Effectiveness, reach, uptake, and feasibility of digital health interventions for adults with hypertension: a systematic review and meta-analysis of randomised controlled trials

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Summary

Background Digital health interventions are effective for hypertension self-management, but a comparison of the effectiveness and implementation of the different modes of interventions is not currently available. This study aimed to compare the effectiveness of SMS, smartphone application, and website interventions on improving blood pressure in adults with hypertension, and to report on their reach, uptake, and feasibility.

Methods In this systematic review and meta-analysis we searched CINAHL Complete, Cochrane Central Register of Controlled Trials, Ovid Embase, Ovid MEDLINE, and APA PsycInfo on May 25, 2022, for randomised controlled trials (RCTs) published in English from Jan 1, 2009, that examined the effectiveness of digital health interventions on reducing blood pressure in adults with hypertension. Screening was carried out using Covidence, and data were extracted following Cochrane's guidelines. The primary endpoint was change in the mean of systolic blood pressure. Risk of bias was assessed with Cochrane Risk of Bias 2. Data on systolic and diastolic blood pressure reduction were synthesised in a meta-analysis, and data on reach, uptake and feasibility were summarised narratively. Grading of Recommendations, Assessment, Development, and Evaluation criteria were used to evaluate the level of evidence. The study was registered with PROSPERO CRD42021247845.

Findings Of the 3235 records identified, 29 RCTs from 13 regions (n=7592 participants) were included in the systematic review, and 28 of these RCTs (n=7092 participants) were included in the meta-analysis. 11 studies used SMS as the primary mode of delivery of the digital health intervention, 13 used smartphone applications, and five used websites. Overall, digital health intervention group participants had a –3·62 mm Hg (95% CI –5·22 to –2·02) greater reduction in systolic blood pressure, and a –2·45 mm Hg (–3·83 to –1·07) greater reduction in diastolic blood pressure, compared with control group participants. No statistically significant differences between the three different modes of delivery were observed for both the systolic (p=0·73) and the diastolic blood pressure (p=0·80) outcomes. Smartphone application interventions had a statistically significant reduction in diastolic blood pressure (–2·45 mm Hg [–4·15 to –0·74]); however, there were no statistically significant reductions for SMS interventions (–1·80 mm Hg [–4·60 to 1·00]) or website interventions (–3·43 mm Hg [–7·24 to 0·38]). Due to the considerable heterogeneity between included studies and the high risk of bias in some, the level of evidence was assigned a low overall score. Interventions were more effective among people with greater severity of hypertension at baseline. SMS interventions reported higher reach and smartphone application studies reported higher uptake, but differences were not statistically significant.

Interpretation SMS, smartphone application, and website interventions were associated with statistically and clinically significant systolic and diastolic blood pressure reductions, compared with usual care, regardless of the mode of delivery of the intervention. This conclusion is tempered by the considerable heterogeneity of included studies and the high risk of bias in most. Future studies need to describe in detail the mediators and moderators of the effectiveness and implementation of these interventions, to both further improve their effectiveness as well as increase their reach, uptake, and feasibility.

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Introduction

Hypertension affects an estimated 1·28 billion people globally and is the leading level 2 risk factor for attributable deaths.[1] Suboptimal blood pressure was estimated in 2009 to incur health-care and indirect costs of $3·6 trillion per annum in total.[2] Current guidelines recommend that adults with hypertension have a blood pressure of less than 140/90 mm Hg (<130/90 mm Hg

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Research in context

Evidence before this study

Digital health interventions have shown promising results for hypertension self-management. We searched MEDLINE, the Cochrane Library, and the PROSPERO systematic review protocol database, from inception to May 1, 2022, to identify meta-analyses that compared the effectiveness of SMS, smartphone applications, and website interventions in adults with hypertension. We identified a 2016 meta-analysis reporting that digital health interventions lowered both systolic and diastolic blood pressure in people with hypertension, compared with usual care. That review was limited by the small number of studies included (seven), their heterogeneity (three used mobile phones, two websites, one email, and one a telephone-linked computer system) and a small pooled sample size. Additionally, due to the rapid advancements in technology, some studies have been published in the 7 years since that review that warrant an update on the evidence. Most importantly, although different modes of digital health such as SMS, smartphone applications, and websites are being employed to deliver interventions, there is no synthesis of their compared effectiveness and implementation to facilitate informed decisions.

Added value of this study

To facilitate clinicians' decisions regarding which digital tool is more effective for self-management of hypertension, to our knowledge we present the first meta-analysis to compare the effectiveness and implementation of SMS, smartphone applications, and website interventions in adults with hypertension. We synthesised results from 29 RCTs from 13 regions, including 7592 participants. We report that digital health interventions are effective in reducing systolic and diastolic blood pressure in adults with hypertension, irrespective of mode of delivery. Although SMS interventions displayed higher reach, smartphone application interventions were associated with a higher participant uptake, but the differences were not statistically significant. Considerable heterogeneity was observed between the included studies, and most were assessed as of high risk of bias.

Implications of all the available evidence

Considering that at least 92% of the global population has access to a digital telecommunication medium and that numerous digital health tools are available for hypertension management, clinicians should familiarise themselves with this modality of intervention delivery and encourage people with hypertension to use evidence-based digital health tools for improving their self-management of hypertension. Digital health interventions now have the option of several modes of delivery and choice should be made based on context, feasibility, economics, and patients' preference, emphasising the importance of study co-design. Future effectiveness studies should focus on head-to-head comparisons of the different modes of delivery, and should describe in detail the mediators and moderators of the effectiveness and implementation of these interventions. Finally, considering that this study identified mostly studies in high-income and upper-middle-income countries, the effectiveness of these interventions in additional lower-middle-income as well as in low-income countries should be examined.

for adults with high cardiovascular risk) to reduce the risk of adverse outcomes.[3,4]

Self-management education and support has been extensively used as a strategy aiming to provide patients with the appropriate health literacy and skills for the successful sustainable control of hypertension.[5] In recent years, digital health interventions have shown promising results as a feasible and effective means of supporting hypertension self-management.[6–8] Digital health interventions allow for a wide reach of populations, with reports from January, 2023, indicating that 6·9 billion people in the world (86% of global population) have access to a smartphone,[9] 7·3 billion (92%) people use a conventional mobile phone,[9] and 5·1 billion (64%) people access the internet.[10] Digital health interventions can be delivered synchronously or asynchronously, thus presenting a more convenient and accessible form of health-care delivery compared with the traditional face-to-face mode.[11] Both synchronous, such as real-time collection and transmission of data (eg, blood pressure measurements, participation in online forums with peers, and video conferencing), and asynchronous capabilities, such as SMS to reinforce healthy lifestyle modifications, have been used for hypertension management.[6,7,12–14]

A 2016 meta-analysis reported that digital health interventions lowered both systolic blood pressure (SBP) and diastolic blood pressure (DBP) in people with hypertension, compared with usual care.[15] However, the analysis was limited by the small number of studies included (seven), their heterogeneity (three used mobile phones, two websites, one email, and one a telephone-linked computer system), and the small pooled sample size. Additionally, due to the rapid advancements in technology, a number of studies have been published in the 7 years since that review that warrant an update on the evidence. Most importantly, although different modes of digital health such as SMS, smartphone applications, and websites are being employed to deliver interventions, there is no synthesis of their compared effectiveness and implementation to facilitate informed decisions.

To facilitate clinicians' decisions regarding which digital tool is more effective for self-management of hypertension, we aim to compare SMS, smartphone applications, and websites, and report on their effectiveness, reach, uptake, and feasibility.

Methods

Search strategy and selection criteria

The protocol and reporting were consistent with the 2020 PRISMA guidelines.[16] APA PsycInfo, CINAHL Complete, Cochrane Central Register of Controlled Trials, Ovid Embase, and Ovid MEDLINE were searched on May 25, 2022, with MeSH and broad search terms. The complete search strategy is in the appendix (pp 2–8). The search strategy was optimised to capture studies in people with type 2 diabetes and hypertension. Due to the volume of data, the findings in people with diabetes are reported separately.[17]

Retrieved studies were imported into Covidence systematic review software (Veritas Health Innovation, Melbourne, VIC, Australia). After removing duplicates, the remaining studies were assessed for eligibility by two researchers (GS and JJ). The inclusion and exclusion criteria are in the appendix (p 8). Briefly, randomised controlled trials (RCTs) of hypertension management programmes in adults, implementing digital health interventions and published in English from Jan 1, 2009, were considered for inclusion. Digital health interventions that only consisted of telecounselling or telemonitoring and did not include an SMS, smartphone application, or website component were excluded. The year 2009 was selected as that was when digital health applications started to become widely adopted.[18] We also hand-searched the reference lists of included articles. The systematic review protocol was registered in PROSPERO, CRD42021247845.

Data extraction

A comprehensive data extraction form was developed (GS) on the basis of the guidelines in the Cochrane Handbook for Systematic Reviews of Interventions.[19] The form was piloted on a subset of the included studies (GS, JJ, and EE), before extracting the following data: publication details (title, journal, and year); authors' details (names, affiliations, funding, and conflicts of interest); study details (start and end date, country, design, purpose, masking and randomisation method, retention rate, and statistical analyses); participants' characteristics (condition, severity of condition, comorbidities, inclusion and exclusion criteria, sample size, recruitment process, and demographics—ie, age, sex, race, ethnicity, income, education, and remoteness of residence); intervention (type, duration, frequency, other details, and primary and secondary outcome); comparison (details of care and other details); results (timepoint for follow-up, primary and secondary outcomes [with SDs, SEs of means, 95% CIs, and statistical significance], and validated tool for measurement); and conclusions.

Evidence and outcomes

The evidence tables summarise the relevant study characteristics, the intervention and comparator treatments, and their outcomes, and report on the effectiveness of the intervention. An intervention was classified as effective if the digital health intervention resulted in statistically significant ($p<0·05$) results, as compared with the control group, and classified as not effective if there were no statistically significant differences between the groups for the primary outcome. The primary endpoint was change in the mean (and 95% CI) of SBP. Secondary endpoints of interest included change in DBP, blood pressure control, total cholesterol, HDL and LDL cholesterol, triglycerides, fasting plasma glucose, changes in medication, and anthropometric outcomes.

See Online for appendix

Quality assessment of included studies

The revised Cochrane risk-of-bias version 2 tool was used to assess the quality of the studies on aspects of selection (random-sequence generation and allocation concealment); performance and detection (masking of participants, personnel, and assessors; deviations from intended interventions; missing outcome data; and measurement of the outcome); appropriateness of analysis (selection of the reported outcome); and bias arising from period and carryover effects (for crossover studies).[20] The pertinent versions of the tool (version 2 subcatagories) were used to appraise the quality in included parallel-group, cluster, and crossover RCTs. Studies were ranked by two authors (GS and EE), with discrepancies resolved by discussion.

For the **systematic review protocol** see https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42021247845

Meta-analysis

Within-group difference in means for SBP and DBP and their SDs for intervention and control groups were entered into Review Manager software (v5.4.1; The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark). To increase the precision of the point estimate, when only between-group differences were reported, the within-group differences were requested from the authors. If SE or 95% CI were reported instead of SD or SE, then these were calculated as described in Chapter 7.7.3.2 of Cochrane's handbook.[21] If none of SD, SE, or 95% CI could be obtained from published data or following communication with the authors, then SDs were imputed according to the recommendations in Chapter 16.1.3.1 of Cochrane's handbook.[21] The effect sizes and SDs of the studies were pooled by use of the random-effects model, because there was substantial heterogeneity.[22] The assumption of homogeneity of true effect sizes was assessed by the Cochran's Q test, and the degree of inconsistency across studies (I^2) was calculated.[23,24] Subgroup analyses, by mode of delivery of the intervention, income economy of the country where the study took place, participants' baseline SBP, and intervention objective, were carried out to assess possible causes of heterogeneity. The robustness of the estimate was assessed via a series of sensitivity analyses that included sequentially removing

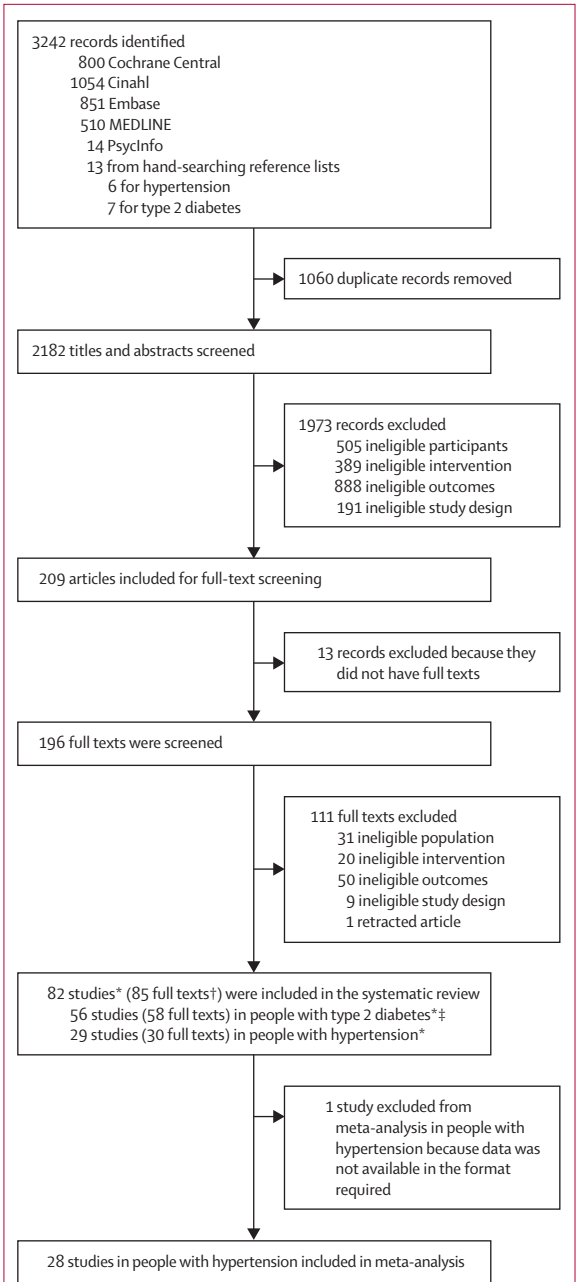

Figure 1: **Study selection**
*Three studies included participants with type 2 diabetes and hypertension. †Three studies' results were reported in two manuscripts. ‡The included studies in people with type 2 diabetes are reported in a separate manuscript.[17]

each study and reanalysing the remaining datasets to identify if a single study was responsible for the direction of associations, and by testing whether the fixed-effects model would produce different results.[21] Publication bias was assessed by visually inspecting a funnel plot of the mean change in SBP and DBP plotted against their corresponding SE, on the assumption that interventions achieving SBP or DBP reductions and with larger samples were more likely to be published.[21]

Quality assessment of the overall evidence

The quality of the overall evidence was assessed using Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) criteria.[25] Briefly, GRADE evaluates the type of evidence, risk of bias, consistency between studies, directness to the research question and precision of the estimate. All 28 studies included in the meta-analysis were given an initial score of +4, because observational studies were excluded. A point was deducted for serious risk of bias (eg, absence of appropriate randomisation), inconsistency (eg, due to substantial heterogeneity I^2>50%),[26] and imprecision (eg, when the 95% CI of the pooled effect overlapped the line of no effect).[27] The scoring process is described in the appendix (p 9).[28]

Evaluation of reach, adoption or uptake, and feasibility of interventions

Data related to reach, adoption or uptake, and feasibility of interventions were extracted by two authors (BY-AA and VK). In line with the Medical Research Council process evaluation framework, reach was defined as the intended audience who came into contact with the intervention.[29] Feasibility was defined as the capability of carrying out an intervention or programme, and was measured in terms of acceptability, adherence, likelihood of cost-effectiveness, or capacity of providers to deliver the intervention.[30] We relied on authors' interpretations to report on study feasibility, because the components of feasibility measurement varied between studies. Based on the Reach, Effectiveness, Adoption, Implementation, and Maintenance framework, adoption or uptake was defined as the reported action of taking up or making use of the intervention or health promotion programme.[31] We considered reach and adoption or uptake at the individual level. Studies using different frameworks were included when their definitions were not considerably different from the aforementioned. We compared reach and uptake of SMS, smartphone applications, and website interventions using the z-test.

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the manuscript.

Results

The database search yielded 3229 records and a further 13 records were identified through hand-searching reference lists. 2182 titles and abstracts were screened (figure 1). 196 full-text articles were assessed for eligibility. 111 articles were removed and the reasons are in the appendix (pp 10–18). 56 studies (58 articles) in people with diabetes are reported in a separate manuscript.[17]

30 articles from 29 studies were included in the systematic review.[32–61]

A total of 7592 participants from 13 regions were included (table 1). 21 studies were conducted in high-income economies, six in upper-middle-income economies, and two in lower-middle-income economies (appendix p 37).[62] 23 studies were conducted in the past 6 years (2016 and after) and six between 2009 and 2015. 25 RCTs employed a parallel group design and four a cluster design. The study characteristics per mode of delivery are described in the appendix (pp 38–39). 11 studies used SMS as the primary mode of delivery of the digital health intervention,[32–36,54–59] 13 used smartphone applications,[37–47,60,61] and five used websites.[48–53] SMS interventions had a mean of 563 (SD 545) participants and 92% (SD 6) retention with a mean duration of 7·9 months (SD 4·8). At baseline, participants were on average 35% (SD 9) men, had a mean age of 55·9 years (SD 6·4), mean SBP of 147·1 mm Hg (SD 11·4), and mean DBP of 87·8 mm Hg (SD 7·0). Smartphone application interventions had a mean of 188 participants (SD 165·4) and 89% (SD 12) retention over a mean duration of 6·5 months (SD 3·7). At baseline, participants were on average 49% (SD 11) men, had a mean age of 50·3 years (SD 6·1), mean SBP of 141·1 mm Hg (SD 8·0), and mean DBP of 83·4 mm Hg (SD 4·6). Website interventions had a mean of 298 participants (SD 114) and 83% (SD 10) retention over a mean duration of 9·6 months (SD 3·3). At baseline, participants were on average 43% (SD 6) men, had a mean age of 61·8 years (SD 3·4), mean SBP of 144·8 mm Hg (SD 9·0), and mean DBP of 83·0 mm Hg (SD 5·1). In 26 of the included 29 RCTs, the participants were on antihypertensive medications. Two studies only included non-medicated participants,[37,38] and in one study most participants were not receiving antihypertensives.[45] 27 RCTs only included participants with uncontrolled hypertension, whereas two RCTs also included participants with controlled hypertension.[53,58]

Study aims or objectives varied considerably. Nine studies assessed the effect of the intervention on blood pressure control or reduction,[36,38,40–42,45,50,59,60] six monitored medication adherence,[41,55,56,58,60,61] two focused on blood pressure monitoring,[54,57] and five evaluated efficacy and implementation of the digital programme.[33,46,48,49,51] Other studies assessed the effect of the intervention on promoting non-pharmacological treatment,[35] increasing health literacy,[34] supporting treatment adherence,[32] reducing sodium intake,[39] and improving patient self-care.[44] One study compared the digital intervention to a successful coaching model,[43] and another one assessed the combined effect of the digital component together with medication on reducing blood pressure.[37] Interventions employed SMS to deliver education, promote medication adherence, provide reminders for blood pressure self-monitoring and for visits to clinics, and for motivational reinforcement.[32,33,55,58,59] Some interventions allowed communication between participants and health-care professionals via bidirectional SMS.[56,57] A study that included linguistically diverse populations adapted the messages to the participants' language.[35] SMS frequency ranged from daily to weekly.

Smartphone applications were also used for education,[37,38] medication reminders,[41] and blood pressure monitoring reminders.[41] Due to the smartphones' capabilities, applications included features enabling the telemonitoring of heart rate,[37] providing electronic medication trays,[61] exercise logs,[45] and allowing participants to create their own self-management plan followed by automatic feedback.[47] Various telemonitoring capabilities were explored including the use of Bluetooth technology for communication between wearable sensors and the application, as well as ingestible sensors.[40,44,45] Communication between participants and health-care professionals was facilitated via audio and visual means,[37] and instant messaging group chats.[42,46]

Website interventions offered telemonitoring via online data recording forms,[48,50,53] and had the ability to notify general practitioners about atypical readings.[49] Automatic prescription generation without the need to see a general practitioner was also used.[49] Finally, other interventions incorporated automatic email reminders,[48,53] and delivered online education sessions.[51,52]

Most studies compared interventions with usual care or an enhanced version of usual care, (eg, some form of education).[32,37,46,47,50] In most, education for the control group occurred only at baseline; however, some offered continuous education. A few studies allowed control participants very limited access to the digital health intervention.[37,43,61]

Of the 29 included studies, 17 were classified as high risk, four studies were classified as having some concerns, and eight studies were assessed as low risk of bias (appendix p 40). Nine studies were assessed as high risk of bias for the randomisation process.[38–43,45,48,49] Three of these concealed the allocation sequence before assigning participants,[42,48,49] and seven did not provide complete information about the randomisation or concealment process.[38–43,45] With regard to deviations from intended intervention, seven did not mask participants and study personnel to intervention assignment;[39,41,42,45,48,49,61] however, such masking is typically not possible in digital interventions. Three studies did not report on the masking of participants.[35,46,61] Regarding attrition bias, 11 studies reported high attrition rates or inadequate methods to eliminate potential bias caused by missing data, or both.[37,45,47–49,51–53,55,57,58,61] In assessing measurement bias, nine studies received a high risk of bias classification for having employed self-reporting of outcomes,[35,39,41,45–47,57,58,61] not providing information on adequate training of personnel for the measurement of outcomes, or not specifying whether outcome assessors were aware of participants' intervention assignment. With regard to the selection of reported results, three

studies did not include all outcome measurements or all forms of data analysis, resulting in a high risk of bias.[38,49,61] Overall, most of the SMS intervention studies were assessed as low risk, but the majority of smartphone and website intervention studies were assessed as high risk.

	Study design; duration; retention	Intervention	Outcomes		Conclusion*
			Primary	Secondary	
Characteristics of included studies that incorporated SMS interventions					
Bobrow et al (2016),[32] South Africa	RCT; 12 months; 1196/1372 (87%)	Automated adherence support system; two groups (informational only and interactive); weekly SMS focused on the techniques of goals and planning, repetition and substitution, social support, and natural consequences; informational only received SMS to motivate adherence to medication, and to provide education about HTN; interactive received all informational only messages and in addition could respond to selected messages using free-to-user "Please-Call-Me" requests	ΔSBP −11 mm Hg (control), −3 mm Hg (informational only), −2·9 mm Hg (interactive); informational only *vs* control, p=0046; interactive *vs* control, p=0·16; proportion blood pressures <140/90 mm Hg for informational only *vs* control 1·42 (p=0·033) and for interactive *vs* control 1·41 (p=0·038)	Satisfaction with treatment for informational only *vs* control was 0 (p>0·99) and interactive *vs* control was 0 (p>0·99); self-reported adherence for informational only *vs* control was 0·04 (p=0·70) and interactive *vs* control was 0·02 (p=0·80); hospital admissions for informational only *vs* control was 0·73 (p=0·24) and interactive *vs* control was 0·94 (p=0·81); medication changes for informational only *vs* control was 118 (p=0·26) and interactive *vs* control was 1·04 (p=0·78)	Effective for BP
Davidson et al (2015),[33] USA	RCT; 6 months; 38/43 (88%)	Motivational and reinforcement SMS, email, or voice mail; smartphone for immediate audio and visual feedback on BP after each measurement; wireless electronic medication tray for reminder signals; wireless Bluetooth-enabled BP monitor	ΔSBP −34·8 mm Hg (intervention) and −12 mm Hg (control; p<0·0001); ΔDBP −7·7 mm Hg and —4·5 mm Hg (control; p=0·001)	SBP control (<140 mm Hg) sustained from months 1 to 6 was 70·6% (intervention) and 6·3% (control; p=0·0004); DBP control (<90 mm Hg) sustained from months 1 to 6 was 94·1% (intervention) and 37·5% (control; p=0·008)	Effective (results not specific to SMS component)
He et al (2017),[54] Argentina	Cluster RCT; 18 months; 1357/1432 (95%)	Community health worker-led home-based intervention (health coaching and home BP monitoring and audit), physician education and BP feedback, and individualised weekly SMS to promote lifestyle changes and reinforce medication adherence	ΔSBP −19·3 mm Hg (intervention) and −12·7 mm Hg (control; p<0·001); ΔDBP −12·2 mm Hg (intervention) −6·9 mm Hg (control; p<0·001)	Proportion of controlled hypertension 72·9% (intervention) and 52·2% (control); adherence to antihypertensive medication 66·1% (intervention) and 53% (control)	Effective
Jahan et al (2020),[34] Bangladesh	Prospective RCT; 5 months; 412/420 (98%)	SMS for education and behaviour changes motivation (eg, PA, healthier diet, and medication adherence); SMS reminders for behaviour changes based on the Dietary Approaches to Stop Hypertension diet	ΔSBP −11·1 mm Hg (intervention) and −8·6 mm Hg (control; p=0·04); ΔDBP −5·0 mm Hg and −4·4 mm Hg (control; p=0·02)	Adherence rate of salt intake was 66·5% (intervention) and 75·8% (control; p=0·04) and PA was 72·7% (intervention) and 82·0% (control; p=0·03)	Effective
Mehta et al (2019),[56] USA	RCT; 4 months; 126/149 (83%)	Bidirectional SMS for medication adherence monitoring	ΔSBP −4·6 mm Hg (intervention) and −4·7 mm Hg (control; p=1·00); ΔDBP 7·3 mm Hg (intervention) and 4·0 mm Hg (control; p=0·31)	Proportion with controlled hypertension 25·0% (intervention) and 37·5% (control)	Not effective
Rehman et al (2019),[35] Pakistan	Pilot prospective RCT; 3 months; 120/120 (100%)	Five SMS per week in Urdu or English, on nutrition education, PA, and motivation; daily SMS reminder to take medicine on time; weekly SMS requesting BP report	ΔSBP −8 mm Hg (intervention) and −2 mm Hg (control); ΔDBP −6 mm Hg (intervention) and −3 mm Hg (control); no statistical significance reported	Intervention group reported feeling "fresher and more energetic" and having "better mood" at the end of the study *vs* the control group	Cannot be assessed with reported data
Schroeder et al (2020),[58] USA	RCT; 12 months; 250/295 (84·7%)	Interactive voice response and SMS; messages included reminders for clinic visits, monthly medication refill reminders, weekly motivational messages	ΔSBP 0·23 mm Hg (intervention) and 1·66 mm Hg (control; p=0·57); ΔDBP 1·34 mm Hg (intervention) and 1·10 mm Hg (control; p=0·88)	Self-reported medication adherence improved comparably in both groups	Not effective
Tahkola et al (2020),[59] Finland	Cluster RCT; 12 months; 111/118 (94%)	Personalised SMS support and a checklist for initiation of antihypertensive medication; information on the checklist was used to personalise SMS support in terms of timing, BP target, and medication	ΔSBP −23 mm Hg (intervention) and −21 mm Hg (control; p=0·61); ΔDBP 1·34 mm Hg (intervention) and 1·10 mm Hg (control; p=0·88)	Medication changes, number of antihypertensives at 12 months, and health-care use was similar in both study groups; patients considered checklist and text message support useful and important	Not effective
Varleta et al (2017),[55] Chile	RCT; 6 months; 291/314 (94%)	SMS related to antihypertensive drug adherence and healthy lifestyle	ΔSBP −7·8 mm Hg (intervention) and −3·2 mm Hg (control; p>0·05); ΔDBP −3·1 mm Hg (intervention) and −0·3 mm Hg (control; p>0·05)	Antihypertensive drug adherence increased from 49% (pre-intervention) to 62·3% (post-intervention) in intervention group and decreased from 59·3% to 51·4% in control group (p=0·01)	Not effective for BP; effective for medication adherence
Zahr et al (2019),[57] USA	RCT; 6 months; 301/430 (70%)	Bidirectional SMS platform incorporated into patients' electronic medical records to allow self-reporting of BP and sending patient messages to remind BP checks and accurate recordings of times	ΔSBP −4·7 mm Hg (intervention) and −5·7 mm Hg (control; p=0·658); ΔDBP −4·3 mm Hg (intervention) and −4·1 mm Hg (control; p=0·851)	72% of the intervention group submitted at least 14 readings, compared with 45% of the control group	Not effective

(Table 1 continues on next page)

	Study design; duration; retention	Intervention	Outcomes		Conclusion*
			Primary	Secondary	
(Continued from previous page)					
Zhai et al (2020),[36] China	Cluster RCT; 3 months; 312/384 (81%)	Personal consultations by trained pharmacy students; SMS every 3 days; intervention group and control group were given standard pharmaceutical care according to the Guidelines for Good Pharmacy Practice	ΔSBP −11·5 mm Hg (intervention) and −9·2 mm Hg (control; p=0·001); ΔDBP 0·3 mm Hg (intervention) and −2·7 mm Hg (control; p=0·06)	8-item MMAS score 0·39 (p=0·04); knowledge score 0·44 (p=0·004)	Effective
Characteristics of included studies that incorporated smartphone app interventions					
Chandler et al (2020),[37] USA	Small-scale efficacy RCT; 12 months; 26/30 (87%)	Tension Tamer app used a smartphone's camera lens to acquire continuous measures of heart rate; audio guide for breathing and relaxation directions	ΔSBP −11·6 mm Hg (intervention) and −0·4 mm Hg (control; p<0·04); percentage of participants with SBP control across the duration of the active trial was 60·3% with Tension Tamer and 35·8% with control (p=0·003)	Percentage meeting the 2017 American College of Cardiology and American Heart Association Revised Guidelines for Controlled SBP (<130 mm Hg) was 91·7% (Tension Tamer) and 50·0% (control; p=0·029); Percentage meeting the 75% adherence benchmark was 38·5% (Tension Tamer) and 27·3% (control; p=0·582)	Effective
Chandler et al (2019),[61] USA	Efficacy RCT; 9 months; 54/56 (96%)	Intervention used the Smartphone Med Adherence Stops Hypertension (SMASH) app which interfaced with a Bluetooth-enabled BP monitor and an electronic medication tray	ΔSBP −30·5 mm Hg (intervention) and −5·0 mm Hg (control; p<0·01); ΔDBP −7·4 mm Hg (intervention) and −10·4 mm Hg (control; p<0·01)	Average medical regimen adherence SMASH was 89·1% to 95·2%	Effective
Cho et al (2020),[38] South Korea	RCT; 6 months; 111/129 (86%)	App for weight management and daily PA and food intake logs, energy intake, and expenditure calculations followed by personalised diet or PA advice; app only and app plus personalised coaching	ΔSBP at week 24 −10·95 mm Hg (control), −7·29 mm Hg (app only), and −7·19 mm Hg (app plus personalised coaching); control *vs* app only p=0·19; control *vs* app plus personalised coaching p=0·16	ΔSBP at week 12 was −7·48 mm Hg (control), −4·84 mm Hg (app only), and −7·82 mm Hg (app plus personalised coaching); control *vs* app only p=0·43; control *vs* app plus personalised coaching p=0·92	Not effective
Dorsch et al (2020),[39]† USA	Single centre prospective pilot RCT; 8 weeks; 48/50 (96%)	Mobile app (LowSalt4Life) with a cloud-based web service to predict when participant was at grocery store, restaurant, or home; contextual just-in-time adaptive messages (push notifications) to assist behaviour change when participant entered store, restaurant, or home	ΔSBP −7·5 mm Hg (intervention) and −0·7 mm Hg (control; p=0·12); change in estimated sodium intake by food frequency questionnaire −1553 mg (intervention) and −515 mg (control; p=0·01)	Change in estimated 24-h urinary sodium excretion at 8 weeks was −462 mg (intervention) and 381 mg (control; p=0·03); change in sodium intake measured by the 24-h urine was −637 mg (intervention) and −322 mg (control; p=0·47)	Not effective
Frias et al (2017),[40] USA	Prospective pilot cluster RCT; 12 weeks; 105/109 (96%)	Smartphone app; ingestible sensor; adhesive wearable sensor patch; provider web portal; feedback for medication taking and other health behaviours to both patients and providers	ΔSBP −21·8 mm Hg (intervention) and −12·7 mm Hg (control); ΔSBP_{I-C} −9·1 mm Hg (95% CI −14·5 to −3·3)	Percentage of participants that reached BP goal was 80·0% (intervention) and 51·7% (control); change=28·3%; ΔHbA_{1c} −0·19 (intervention) and +0·26% (control); $HbA_{1c\ intervention-control}$ −0·48% (95% CI −1·04 to −0·09)	Effective for BP control
Gong et al (2020),[41] China	Multicenter RCT; 6 months; 443/480 (92%)	Smartphone app that provides drug dose and BP measurement reminders	ΔSBP −8·99 mm Hg (intervention) and −5·92 mm Hg (control; p<0·05); ΔDBP −7·04 mm Hg (intervention) and −4·14 mm Hg (control; p<0·05); Percentage of participants with controlled BP 77% (intervention) and 67% (control; p=0·011)	Medication adherence was 55% (low), 42% (medium), and 3% (high) in intervention and 68% (low), 30% (medium), and 2% (high) in control (p=0·004)	Effective
Li et al (2019),[42] China	Prospective cluster RCT; 6 months; 253/462 (55%)	Group chat (WeChat) lasting >1 h; health education; health promotion; BP monitoring	ΔSBP −5·3 mm Hg (intervention) and 1·6 mm Hg (control; p=0·011); ΔDBP −1·1 mm Hg (intervention) and 2·0 mm Hg (control; p=0·016); BP control 83·6% (intervention) and 63·6% (control; p<0·001); BP monitoring (at least once a week) 57·3% (intervention) and 58·7% (control; p=0·001)	Hypertension knowledge 2·3 (intervention) and 0·8 (control; p=0·110); self-efficacy 0·8 (intervention) and −0·6 (control; p=0·086); self-management 7·3 (intervention) and −1·4 (control; p<0·001); Social support 0·4 (intervention) and 0·7 (control; p=0·309)	Effective
Moore et al (2014),[43] USA	RCT; 12 weeks; 42/44 (95%)	Nurse coach helped patients adopt lifestyle changes and medication adjustment using integrated messaging on tablet app; patients self-tracked medication adherence and BP via wireless device	ΔSBP −26·3 mm Hg (intervention) and 16·0 mm Hg (control; p=0·009)	Percentage of participants reaching goal BP ≤130/80 mm Hg 75·0% (intervention) and 31·8% (control; p=0·003); percentage of participants reaching goal BP ≤140/90 mm Hg 100% in each group	Effective
Morawski et al (2018),[60] USA	RCT; 12 weeks; 411/412 (99·8%)	Medisafe app, which includes reminder alerts, medication adherence reports, and optional peer support	ΔSBP −10·6 mm Hg (intervention) and −10·1 mm Hg (control; p=0·78)	MMAS improved by 0·4 (intervention) and unchanged (control; p=0·01)	Not effective for BP

(Table 1 continues on next page)

	Study design; duration; retention	Intervention	Outcomes		Conclusion*
			Primary	Secondary	
(Continued from previous page)					
Or et al (2020),[44] Hong Kong	RCT; 24 weeks; 290/299 (97%)	Smartphone app to record BP and blood glucose via Bluetooth-connected monitors; data accessible by health professionals via web portal; education for the prevention of T2D and HTN, self-care, diet, exercise, health plans, and stress management	ΔSBP +0·5 mm Hg (intervention) and −2·8 mm Hg (control; p=0·10); ΔDBP −0·1 mm Hg (intervention) and −0·5 mm Hg (control; p=0·73)	ΔHbA$_{1c}$ −0·45% (intervention) and −0·35% (control; p=0·52)	Not effective
Petrella et al (2014),[45] Canada	RCT; 52 weeks; 127/149 (85%)	Smartphone data portal-equipped monitoring app; Bluetooth-enabled BP monitor; Bluetooth-enabled glucometer; pedometer; participants logged exercise using mHealth tools	Change in between groups mean at 12 weeks for SBP −5·68 mm Hg (p=0·03) and DBP −2·55 mm Hg (p=0·06)	At 52 weeks HbA$_{1c}$ reduced in intervention only (p<0·001); HOMA-IR higher in intervention *vs* control (p<0·05); TC reduced in both groups (p<0·001); LDL reduced in both groups (p<0·05)	Effective for SBP but not DBP
Sun et al (2020),[46] China	RCT; 3 months; 117/120 (98%)	Patients stratified into three WeChat groups according to cardiovascular risk (low, middle, and high); health education; health behaviour promotion; BP monitoring	ΔSBP −10·92 mm Hg (intervention) and −3·43 mm Hg (control; p<0·001); ΔDBP −5·68 mm Hg (intervention) and −3·33 mm Hg (control; p=0·016)	ΔBMI −0·49 kg/m^2 (intervention) and −0·06 kg/m^2 (control; p=0·185)	Effective for BP
Yun et al (2020),[47] South Korea	RCT; 12 weeks; 80/106 (76%)	Smartphone app; for patient self-assessment, self-planning, self-learning, and self-monitoring by automatic feedback; patients created own health management weekly plan and monitored their progress on vegetable and fruit intake, PA, and medication schedule	ΔSBP (patients with HTN) −17·5 mm Hg (intervention) and −11·6 mm Hg (control; p=0·41); percentage that met target clinical indicators for HTN 72·7% (intervention) and 35·7% (control; p=0·035)	ΔHbA$_{1c}$ −0·71% (intervention) and −0·22% (control; p=0·014); ΔLDL (patients with high LDL) −23·7 mg/dL (intervention) and −25·3 mg/dL (control; p=0·72)	Not effective
Characteristics of included studies that incorporated website interventions					
Bove et al (2013),[48] USA	RCT; 6 months; 206/241 (85%)	Web-based; optional telephone communication system; instructed to report health data through web form or telephone; received automatic email or call as reminders to report	Percentage at goal BP 54·5% (intervention) and 52·3% (control; p=0·430); ΔSBP −18·2 mm Hg (intervention) and −13·9 mm Hg (control; p=0·118); ΔDBP −7·1 mm Hg (intervention) and −4·9 mm Hg (control; p=0·166)	Change in FBG, TC, HDL, LDL, TG, and BMI were all non-significant	Not effective
Bray et al (2015),[49] UK	RCT; 12 months; 203/263 (77%)	Web-based; automated telemonitoring of BP that notified the GP of high or low readings; GP received monthly summary results; prescriptions generated without need to see GP	ΔSBP −18·3 mm Hg (intervention) and −12·8 mm Hg (control); ΔDBP −7·8 mm Hg (intervention) and −6·8 mm Hg (control); between groups statistical differences not reported	Controlled BP 71%; controlled SBP 70%; controlled DBP 82%; between groups statistical differences not reported	Cannot be assessed with reported data
Kao et al (2019),[50] Taiwan	RCT; 6 months; 215/222 (97%)	Website for personal information collection, individual physical data recordings, BP recordings, patient education regarding HTN, and consultations; self-titration of BP medications	3 months between group change in SBP −21·4 mm Hg (p<0·001) and DBP −5·4 mm Hg (p<0·001); 6 months between group change in SBP −27·8 mm Hg (p<0·001) and DBP −9·7 mm Hg (p<0·001)	3 months between group change in DDD −0·202 (p=0·003) and HRQoL 0·96 (intervention) and 0·81 (control; p<0·001); 6 months between group change in DDD −0·236 (p=0·001) and HRQoL 0·99 (intervention) and 0·78 (control; p<0·001)	Effective
Liu et al (2020),[51] 2020, Canada and Nolan et al (2018),[52] Canada	Multicentre RCT; 12 months; 197/264 (75%)	Emails promoting healthy lifestyle; via links to online sessions for e-counselling that included motivational interviewing and cognitive behavioural therapy to promote adherence to self-care behaviours	ΔSBP −10·1 mm Hg (intervention) and −6·0 mm Hg (control; p=0·02); ΔDBP −3·5 mm Hg (control) and −4·9 mm Hg (intervention; p=0·17); change in pulse pressure −2·7 mm Hg (control) −5·2 mm Hg (intervention; p=0·04)	Framingham risk index reduction −1·9% (intervention) and −0·02% (control; p=0·02); change between groups in improving steps per day (p=0·02), diet (p=0·22), TC (p=0·11), LDL (p=0·68) non–HDL (p=0·3)	Effective
Thiboutot et al (2013),[53] USA	Cluster RCT; 12 months; 418/500 (84%)	Web-based; HTN feedback based on patient's self-report of health variables; printable pocket chart to record BP to be entered into the website; automated reminders to use the website before physician visits	Participants with controlled BP 71·3% (intervention) and 65·6% (control; p=0·27)	Change in number of BP medications used in each group over the 12-month study −0·17 (intervention) and −0·28 (control; p=0·64)	Not effective

App=application. BP=blood pressure. DBP=diastolic blood pressure. DDD=overall antihypertensive defined daily dose. FBG=fasting blood glucose. GP=general practitioner. HbA$_{1c}$=glycated haemoglobin A$_{1c}$. HDL=high-density lipoprotein. HOMA-IR=homoeostatic model of assessment of insulin resistance. HRQoL=health-related quality of life. HTN=hypertension. LDL=low-density lipoprotein. MMAS=Morisky medication adherence scale. PA=physical activity. RCT=randomised control trial. SBP=systolic blood pressure. T2D=type 2 diabetes. TC=total cholesterol. TG=triglycerides. *A study was identified as effective if the reduction in the primary outcome due to the intervention and the difference in the reduction between the intervention and the control group were both statistically significant and clinically meaningful as defined in the methods section. †Authors report that even though participants were diagnosed with hypertension, their prehypertensive blood pressure baseline range might be the result of hypertensive medication treatment, as reported in the article. A full version of the study characteristics including details on participant baseline characteristics and the control group can be found in the appendix (pp 19–36).

Table 1: **Characteristics of included studies that incorporated SMS, smartphone app, and website interventions**

28 studies (n=7092 participants) were included in the meta-analysis on blood pressure reduction.[32–52,54–61] 17 of these 28 were assessed as high risk of bias.[35,37–42,45–49,51,52,55,57,58,61] Overall, the digital health intervention group had a –3·62 mm Hg (95% CI –5·22 to –2·02] greater reduction in SBP than the usual care group (figure 2). This difference in reduction between intervention and control groups was statistically significant in the combined effect

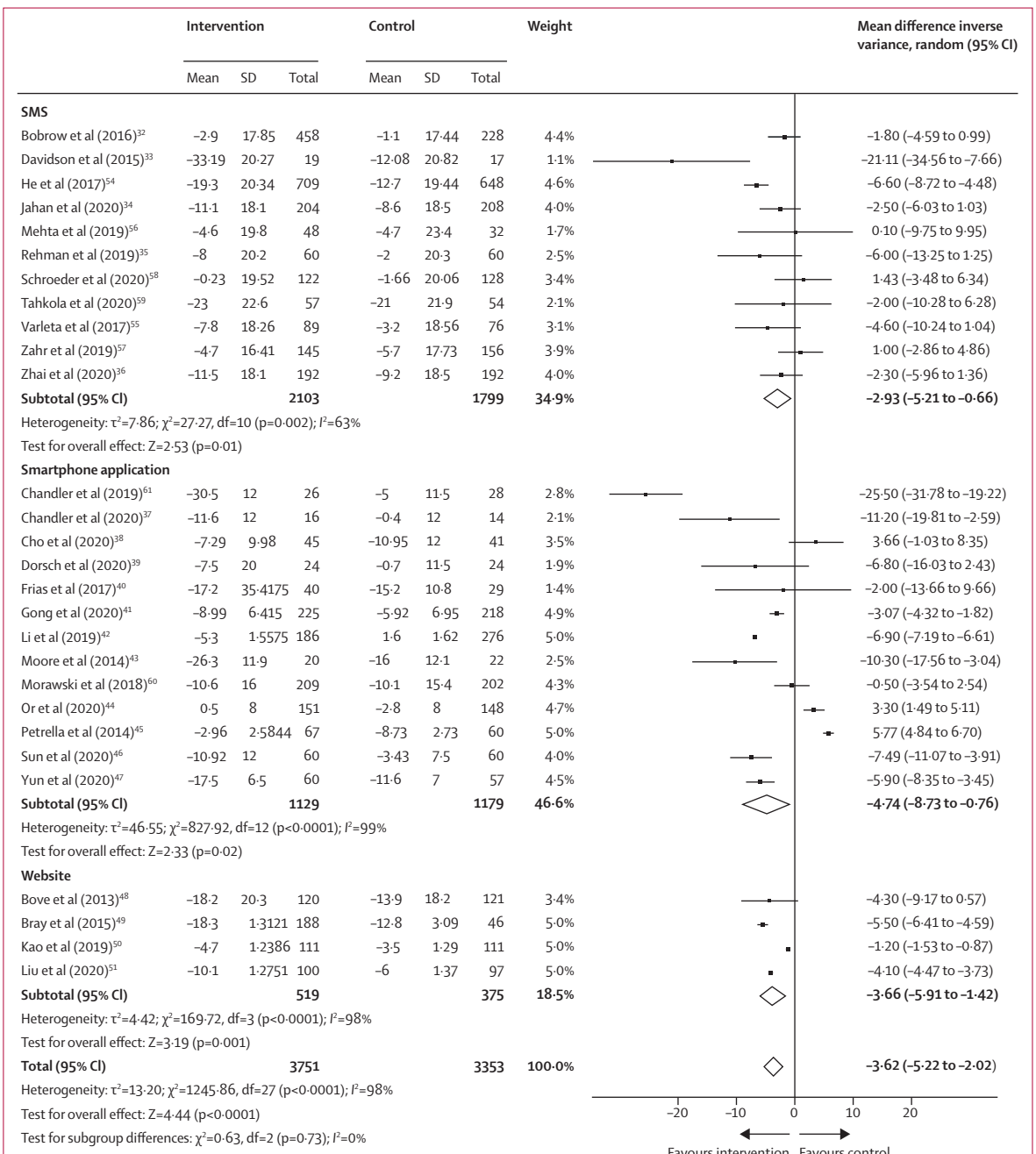

Figure 2: **Systolic blood pressure meta-analysis**
Forest plot of mean difference in systolic blood pressure (expressed as mm Hg) between the digital health intervention and the usual care croup, and subgroup analysis by mode of delivery of the intervention (SMS, smartphone application, and website). The size of the squares indicates the weight of the evidence from each of the studies. Studies with CI (horizontal line) crossing zero (vertical line) are inconclusive. Powerful studies (those with more participants) have narrower CIs. The diamonds represent the summary effect sizes in each of the subgroups and in the overall sample, with the width of the diamond indicating the 95% CI. A statistically significant greater reduction in systolic blood pressure is seen in the digital health intervention group, compared with the control group in the overall sample and with all three modes of delivery. Smartphone application interventions displayed the greatest reduction, compared with SMS and websites, but the differences between the three modes were not significant. The data present substantial heterogeneity.

(SMS, smartphone application, and website interventions combined) as well as for each of these three different modes of delivery individually. Subgroup comparisons revealed that interventions that employed smartphone applications had greater SBP reduction (–4·74 mm Hg [–8·73 to –0·76]) than interventions that used SMS (–2·93 mm Hg [–5·21 to –0·66]) or websites (–3·66 mm Hg [–5·91 to –1·42]), but the difference between groups was not significant (p=0·73). The overall heterogeneity between the studies was significant (χ^2=1245·86, p<0·0001) and considerable in magnitude (I^2=98%). Smartphone application studies (I^2=99%) and website studies (I^2=98%) displayed greater heterogeneity than SMS studies (I^2=63%).

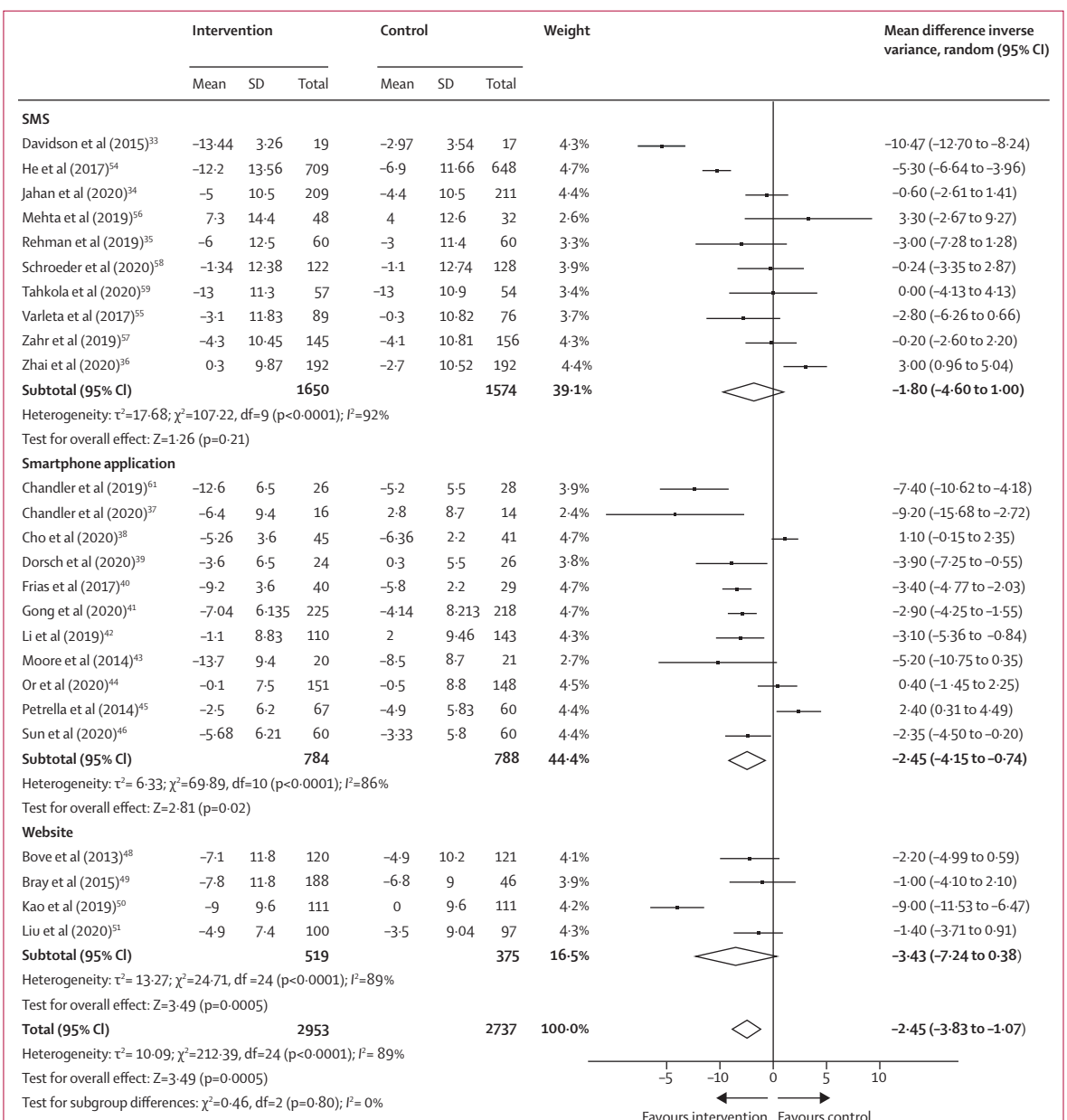

Figure 3: **Diastolic blood pressure meta-analysis.**
Forest plot of mean difference in diastolic blood pressure (expressed as mm Hg) between the digital health intervention and the usual care croup, and subgroup analysis by mode of delivery of the intervention (SMS, smartphone application, and website). The size of the squares indicates the weight of the evidence from each of the studies. Studies with CI (horizontal line) crossing zero (vertical line) are inconclusive. Powerful studies (those with more participants) have narrower CIs. The diamonds represent the summary effect sizes in each of the subgroups and in the overall sample, with the width of the diamond indicating the 95% CI. A statistically significant greater reduction in diastolic blood pressure is seen in the digital health intervention group, compared with the control group in the overall sample and when smartphone applications were the delivery medium, but not when SMS or websites were used to deliver the intervention. The data present substantial heterogeneity.

Subgroup analyses by income-economy, as per the World Bank classification,[62] by baseline SBP values, and by study aim or objective were conducted to explore potential sources of heterogeneity. Grouping the interventions by income-economy reduced the magnitude of heterogeneity, though it remained significant for all the subgroups apart from the group of the SMS studies that were conducted in low-income economy countries (appendix pp 41–42). Compared with the control group, all interventions produced statistically significant greater reductions in SBP, apart from SMS interventions in low-middle-income countries and high-income countries, and smartphone application interventions in high-income countries. Differences within the subgroups were not statistically significant. Next, we grouped interventions by participants' baseline SBP values—ie, interventions that included participants with baseline SBP of 150 mm Hg or less and interventions in participants with baseline SBP of more than 150 mm Hg (thresholds were selected to create equal groups for comparison; appendix pp 43–44). This grouping removed the heterogeneity for SMS interventions in participants with baseline SBP of 150 mm Hg or less and for website interventions in participants with baseline SBP of more than 150 mm Hg. For the remaining groups, the magnitude of heterogeneity remained significant. Compared with the control group, all interventions produced statistically significant greater reductions in SBP, apart from smartphone application interventions in participants with a baseline SBP of more than 150 mm Hg and website interventions in participants with a baseline SBP of 150 mm Hg or less. Finally, we grouped the interventions according to their study aim or objective—eg, blood pressure monitoring or control, medication adherence, and programme evaluation (appendix pp 45–46). We did not include studies in this subgroup analysis that had objectives that were not present in another study. Despite grouping them by study objective, heterogeneity remained high, apart from the SMS subgroups of studies that aimed to assess blood pressure control or medication adherence. Only smartphone application interventions that assessed medication adherence and website interventions that conducted programme evaluations displayed statistically significant reductions in SBP, compared with the control.

Overall digital health interventions had a –2·45 mm Hg (95% CI –3·83 to –1·07) greater reduction in DBP than usual care. Smartphone application interventions were the only ones to have a statistically significant reduction in DBP (–2·45 mm Hg [–4·15 to –0·74]); statistically significant reductions were not seen for SMS interventions (–1·80 mm Hg [–4·60 to 1·00]) or website interventions (–3·43 mm Hg [–7·24 to 0·38]; figure 3). However, subgroup differences were again not statistically significant (p=0·80).

The sensitivity analyses to assess the robustness of the effect estimate for the SBP and DBP outcomes are described in the appendix (pp 47–48). Overall, the effect estimate was not sensitive to individual studies. Publication bias was assessed via visual inspection of a funnel plot. The SBP data displayed a slight asymmetry due to an excess of large-sample-size smartphone

	Percentage reach (randomly assigned proportion)	Percentage uptake	Feasibility
SMS interventions			
Bobrow et al (2016)[32]	35·8% (66·7%)	50·2%	NR; reported on the adherence and satisfaction
Davidson et al (2015)[33]	NR (50·0%)	NR	Feasible based on recruitment and retention rates, adherence to medication and blood pressure, and response rate high (94·0%)
He et al (2017)[54]	14·8% (49·6%)	76·3%	NR; reported high adherence
Jahan et al (2020)[34]	46·4% (49·8%)	NR	NR; reported on adherence
Mehta et al (2019)[56]	4·4% (35·8%)	79·4%	NR; reported high adherence
Rehman et al (2019)[35]	NR (50·0%)	100·0%	NR; reported on adherence, satisfaction, effectiveness, and usability
Schroeder et al (2020)[58]	9·9% (50·2%)	47·0%	Feasible based on high recruitment rate, retention, and satisfaction
Tahkola et al (2020)[59]	NR (50·0%)	NR	NR; reported 49·0% were willing to continue SMS support
Varleta et al (2017)[55]	26·9% (51·9%)	NR	NR
Zahr et al (2019)[57]	27·9% (50·0%)	94·9%	NR
Zhai et al (2020)[36]	43·2% (50·0%)	68·0%	Feasible based on high acceptability
Smartphone application interventions			
Chandler et al (2020)[37]	10·6% (48·8%)	60·0%	Feasible based on acceptable adherence of 75·0% and effectiveness
Chandler et al (2019)[61]	10·6% (50·0%)	60·0%	NR; reported high satisfaction and usability
Cho et al (2020)[38]	NR (55%)	87·5%	NR
Dorsch et al (2020)[39]	7·52% (48%)	100·0%	NR; reported usability and convenience
Frias et al (2017)[40]	46·3% (69·5%)	86·0%	NR; reported on adherence, effectiveness, and high satisfaction
Gong et al (2020)[41]	NR (50·0%)	NR	NR; reported on adherence and effectiveness
Li et al (2019)[42]	18·7% (46·4%)	78·1%	NR; reported high rates of fidelity
Moore et al (2014)[43]	NR (50·0%)	NR	NR; reported on efficacy
Morawski et al (2018)[60]	3·8% (50·8%)	90·0%	NR
Or et al (2020)[44]	33·3% (50·5%)	NR	NR; reported cost-effectiveness, convenience of use, and reliability
Petrella et al (2014)[45]	31·5% (50·3%)	NR	Feasible based on efficacy, sustainability, and high compliance rates
Sun et al (2020)[46]	NR (50·0%)	NR	Feasible based on effectiveness
Yun et al (2020)[47]	42·1% (50·0%)	NR	NR
Website interventions			
Bove et al (2013)[48]	30·5% (49·8%)	65·0%	NR; reported high usability
Bray et al (2015)[49]	15·9% (49·9%)	72·0%	Feasible based on high persistence (89·0% at 12 months) and fidelity of patient self-titration
Kao et al (2019)[50]	31·2% (50·0%)	100·0%	NR; reported on effectiveness and low cost
Liu et al (2020)[51] and Nolan et al (2018)[52]	21·8% (50·4%)	NR (control 75·2%)	Feasible based on increasing accessibility to internet
Thiboutot et al (2013)[53]	5·9% (56·4%)	82·2%	NR; reported high adherence and high fidelity

NR=not reported.

Table 2: **Reach, uptake, and feasibility of included studies**

application interventions with negative effects on the outcome (SBP increase), as well as one medium-size smartphone application intervention and one small-size SMS intervention, both of which had a positive effect on the outcome (SBP decrease; appendix p 49). The DBP data exhibited a more symmetric distribution (appendix p 50). In summary, neither the SBP nor the DBP funnel plot indicated publication bias. Overall, the level of evidence was low due to considerable heterogeneity of included studies, and the high risk of bias in most.

Interventions that recruited participants with higher baseline values for blood pressure reported greater effectiveness.[33,43,54,61] However, some interventions were not effective despite including participants with high baseline values.[35,59] Subgroup meta-analysis revealed that SMS interventions that included participants with higher baseline SBP (>150 mm Hg) had four-times greater reductions in SBP by the time of follow-up than SMS interventions that included participants with lower baseline SBP (≤150 mm Hg). Similarly, website interventions in participants with higher baseline SBP resulted in twice the reduction of SBP than website interventions in participants with lower baseline SBP (≤150 mm Hg). However, participants' baseline SBP was not an effect moderator in smartphone application interventions (appendix pp 43–44).

22 studies reported an intervention reach based on the assessed population for inclusion with a median reach of 21·8% (range 3·8–46·4),[32,34,36–40,42,44,45,47–58,60] whereas seven reported only the randomly assigned populations, with a median of 50% randomly assigned to the intervention group (table 2).[33,35,41,43,46,59,61] 16 studies reported on intervention uptake, with a median uptake of 79·4% (47·0–100·0).[32,35,36,39,40,42,48–50,53,54,56–58,60–61] SMS interventions reported higher reach, but smartphone application interventions reported higher uptake, compared with the other two modes of delivery. However, differences were not significant (appendix p 51).

Eight studies reported delivering feasible interventions, based on measures of meeting recruitment target, high response rate, retention, adherence and compliance, efficacy, sustainability, fidelity, cost-effectiveness, and high accessibility (table 2).[33,36,37,45,46,49,51,52,58] 21 studies did not conclude on feasibility, but reported high satisfaction, usability, convenience, and clinical effectiveness.[32,34,35,38–44,47,48,50,53–57,59–61]

Discussion

To the authors' knowledge, this study presents the first synthesis of the comparative effectiveness and implementation of different digital health intervention delivery modes in reducing SBP and DBP in adults with hypertension. The meta-analysis of 28 studies (n=7092 participants) identified that digital health interventions were more effective in reducing both SBP and DBP than usual care, with no significant difference between the modes of delivery.

The reductions in SBP and DBP were clinically important. Previous analysis of 29 RCTs showed that SBP and DBP reductions of even 2 mm Hg can significantly reduce the incidence of cardiovascular disease, and therefore reductions of this magnitude are clinically important.[63] The magnitude of the reduction might have been even larger if more non-medicated participants were included. Most studies included participants on antihypertensive medications, with only two studies including non-medicated participants.[37,38] However, only one of these studies achieved significant blood pressure reduction.[37] Another moderator could be the inclusion of participants with controlled hypertension that was observed in two RCTs.[53,58] Indeed, these studies did not report significant reductions. Smartphone application interventions were the only ones to produce statistically significant reductions in DBP. Possibly, due to the greater range of capabilities that smartphones offer, a more technologically sophisticated intervention (eg, the use of wearable sensors) is permitted than in SMS and website interventions.[40] Baseline hypertension was an effect moderator, which can be explained homoeostatically, because the further a physiological value deviates from the normal range the more the homoeostatic pressure to correct this following intervention.[64] Future studies should incorporate effect modification analyses based on baseline blood pressure. Education was also associated with effectiveness,[40,41] in agreement with previous reports.[65] However, with few exceptions,[66] hypertension prevalence is higher in populations of a lower education status,[67] thus, future interventions should aim to optimise the effectiveness in these populations.

We identified one study comparing the implementation of smartphone applications with SMS interventions in people with serious mental illness.[68] The acceptability of SMS and smartphone application interventions by people with hypertension,[69–71] has been confirmed in primary care. In our study, a higher reach was reported with SMS interventions than other delivery modes. Indeed, more people own a telephone with SMS capability than own a smartphone or have access to the internet.[9,10] Smartphone application interventions reported the highest uptake, which might reflect patients' preference. However, few studies reported on co-design of interventions. Future research should explore participants' preferences regarding delivery modes, and highlight the key moderators and mediators of reach, uptake, acceptability, and adherence to interventions. Most study authors reported reach and uptake at the participant level. Future studies should also report reach and adoption at the implementer's level and at the broader community or cohort's level.

Strengths of our study include the use of rigorous standard methodology as documented in the PRISMA and Cochrane guidelines; a large, demographically and culturally diverse population from 13 regions representing lower-middle-income, upper-middle-

income, and high-income economy countries from five continents; the direct communication with studies' authors to obtain accurate data for the analyses; the comprehensive series of sensitivity analyses performed to ensure the robustness of the calculated summary effect size; and the inclusion of implementation metrics.

Our study also has limitations. First, searches were restricted to articles published in English. However, reports indicate that inclusion of non-English publications affects only one out of every 36 meta-analyses.[72] Second, the adult filter is not consistent between databases. In MEDLINE, the filter is older than 19 years, whereas for Embase and PsycInfo it is older than 18 years. This difference means that articles listed in MEDLINE with participants aged between 18 and 19 years might have been missed, but the proportion of the population with hypertension at that age is small.[73] Third, we reported on reduction in blood pressure, instead of the proportion of participants having blood pressure control. We chose the reduction in blood pressure due to the absence of a clear consensus on the definition of hypertension that ranges from 130/80 mm Hg to 140/90 mm Hg.[74–77] Although not reporting on having control of blood pressure limits conclusions regarding the clinical significance of the findings, even small reductions of 2 mm Hg or more in SBP and DBP can significantly reduce the hypertension sequalae, and therefore the reductions reported in this study are clinically important.[63] Fourth, few smartphone application interventions reported on the frequency of use of the application and time spent using it, limiting the analysis and conclusions with respect to a dose–response relationship. Fifth, we compared SMS, smartphone applications, and websites, but we did not include interventions that were delivered solely via telecounselling or telemonitoring without the use of SMS, smartphone applications, and websites. Sixth, we identified studies from high-income and upper-middle-income countries, primarily, meaning that the findings cannot be generalised. Although it has been reported that upper-middle-income countries have a higher prevalence of hypertension than lower-middle-income and low-income-countries,[78] it is important for future research to collect evidence in these settings too due to the known health-care equity disparities,[79,80] especially because reports indicate a transition of hypertension from primarily a burden in high-income countries to one that is now highly prominent in low-income and middle-income countries.[81] Seventh, there was a mix of methodologies used to measure blood pressure, with 13 of the studies reporting measurements being done by trained staff at a clinic, and the remaining studies trained participants to take measurements themselves. Additionally, there was a range of blood pressure monitoring devices being used, with the validity and accuracy of some not consistently reported across all the studies. Eighth, there was considerable heterogeneity. An inherent source of heterogeneity in our study was the inclusion of smartphone application interventions, because these applications themselves are heterogeneous. We ran a series of heterogeneity analyses to explore potential sources, such as subgrouping the studies by countries' economic status, by participants' baseline blood pressure, and by study objectives. The analyses could not fully elucidate the reasons for heterogeneity.

Considering the comparable effectiveness of SMS, smartphone applications, and website interventions, clinicians should make digital health intervention decisions based on the context, feasibility, economics, and patients' preference. Clinicians can leverage the high rates of penetration (reach and uptake) in diverse populations to deliver interventions. This approach is particularly important for rural and remote areas, where health services are limited, but hypertension prevalence is higher.[82–84] Future studies should focus on head-to-head comparisons of the different modes of delivery, including the different settings and demographics that favour selection of one mode over the other. Studies should also aim to describe in detail the mediators and moderators of the effectiveness and implementation of these interventions, such as the optimal communication mode between participants and health-care practitioners, user interface, dose of education sessions, and frequency of reminders delivered via the digital tools. The effectiveness of these interventions in additional lower-middle as well as in low-income countries warrants examination.

DigiCare4You Consortium

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Contributors

GS, GM, and YM conceptualised the study. GS and GM designed the methodology. GS, EE, JJ, BY-AA, and VK did the data collection. GS, EE, JJ, BY-AA, VK, DK, and NV did the data analysis. GS wrote the original draft of the manuscript. All authors reviewed and edited the manuscript. GS supervised the data collection and analyses. GS and GM did project administration. GM, RV, RW, LA, BO, and YM acquired funding. All authors had access to all the raw data sets. GS and GM verified the data. All authors have read and agreed to the final version of the manuscript and to the submission for publication.

Declaration of interests

LA received consulting fees from Mundipharma for advice on cost-effectiveness of SGLT2 inhibitors for the management of type 2 diabetes; received honoraria from Boehringer Ingelheim and Mundipharma for lectures on health economic aspects of diabetes; and is a member of the board of the AstraZeneca Foundation. All other authors declare no competing interests.

Data sharing

Template data collection forms, data extracted from included studies, and data used for analyses can all be made available upon from the corresponding author.

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