricular tachycardias using single-lead ECG devices as the P wave is often not readily discernible. The use of different automated algorithms makes AF definitions non-standardised and can potentially create issues with both overdiagnosis and underdiagnosis.

There are other limitations in this analysis. The efficacy of intermittent monitoring is critically dependent on AF burden and density. All studies varied in their monitoring period and strategy. The linear regression model used was able to determine a total intermittent monitoring time, which produced similar AF detection rates to 24 hours continuous monitoring. However, it is difficult to translate the total monitoring time into an effective monitoring strategy. For example, we are unable to determine from our analysis if 12×60 s recordings over 12 consecutive days is different to 2×60 s recordings daily for six consecutive days. The definitions of AF also vary between studies. Many are based on individual physician interpretation and criteria for diagnosis were not explicitly specified. The duration of AF varied from 10 to 30 s between studies, although a cut-off of 30 s was the most widely adopted practice.

CONCLUSION

Single-lead portable ECG devices may offer an efficient screening option for AF compared with 24 hours Holter monitoring. Total monitoring time is related to AF detection and a total of 19 min may achieve a similar detection rate to 24 hours Holter monitoring.

Contributors SR performed the literature search and analysis of individual studies. Involved in the statistical analysis, manuscript preparation and editing. THM is guarantor. Developed project idea/rationale. Involved in data analysis and manuscript preparation and editing. NN was involved in data and statistical analysis as well as manuscript preparation and editing. DDS performed the literature search and analysis of individual studies. Involved in the manuscript preparation and editing. DJP was involved in analysis of individual studies and statistical analysis. Involved in manuscript preparation and editing. JMK was involved in the project outline, data analysis, manuscript preparation and editing.

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Data sharing statement There are no remaining unpublished data.

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