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Review article

The digital prescription: A systematic review and meta-analysis of smartphone apps for blood pressure control

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ABSTRACT

Objective: Assess the effectiveness of digital health interventions (DHIs) in reducing blood pressure (BP) among individuals with high blood pressure and identify the impact of age, sex, and phone-based delivery methods on BP.

Methods: A systematic review and *meta*-analysis was undertaken according to the PRISMA and JBI. A comprehensive search was conducted across multiple databases. Randomised controlled trials (RCTs), mixed methods, descriptive, and experimental studies enrolling adult patients (≥ 18 years) with high BP and containing DHIs with blood pressure management aspect were included. We used a random-effects *meta*-analysis weighted mean difference (MD) between the comparison groups to pool data from the included studies. The outcome included the pooled MD reflecting systolic (SBP) or diastolic (DBP) change from baseline to 6-month period. Risk of bias was assessed using standardised tools.

Results: Thirty-six studies with 33,826 participants were included in the systematic review. The pooled estimate (26 RCTs) showed a significant reduction in SBP (MD = −1.45 mmHg, 95 % CI: −2.18 to −0.71) but not in DBP (MD = −0.50 mmHg, 95 % CI: −1.03 to 0.03), with evidence of some heterogeneity. Subgroup analysis indicated that smartphone app interventions were more effective in lowering SBP than short message services (SMS) or mobile phone calls. Additionally, the interventions significantly reduced the SBP compared with the control, regardless of participant sex.

Conclusion: Our findings indicate that DHIs, particularly smartphone apps, can lower SBP after 6 months in individuals with hypertension or high-risk factors, although changes might not be clinically significant. Further research is needed to understand the long-term impact and optimal implementation of DHIs for BP management across diverse populations.

1. 1.Introduction

Hypertension is defined as systolic blood pressure (SBP) above 140 mmHg or diastolic blood pressure (DBP) greater than 90 mmHg [1]. The condition is a major global public health concern [2–6], with 30 % of adults in England living with the condition [7]. However, management tends to vary by sex and age, with men aged 45–64 having higher rates of untreated or larger detection rates of hypertension compared to women, while women over 65 are at the highest risk [7]. The rising prevalence among young adults is also a growing public health concern [8–10].

However, it is preventable through lifestyle choices such as a balanced, low-sodium diet, regular physical activity, and avoiding tobacco and alcohol [11–13]. Conventionally, ambulatory blood pressure checks, routine clinical appointments and pharmacological treatment are used to prevent and manage hypertension [14,15]. However, emerging digital health interventions (DHIs) also offer novel strategies to address the self-management of hypertension [16–18]. eHealth and mobile health are examples of digital health approaches that involve delivering or enhancing health services through the use of the Internet

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and associated technologies [19]. These interventions can be feasibly implemented for population groups with limited access to traditional healthcare services [20]. Therefore, DHIs involving management approaches have the potential to enhance self-care activities, improve medication adherence, and ultimately reduce blood pressure (BP) levels [21,22]. Digital approaches for BP management include short message service (SMS) for motivational messages and medical adherence [23–25], remote blood pressure tracking with healthcare feedback [26,27], and behaviour change cues [28–31].

Such tools show promise for BP control among underserved populations, such as women and ethnic minorities [32]. For instance, while digital approaches could enhance CVD prevention, especially for women during pregnancy/postpartum [33], evidence regarding their effectiveness across different age groups remains limited and inconclusive. While self-management strategies are generally preferred for younger adults with early-stage hypertension [34,35], the optimal modality and delivery of these interventions for specific age groups require further investigation [36]. To address these gaps, we aimed to synthesise evidence on the effectiveness of DHIs in managing BP in adults with hypertension and to examine potential variations in their effectiveness based on age, sex, and the delivery mode of phone-based interventions.

2.Methods

This review followed the guidance of the JBI Manual for Evidence Synthesis and the Cochrane Handbook for Systematic Reviews of Interventions [37,38], and followed the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) [39]. The review protocol was pre-registered on the International Prospective Register of Systematic Reviews (PROSPERO; CRD42023480389).

1.1. Search strategy

We conducted a computerised systematic search in PubMed, the Cochrane Library/Cochrane Central Register of Controlled Trials (CENTRAL; cochranelibrary.com/central), the Web of Science (WoS), and PsycINFO (Psychology and Behavioural Sciences) from January 2013 to November 2023. This period captured the latest advancements in digital technology in hypertension management [40].

The search strategy was developed using text keywords and the Medical Subject Headings (Mesh) from relevant reviews and recently published literature (Supplementary Text S1-S4).

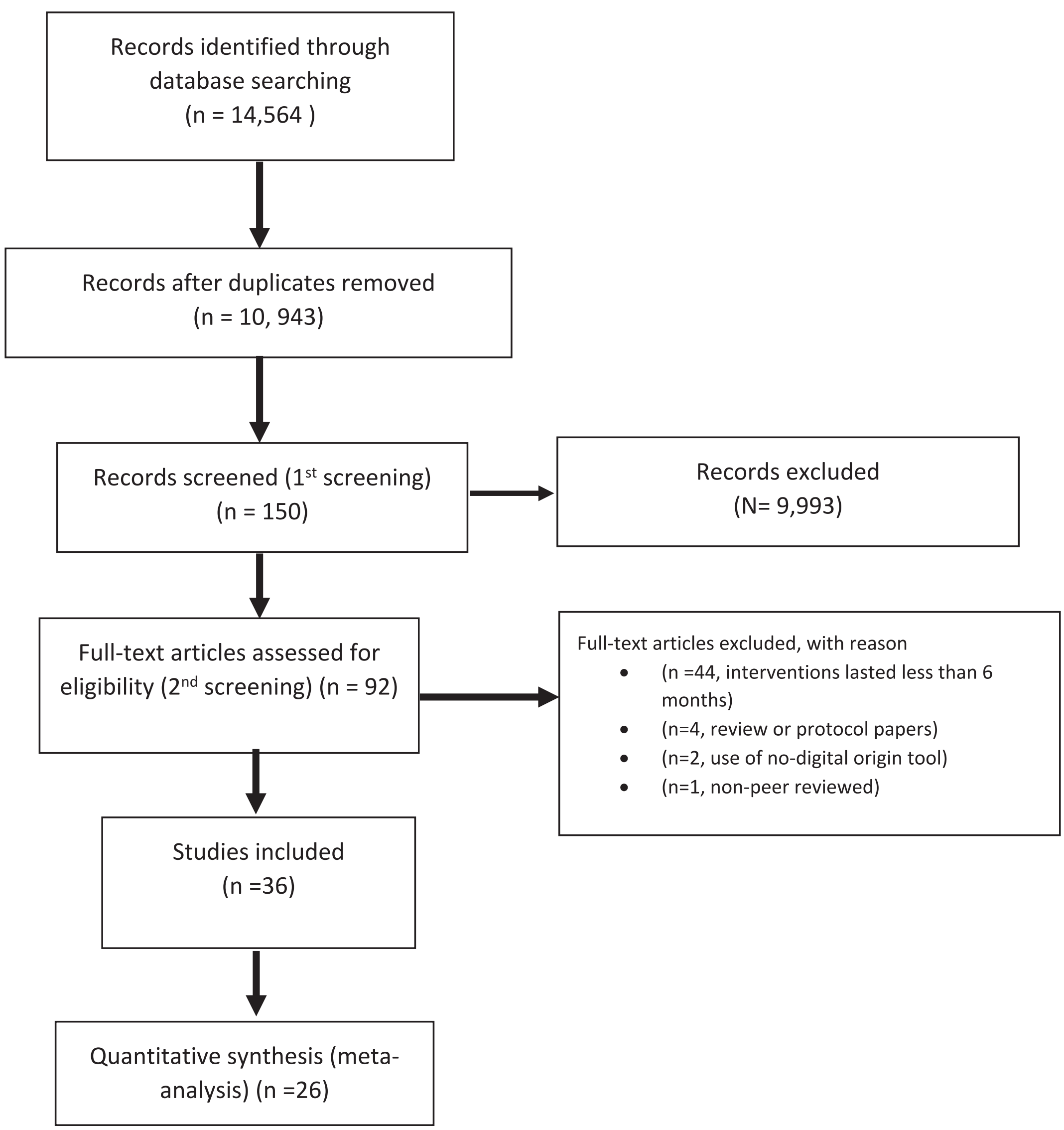

Fig. 1. The PRISMA flowchart summarises the search results. The 92 publications were retrieved for full-text review, and 26 RCTs were considered appropriate for *meta*-analysis (Moher et al., 2009). RCT, randomised controlled trial.

1.2. Selection criteria and data extraction

The following inclusion criteria were used:

(1) Published RCTs, observational and quantitative studies comparing the effects of DHIs versus usual care on controlling BP.
(2) Published in the English language.
(3) Participants aged ≥ 18 years.
(4) Participants living with a high blood pressure condition.
(5) A follow-up duration of 6 months.

The review included randomised controlled trials and quantitative studies (descriptive and experimental) testing DHIs on BP control in adults living with high BP. Studies published between 2013 and 2023 and in English were included.

This review excluded studies of pregnant women with high blood pressure and preeclampsia.

The screening involved two phases: (I) titles and abstract and (II) full-text screenings of every record retrieved by the lead reviewer (EMY) (Fig. 1). A randomly selected 10 % sample were independently screened by a third investigator (AM). Any discrepancies were resolved through discussion with the review team.

A standard data extraction form was used. We synthesised the numeric data on participants' socioeconomic status (SES) indicators, sex, and ethnicity proportions. Types of DHIs (setting, delivery, additional enhancement), the primary objectives of the interventions, and the geographical location were also summarised (Supplementary Table S1). Narrative synthesis was used to summarise the outcomes (primary and secondary) (Supplementary Table S2).

1.3. Quality assessment

The risk of bias of RCTs was assessed using the Cochrane Risk of Bias Tool, version 2[41]. The mixed-methods appraisal tool (MMAT) was used to assess the risk of bias in mixed-method, non-randomised, and quantitative studies [42].

Evidence of RCT studies was graded following a Grading of Recommendations Assessment Development and Evaluation (GRADE) approach [37,43]. The evidence rating was conducted using the GRADE Pro GPT software [44].

1.4. Outcome measures

Data were extracted for measurements of SBP and DBP after six months of follow-up (Supplement Table S2), as well as health behaviours and characteristics of digital tools (co-designed and end-users) (Supplement Table S3). The primary outcome was the pooled mean difference (MD) of SBP from baseline to a 6-month follow-up period between the intervention group (DHIs) and the control group (usual care). The secondary outcome was the pooled difference of MD of DBP from baseline to a 6-month follow-up between the two groups.

1.5. Analysis Plan

A random-effects *meta*-analysis was performed to estimate the weighted, pooled effect for each SBP and DBP at 6 months of follow-up, allowing for the true effect to vary across the individual studies [45]. The included studies consistently use MD as the outcome measure for BP, allowing for pooling and comparison across the studies. Consequently, MD was selected as the appropriate outcome measure for BP. A standard formula was used to obtain missing SD measures [37]. The MDs were pooled using a random-effects model with inverse variance weighting. Heterogeneity in effect estimates was quantified using the I^2 statistic, which estimates the proportion of variability attributable to differences between studies rather than change [45]. Further exploration of heterogeneity was conducted through subgroup analysis to assess whether age, sex or the DHI delivery mode of the intervention interacted with the variation in reducing SBP. This was followed by a sensitivity analysis of the intervention delivery mode to examine their respective effect on lowering SBP.

The *meta*-analysis was conducted using RevMan (version 5.4; The Cochrane Collaboration)[46]. A two-tailed *P*-value of < 0.05 indicated statistically significant.

2. Results

2.1. Studies characteristics

Searches yielded 10,943 results after removing duplicates, of which 92 were retrieved for full-text screening (Fig. 1). A total of 36 studies [47–85] were included in this review, of which 26 RCTs [48,52,53,58,60–64,67–77,79,81–85] were considered appropriate for *meta*-analysis. Seven studies were conducted by phone and a web-based platform [48–51,51,70], and sixteen interventions used phone-based delivery (Short Message Service [SMS], calls, and apps)[52,58,60,62–64,67,68,72,74–77,81,82,84] (Supplement Table S3). Four studies used only a digital device (e.g., a wearable BP monitor) as the telehealth method for remote management of BP [58,59,65,71]. Patients were the primary end-users [47–49,51,52,59,60,62–64,66–70,72–78,81–85], with some studies involving both patients and healthcare professionals [58,61,66] (Supplement Table S3). Health workers included nurses, community health workers (CHWs), nutritionists, and pharmacists. Five studies [50,53,63,75,84] (10 %) reported using a co-design framework after the intervention (Supplement Table S3). Additionally, 18 studies involved medication management [47,48,52,59–61,63,70,71,74,76–79,79,81,82,84], and six studies involved health education for hypertension control [48,51,52,59,60,72,82] as part of the DHI (Supplement Table S4). Other intervention components included lifestyle behaviour components (67 %); 17 studies advocated for physical activity [47,48,51,53,61,64,67,69,70,72,75,78,79,81–84], and 15 studies enforced the dietician regulations (salt intake and fruit/vegetable intake for hypertension control [47,48,51,53,58,61,67,69,70,72,79,81–84]. Meanwhile, 10 studies applied health education and medication management within the intervention.

Most of the studies were conducted in the United States of America (n = 18, 39 %). A large proportion of studies were based in Western Europe (n = 11): Scotland, United Kingdom, Spain, Sweden, Germany, and Ireland. The remaining studies were undertaken in China, Hong Kong, Cambodia, India, Japan, South Korea, Russia, Iran, Sub-Sahara Africa, and Australia.

2.2. Baseline Sociodemographic characteristics

The participant sample comprised 46 % male and 54 % female individuals, with a mean pooled age of 56 years (range, 20–90 years) (Supplement Table S1). Overall, 64 % were White, 33.5 % were Black, and 2.5 % were Asian. Among the participants who reported SES indicators (78 %), half stated that their study population primarily consisted of individuals with high SES. This group was characterised by higher employment rates, completion of post-secondary education, and higher income levels. Meanwhile, 16 % stated a low SES.

2.3. Effects of digital health interventions on blood pressure

This *meta*-analysis found that DHIs have a small but significant effect on reducing SBP by 1.45 mmHg [95 % IC: 2.18–0.71, p = 0.0001; Fig. 2] at 6 months follow-up among those in the intervention group compared to those in the usual care group.

There was no significant pooled effect for DBP. Compared to the control group, the interventions had a small effect in changing DBP by −0.50 mmHg [95 % IC: 1.03–0.03; Fig. 3].

Heterogeneity between studies was moderate for blood pressure

Study or Subgroup	Intervention Mean	Intervention SD	Intervention Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Random, 95% CI
Abel 2023	128.73	12.89	42	128.42	11.82	41	1.7%	0.31 [-5.01 , 5.63]
Apiñaniz 2019	122.3	11	54	123.7	11	56	2.6%	-1.40 [-5.51 , 2.71]
Bae 2021	126.6	15.799465	377	128.4	15.694995	350	5.8%	-1.80 [-4.09 , 0.49]
Cheung 2023	128.8	14.296277	403	127.9	14.314111	404	6.7%	0.90 [-1.07 , 2.87]
Gallagher 2022	107.2	13.7	194	108.9	14.6	196	4.5%	-1.70 [-4.51 , 1.11]
Gong 2020	134.52	7.066	225	135.27	8.094	218	8.8%	-0.75 [-2.17 , 0.67]
Green 2014	136.4	13.9	44	139.1	14	46	1.4%	-2.70 [-8.47 , 3.07]
Hageman 2014	121.4	8.023506	210	123.2	10.5	53	4.1%	-1.80 [-4.83 , 1.23]
Hoppe 2023	128.14	11.36	100	130.69	13.99	102	3.3%	-2.55 [-6.06 , 0.96]
Jahangiry 2015	120	10	80	124	8	80	4.5%	-4.00 [-6.81 , -1.19]
Kario 2021	137.93	28.59026946	73	135.358	28.59026946	78	0.6%	2.57 [-6.55 , 11.70]
Kerry 2013	138.8	20.8	168	135.4	19.2	169	2.4%	3.40 [-0.87 , 7.67]
Laing 2014	125.66	40.25194975	105	124.5	40.25194975	107	0.4%	1.16 [-9.68 , 12.00]
Leupold 2022	134.3	14.5	265	137.8	15.5	260	5.0%	-3.50 [-6.07 , -0.93]
Li 2019	130.5	20.047306	186	136.8	24.051146	276	2.6%	-6.30 [-10.34 , -2.26]
Mancheno 2021	135.6	18.3	295	135.7	16.9	316	4.5%	-0.10 [-2.90 , 2.70]
McKinstry 2013	140	11.3	200	144.3	13.4	201	5.4%	-4.30 [-6.73 , -1.87]
McManus 2021	138.7	17	305	140.9	16	317	5.0%	-2.20 [-4.80 , 0.40]
Muldoon 2022	148.6	15.682475	41	151.2	13.840236	21	0.9%	-2.60 [-10.22 , 5.02]
Peiris 2019	147.22	25.53	4348	148.14	24.8	4294	10.3%	-0.92 [-1.98 , 0.14]
Pletcher 2023	140	19	1051	140	19	1050	8.0%	0.00 [-1.62 , 1.62]
Pogosova 2021	131	12.4	50	135.3	13.2	50	1.8%	-4.30 [-9.32 , 0.72]
Schroeder 2020	136.2	18	129	136.1	18.4	131	2.3%	0.10 [-4.32 , 4.52]
Wang 2023	128.2	8.4	24	126.9	9.3	25	1.9%	1.30 [-3.66 , 6.26]
Watson 2015	127.17	6.726051	32	127.18	9.616887	33	2.7%	-0.01 [-4.03 , 4.01]
Zha 2020	137.38	4.86	12	140.88	5.01	13	2.8%	-3.50 [-7.37 , 0.37]
Total (95% CI)			**9013**			**8887**	**100.0%**	**-1.45 [-2.18 , -0.71]**

Heterogeneity: Tau² = 1.08; Chi² = 39.08, df = 25 (P = 0.04); I² = 36%
Test for overall effect: Z = 3.86 (P = 0.0001)
Test for subgroup differences: Not applicable

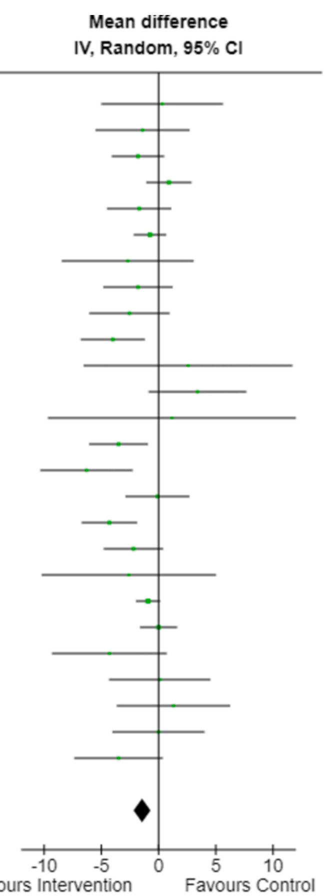

Fig. 2. A forest plot of the effect of digital health interventions for the reduction of systolic blood pressure at a 6-month intervention period. The mean difference of SBP was available for 26 studies that included 17,900 participants. The weight of the evidence from each study is reflected in the size of the green squares. The black diamond represents the effect size of the pooled studies, and its width represents the 95 % IC. Compared with the usual care group (control group), the DHIs group (intervention) had a reduction in SBP (MD = -1.45 mmHg [95 %IC: −2.18 to −0.71] mmHg), with evidence of moderate heterogeneity (I^2 = 36 %). CI: confidence interval, DHI: digital health intervention, IV: inverse variance, MD: mean difference, SBP: systolic blood pressure, SD: standard deviation.

outcome measurements (SBP, I^2 = 36 %, p = 0.04; DBP, I^2= 40 %, p = 0.03), suggesting sources other than randomisation could contribute to variability. The I^2 statistic indicated that 64 % of the variation in SBP effects across studies was attributable to between-study differences.

2.4. Subgroup analyses and sensitivity analysis

Planned subgroup analysis to investigate the influence of age on the effectiveness of DHIs could not be completed due to insufficient reporting of relevant data in the included studies.

Subgroup analyses by sex revealed that being male/female did not significantly impact (0.22 mmHg; p = 0.92) the reduction of SBP at 6 months, although there was evidence of heterogeneity across studies (Fig. 4).

Subgroup analysis by the mode of phone-based delivery showed a significant reduction in the SBP between the treatment and usual care groups (−1.42 mmHg [95 % IC: −2.02 to −0.81], p < 0.00001, Table 1).

Smartphone apps were the only method of DHI delivery with a greater and significantly reduced SBP (MD = -1.94 mmHg [-3.38 to −0.50], p = 0.008, n = 2,304), with no support for SMS (MD = -0.19 mmHg [-1.60 to 1.23], n = 951) or mobile phone calls (MD = −1.09 mmHg [-5.49 to 3.31], n = 318). Sensitivity analysis pointed to the robustness of the *meta*-analysis models for the phone-based delivery method when each study was removed, and minimal change in the pooled effect was shown (Supplementary Figure S1-S3).

2.5. Quality assessment

Among the RCTs, 42 %, 30 %, and 27 % were categorised as low risk, having some concerns, and high risk of bias, respectively (Supplement Figure S4). Twelve studies were considered to have high risk or some concerns of bias for the measurement of the outcome. Five studies reported the use of an unsuitable BP measurement method (e.g., unvalidated BP tool, BP readings did not follow clinical guidelines) [48,52,73,75,85]. Seven studies did not report on the blinding of the outcome assessors [61,62,67,69,71,74,76]. Fifteen studies deviated from the proposed intervention, without blinding the respondents and personnel to the intervention task; however, such blinding is not feasible in DHIs [48,52,53,60,61,64,67–69,71,73,74,76,82,85]. Four acquired high or some concerns risk of bias for the imbalance of critical baseline characteristics [61,67,68,77].

We assessed the quality of non-randomised studies using the MMA [42]. One study employed a quantitative descriptive design [65], raising concerns about the sample's representativeness and the potential for nonresponse bias. Two of the three non-randomised studies reported some concerns regarding missing data [49,66], while two others failed to address confounding factors in their designs adequately [50,59] (Supplementary Table S5).

Three studies used a mixed-methods approach. Two demonstrated robust integration of quantitative and qualitative compounds [69,80], while the remaining study lacked clarity in its mixed-methods design [56].

The GRADE assessment summarised the quality of the evidence as

Study or Subgroup	Intervention Mean	Intervention SD	Intervention Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Random, 95% CI
Abel 2023	77.42	8.46	42	79.39	7.22	41	2.1%	-1.97 [-5.35 , 1.41]
Cheung 2023	77.4	9.190464	403	77	9.201928	404	7.9%	0.40 [-0.87 , 1.67]
Gallagher 2022	73.6	10.1	194	73.9	9.6	196	4.8%	-0.30 [-2.26 , 1.66]
Gong 2020	76.86	7.236	225	78.44	8.237	218	6.9%	-1.58 [-3.03 , -0.13]
Green 2014	84	10.2	44	84.6	9.5	46	1.5%	-0.60 [-4.68 , 3.48]
Hageman 2014	73.5	5.886452	219	72.9	7.5	53	4.2%	0.60 [-1.56 , 2.76]
Hoppe 2023	84.61	8.24	100	85.89	9.19	102	3.6%	-1.28 [-3.69 , 1.13]
Jahangiry 2015	78	6	80	82	6	80	5.2%	-4.00 [-5.86 , -2.14]
Kario 2021	86.4	8.916428826	68	86.7	8.916428826	72	2.6%	-0.30 [-3.26 , 2.66]
Kerry 2013	74.1	12.3	168	72.4	11.1	169	3.4%	1.70 [-0.80 , 4.20]
Leupold 2022	83.1	9.7	265	83.4	10.6	260	5.6%	-0.30 [-2.04 , 1.44]
Li 2019	81.9	11.406226	186	83.1	13.080448	276	4.0%	-1.20 [-3.45 , 1.05]
McKinstry 2013	83.4	9.1	200	84.3	10.4	201	5.0%	-0.90 [-2.81 , 1.01]
McManus 2021	79.9	9.7	305	80.2	10.3	317	6.3%	-0.30 [-1.87 , 1.27]
Muldoon 2022	79.9	9.7	305	80.2	10	317	6.4%	-0.30 [-1.85 , 1.25]
Peiris 2019	84.69	12.81	4348	84.4	13.1	4294	12.5%	0.29 [-0.26 , 0.84]
Pletcher 2023	81	11	1051	81	12	1050	9.6%	0.00 [-0.98 , 0.98]
Pogosova 2021	80.6	7.3	50	83.6	7.8	50	2.6%	-3.00 [-5.96 , -0.04]
Schroeder 2020	83.6	13.3	148	82.1	11.6	147	2.8%	1.50 [-1.35 , 4.35]
Wang 2023	79.9	10.9	24	81.6	8.9	25	0.8%	-1.70 [-7.28 , 3.88]
Watson 2015	82.87	6.726051	32	84.27	9.546382	33	1.6%	-1.40 [-5.40 , 2.60]
Zha 2020	88.8	7.45	12	88.1	9.41	13	0.6%	0.70 [-5.93 , 7.33]
Total (95% CI)			**8469**			**8364**	**100.0%**	**-0.50 [-1.03 , 0.03]**

Heterogeneity: Tau² = 0.50; Chi² = 35.07, df = 21 (P = 0.03); I² = 40%
Test for overall effect: Z = 1.86 (P = 0.06)
Test for subgroup differences: Not applicable

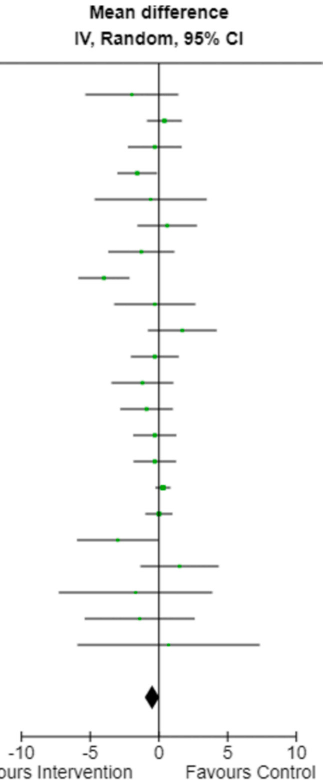

Fig. 3. A forest plot of the effect of digital health interventions for the reduction of systolic blood pressure at a 6-month intervention period. The mean difference of DBP was available for 26 studies that included 17,900 participants. The weight of the evidence from each study is reflected in the size of the green squares. The black diamond represents the effect size of the pooled studies, and its width represents the 95 % IC. Compared with the usual care group (control group), the DHIs group (intervention) had a reduction in DBP (MD = -0.50 mmHg [95 %IC: −1.03 to 0.03] mmHg), with evidence of moderate heterogeneity (I^2 = 40 %). CI: confidence interval, DHI: digital health intervention, IV: inverse variance, MD: mean difference, SBP: systolic blood pressure, SD: standard deviation.

"high," indicating high confidence that the true effect lies close to the estimated effect. All factors that could influence the certainty of the evidence, including the risk of bias, inconsistency, indirectness, and imprecision, were classified as "not serious" (Supplement Table S6).

3. Discussion

This systematic literature review and *meta*-analysis investigated 41 studies on the effectiveness of lowering BP among individuals with hypertension or at high risk. Our findings revealed that DHIs can lead to a modest but significant reduction in SBP by ∼ 1.45 mmHg more than usual care. The smaller ∼ 0.50 mmHg reduction in effect on DBP was not significant, although SBP is generally regarded a more appropriate indicator for monitoring BP [86]. Subgroup analysis revealed that the effect on SBP was statistically significant for DHIs delivered through smartphone applications but not for other delivery methods, such as SMS or mobile phone calls. The *meta*-analysis also found no significant differences between females and males for SBP changes.

Our *meta*-analysis demonstrated a statistically significant reduction in SBP associated with DHI use; the magnitude of the reduction may not have reached clinically significance. Yet, Lewington et al. (2002) reviewed 61 prospective observational studies and linked a ∼ 2 mmHg in SBP or ∼ 1 mmHg in DBP with a reduction of up to 10 % in cardiovascular mortality [87].

This analysis reported more modest reductions in BP compared with other *meta*-analyses [32,88,89]. Katz et al. (2024) reported a large *meta*-analysis of 28 RCTs, which showed a greater effect in SBP with ∼ 4.24 mmHg at 6 months using different types of delivery for the DHIs [32]. Lu et al. (2019) *meta*-analysis of 11 RCTs, reported reductions of SBP ∼ 3.85 mmHg and ∼ 1.11 mmHg in DBP among participants receiving smartphone app interventions compared with the usual care [89]. Our *meta*-analysis included 10 RCTs [60,62,67,69,75,76,81,83–85] with participants who had controlled hypertension, which may have been a factor moderating the effectiveness of the DHIs. In contrast, studies by Zhou et al. and Lu et al. targeted participants with uncontrolled hypertension and achieved a clinically significant reduction of SBP [78]. While these studies did not report significant changes in BP, this suggests that the effectiveness of DHIs may be greater in populations with more poorly controlled BP. Compared to the *meta*-analysis conducted by Sakima et al., our *meta*-analysis exhibited less heterogeneity [88]. Our stricter inclusion criteria, focusing on RCTs published within the last 5 years and utilizing validated blood pressure measurement methods, may have contributed to the lower observed heterogeneity compared to Sakima et al., whose analysis included a broader range of study designs and publication dates. This heterogeneity underscores the need for standardised reporting and robust methodological approaches in future DHI research.

The relationship between the effectiveness of DHIs on BP and the duration of the intervention was not examined here. Katz et al. (2024) reported BP changes at 3 and 6 months after the DHI compared to usual care [32], but the available evidence on the long-term effects of DHI on BP control is limited. Few studies report BP changes and hypertension control beyond 12 months. While our analysis is consistent with findings from Uhlig et al.[90], demonstrates the effectiveness of DHIs in lowering SBP at 6 months, long-term impact of these interventions remains uncertain. Uhlig's finding of reduced effectiveness at 12 months suggests the difficulty of sustaining behaviour change over time. This difference between short-term and long-term outcomes may be due to several factors. First, enthusiasm for DHIs may decrease as motivation wears off or users experience 'app fatigue'. Second, many DHIs lack ongoing support and feedback, which are crucial for maintaining motivation and adherence. Finally, the inherent complexity of long-term behaviour

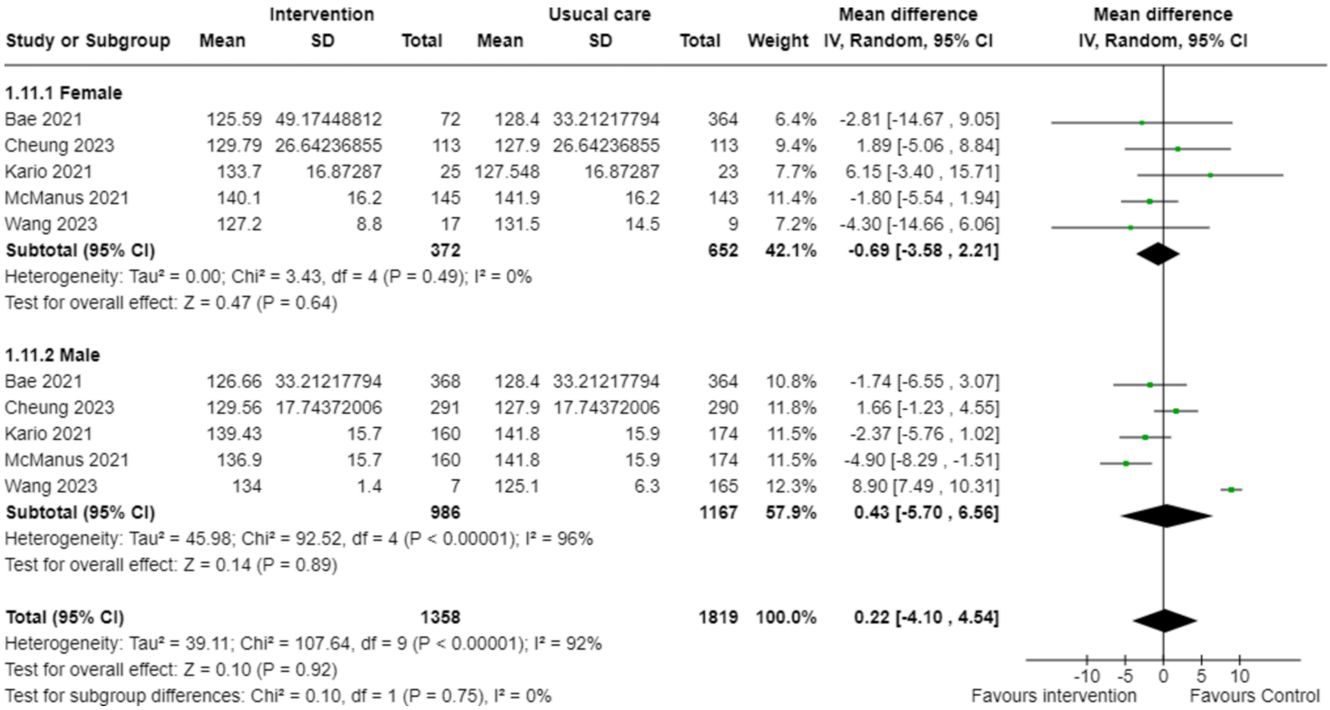

Fig. 4. A forest plot of the effectiveness of digital health interventions for the reduction of systolic blood pressure at a 6-month intervention period between males and females. The weight of the evidence from each study is reflected in the size of the green squares. The black diamond represents the effect size of the pooled studies, and its width represents the 95 % IC. Compared with the usual care group (control group), the overall effect did not favour the DHIs group (intervention) (MD = 0.22 mmHg [95 %IC: −4.10 to 4.54] mmHg), with evidence of heterogeneity between studies (I^2 = 92 %). For females, the effect was slightly greater but not significant (MD = -0.69 mmHg [95 %IC: −3.58 to 2.21] mmHg) than the male group (MD = 0.43 mmHg [95 %: −5.70 to 6.56] mmHg). DHI: digital health intervention, IV: inverse variance, MD: mean difference, SBP: systolic blood pressure, SD: standard deviation.

Table 1
Effects of DHIs on SBP in the delivery method.

Subgroups	Trials	Intervention	Control	Mean Difference	Heterogeneity (%)		Test for Overall Effect		P heterogeneity
	N	N	N	Mean (95 %)	I^2	P value	Z	P value	P value
Phone-based mode delivery									<0.00001
Smartphone-app	9	2,304	2,389	−1.94 [-3.38, −0.50]	57	0.02	2.64	<0.01	
Short Messages Services	4	951	926	−0.19 [-1.60, 1.23]	4	0.37	0.26	0.79	
Phone Calling	3	318	321	−1.09 [-5.49, 3.31]	69	0.04	0.49	0.49	

App application, *CI* confidence interval, *N* number.

change, especially for chronic conditions like hypertension, poses a significant challenge. Maintaining healthy habits long-term can be challenging due to fluctuating motivation, other priorities, and environmental factors [91]. Future research should focus on ways to improve long-term engagement with digital health interventions, like adding personalised feedback, gamification, and social support features.

DigiCare4You Consortium (2023) *meta*-analysis reported that DHI effectively lowered SBP by 3.62 mmHg and DBP by 2.45 mmHg in adults with hypertension, irrespective of the mode of intervention delivery [92]. However, smartphone app interventions had a greater effect on reducing SBP and DBP than SMS interventions, a finding that aligns with emerging evidence highlighting the potential of app-based interventions [14,26,93]. Smartphone apps' interactive and engaging nature may contribute to their effectiveness by promoting patient engagement, self-monitoring, and adherence to treatment plans. Given the high proportion of patients with access to digital communication devices (e.g., smartphones and tablets) and various digital health tools for managing hypertension, other factors examined here could inform the choice of DHI (e.g., patient preference, feasibility, and SES).

The strength of our review lies in using standardised methodology as documented in PRISMA [38] under the Cochrane guidance for systematic reviews [37] and not restricting the search by study type. Secondly, this review did not exclude participants with other comorbidities, such as diabetes. Thirdly, the sensitivity analysis was conducted to guarantee the robustness of the pooled estimates. Fourthly, the large number of RCTs (n = 26) and sample size (n = 17,900) contributed to the reliability of the results.

However, this review has some limitations. First, we were unable to conduct all planned subgroup analyses, particularly regarding the influence of young adults, as 73 % of the RCTs did not report outcomes by age subgroup, a common limitation in evidence synthesis [94]. This might be because subgroup analysis tends to be reported on large RCTs [95]. Further exploration should prioritise standardised reporting of subgroup analyses to enable a more comprehensive understanding of DHI across different stages of adulthood.

Second, some eligible studies were ongoing and could not be included. Third, only considered English language publications could be included. Fourth, we compared SMS, smartphone applications, and phone calling as delivery modalities but did not include non-digital interventions provided solely through telemonitoring. Finally, the studies we identified were predominantly from high-income countries, and most participants were drawn from high-income households, limiting the generalisability of our findings.

Despite these limitations, our findings have important implications for clinical practice and future research. Integrating smartphone apps into routine hypertension care holds promise for empowering patients and improving blood pressure control. Based on our findings, smartphone apps appear to be the most effective phone-based intervention for blood pressure management. This suggests that healthcare providers should be familiar with various phone-based interventions and encourage people with hypertension to consider using smartphone-based apps for blood pressure management. Providers also need to understand the features of different digital healthcare delivery options and aim to provide patient-centred medical care.

Future research should prioritise longer follow-up periods (>1 year) to examine DHI effectiveness, explore the impact of DHIs on diverse populations and across various stages of hypertension, and investigate the underlying mechanisms by which DHIs exert their effects. Additionally, the co-design of DHIs with patients and healthcare providers, which was reported in only five of the 41 studies reviewed, could enhance their acceptability, usability, and, ultimately, their effectiveness in real-world settings.

4. Conclusion

In this review of DHIs for high blood pressure management in individuals with hypertension or high-risk factors, a significant modest difference in SBP between the intervention and control groups was detected 6 months from the start of the intervention. These findings provide some evidence supporting the potential of DHIs for self-management of hypertension, regardless of sex. However, our analysis was unable to determine if the observed reductions in SBP varied by age due to limitations in the available data. Further research is needed to investigate these potential differences and tailor DHI implementation strategies across different demographic groups.

We also underscored the variability in the efficacy of DHIs based on the mode of delivery, with smartphone applications showing the greatest potential for reducing SBP. Moreover, this review suggests that even within a particular mode of delivery, the specific design features and characteristics of the interventions can significantly influence their effectiveness, warranting further investigation. The magnitude of BP reduction suggests that DHIs may offer a valuable adjunct approach to traditional hypertension management strategies. Given the widespread adoption of digital technologies in healthcare settings, prioritising long-term assessment of DHIs and exploring their impact on diverse populations and across various stages of hypertension is critical for leveraging their full potential.

CRediT authorship contribution statement

Emily Motta-Yanac: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Victoria Riley:** Writing – review & editing, Supervision. **Naomi J. Ellis:** Writing – review & editing, Supervision. **Aman Mankoo:** Data curation. **Christopher J. Gidlow:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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