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Technology-supported behavior change interventions for reducing sodium intake in adults: a systematic review and meta-analysis

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Yong Yang Yan¹, Lily Man Lee Chan¹, Man Ping Wang¹, Jojo Yan Yan Kwok¹, Craig S. Anderson² & Jung Jae Lee¹ ✉

The effects of technology-supported behavior change interventions for reducing sodium intake on health outcomes in adults are inconclusive. Effective intervention characteristics associated with sodium reduction have yet to be identified. A systematic review and meta-analysis were conducted, searching randomized controlled trials (RCTs) published between January 2000 and April 2023 across 5 databases (PROSPERO: CRD42022357905). Meta-analyses using random-effects models were performed on 24-h urinary sodium (24HUNa), systolic blood pressure (SBP), and diastolic blood pressure (DBP). Subgroup analysis and meta-regression of 24HUNa were performed to identify effective intervention characteristics. Eighteen RCTs involving 3505 participants (51.5% female, mean age 51.6 years) were included. Technology-supported behavior change interventions for reducing sodium intake significantly reduced 24HUNa (mean difference [MD] -0.39 gm/24 h, 95% confidence interval [CI] -0.50 to -0.27 ; $I^2 = 24\%$), SBP (MD -2.67 mmHg, 95% CI -4.06 to -1.29 ; $I^2 = 40\%$), and DBP (MD -1.39 mmHg, 95% CI -2.31 to -0.48 ; $I^2 = 31\%$), compared to control conditions. Interventions delivered more frequently (\leq weekly) were associated with a significantly larger effect size in 24HUNa reduction compared to less frequent interventions ($>$ weekly). Other intervention characteristics, such as intervention delivery via instant messaging and participant-family dyad involvement, were associated with larger, albeit non-significant, effect sizes in 24HUNa reduction when compared to other subgroups. Technology-supported behavior change interventions aimed at reducing sodium intake were effective in reducing 24HUNa, SBP, and DBP at post-intervention. Effective intervention characteristics identified in this review should be considered to develop sodium intake reduction interventions and tested in future trials, particularly for its long-term effects.

Excessive sodium intake (≥ 2 gm of sodium or equivalent to ≥ 5 gm of salt intake daily¹) is the leading dietary risk factor of hypertension (HTN) and cardiovascular disease (CVD)^{1,2}, causing 1.65 million global deaths related to CVD annually². The World Health Organization (WHO) recommends adults consume less than 2 gm of sodium daily³, as reducing sodium intake can lower blood pressure (BP)^{4,5}, thereby reducing death and disability attributable to CVD⁶. However, most adults consume an average of

3.5–5.5 gm sodium daily³, which is significantly higher than the recommended amount.

Changing consumers' sodium intake behavior through education is a sodium reduction strategy proposed by the WHO⁷. A narrative systematic review reported that behavior change interventions improved sodium intake behavior and/or reduced sodium intake⁸. A meta-analysis further confirmed the effect of sodium reduction behavior change interventions⁹.

¹School of Nursing, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong, China. ²The George Institute for Global Health, Faculty of Medicine, University of New South Wales, Sydney, Australia. ✉e-mail: leejay@hku.hk

However, these two reviews primarily included interventions with a face-to-face delivery mode. Technology-supported interventions, targeting to modify individuals' sodium intake behavior by using technological tools (e.g., telephone, video, web/mobile applications, and digital devices)^{9,10}, have been increasingly used to reduce sodium intake in order to reach a wider population and reduce costs^{7,9}. A narrative systematic review identified that 64% of interventions supported by mobile applications (app) or short message services (SMS) have beneficial effects on sodium reduction¹¹. However, no meta-analysis has been conducted to quantify the intervention effects on sodium intake and BP¹¹. Given increasing studies of technology-supported interventions in sodium intake reduction have been published in recent years^{12,13}, it is timely to conduct a systematic review and meta-analysis to synthesize the evidence.

Identifying effective intervention characteristics, such as delivery technology type, delivery frequency, and behavior change techniques (BCTs), can help develop more effective behavior change interventions¹⁴ to address the complexity¹⁵ and resource consumption⁸ involved in changing an individual's sodium intake behavior. BCTs are the smallest replicable intervention components intended to alter or redirect causal processes that regulate behavior^{16,17}. Specifying the BCTs applied in behavior change interventions can facilitate a better understanding of the mechanisms of initiating and sustaining desired behaviors and the replication of interventions across diverse settings^{16,17}. Yet, the effective intervention characteristics associated with sodium reduction, including BCTs, have not been explored.

This systematic review and meta-analysis aimed to evaluate the effects of technology-supported behavior change interventions for reducing sodium intake on sodium reduction, systolic blood pressure (SBP), and

diastolic blood pressure (DBP) and explore effective intervention characteristics associated with sodium reduction.

Results

Study characteristics

A total of 28,837 articles were retrieved, and 18 randomized controlled trials (RCTs) (19 comparisons) were included in the final review (Fig. 1)^{12,13,18–33}. Study characteristics are shown in Table 1 and Supplementary Table 1. The RCTs were published between 2005 and 2023 from 10 countries. Nine RCTs (3 each) were conducted in Japan^{25–27}, Thailand^{28,30,31}, and the United States^{19,20,23}, with over half ($n = 10$) conducted in Asia^{12,22,24–28,30–32} (Supplementary Fig. 1). The review included 3505 participants, with 51.5% ($n = 1805$) being female (sex not disclosed in one RCT²⁸). Participants' mean age ranged from 28.5 to 66.3 years (median 54.5; mean 51.6 [standard deviation, SD 12.2]). Nine RCTs recruited hypertensive patients^{13,18,19,22,25,28,30,32,33}, three recruited healthy/normative participants^{23,24,29}, two recruited patients with heart disease (i.e., heart failure²⁰, prior acute coronary syndrome, revascularization, or exertion angina²¹), and four recruited hypertensive and healthy/normative participants^{12,26,27,31}. The intervention settings were nonhealthcare settings ($n = 12$)^{12,18,19,21–26,28,29,33}, healthcare settings ($n = 3$)^{20,30,31}, and the combination of nonhealthcare and healthcare settings ($n = 3$)^{13,27,32}. Nonhealthcare settings included homes, grocery stores, restaurants, schools, and worksites. The intervention duration ranged from 1 to 12 months (median 2; mean 2.8 [SD 2.6]), and the follow-up duration ranged from 0 to 9 months (median 0; mean 0.8 [SD 2.1]).

Fig. 1 | PRISMA flow chart of study selection. The flow chart, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, illustrates the detailed process of study search and selection.

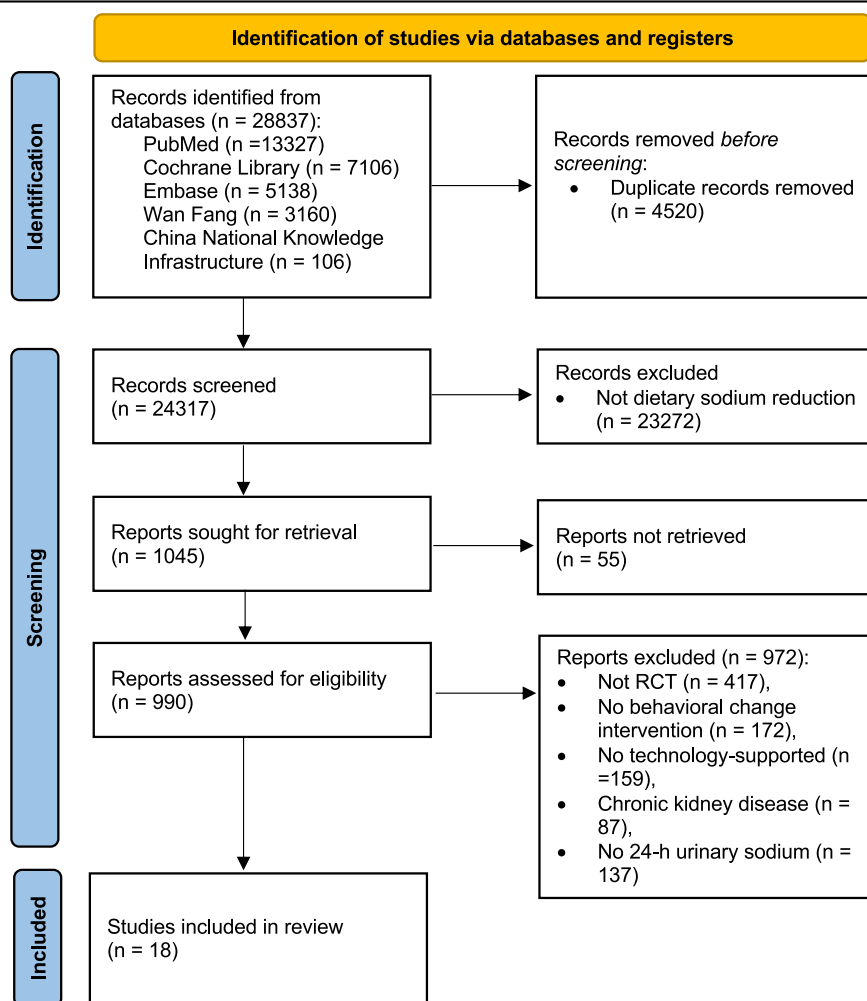


Table 1 | Study Characteristics

Author, Year, Country	Sample Size (IG, CG), No. Female (%)	Mean Age (years)	Health Status	Intervention Setting	Intervention + Follow-up Duration	Technology Type
Cornelio ¹⁸ , 2014, Brazil	119 (62, 57), 119 (100.00%)	59.00	HTN	Nonhealthcare setting	2 months + 1 month	Telephone call
Dorsch ¹⁹ , 2020, USA	50 (24, 26), 30 (60.00%)	57.43	HTN	Nonhealthcare setting: home, grocery store, and restaurant	2 months + 0 month	App developed for sodium reduction (LowSalt4Life)
Dunbar ²⁰ , 2005, USA	61 (32, 29), 28 (45.90%)	61.00	Heart disease	Healthcare setting	3 months + 0 month	Telephone call + Video (Primary type: Telephone call)
Eyles a ²¹ , 2017, New Zealand	66 (33, 33), 11 (16.67%)	64.00	Heart disease	Nonhealthcare setting: grocery store	1 month + 0.5 month	App developed for sodium reduction (SaltSwitch) + Email + Telephone call (Primary type: SaltSwitch)
Eyles b ²² , 2023, New Zealand	168 (84, 84), 74 (49.01%)	54.50	HTN	Nonhealthcare setting: home and grocery store	3 months + 0 month	App developed for sodium reduction (SaltSwitch) + SMS + Video (Primary type: SaltSwitch)
He ¹² , 2022, China	1184 (594, 590), 633 (63.46%)	45.80	HTN + Healthy adults	Nonhealthcare setting: home and school	12 months + 0 month	App developed for sodium reduction (AppSalt) + Instant messaging App (WeChat) (Primary type: AppSalt)
Hwang ²³ , 2014, South Korea	245 (119, 126), 123 (50.20%)	49.56	HTN	Nonhealthcare setting	2 months + 2 months	Telephone call
Ipijian ²³ , 2017, USA	30 (15, 15), 23 (76.67%)	34.40	Healthy population	Nonhealthcare setting	1 month + 0 month	App developed for sodium reduction (MyFitnessPal)
Jarrar ²⁴ , 2022, United Arab Emirates	121 (IG1: 41, IG2: 41, CG: 39), 60 (49.59%)	28.50	Healthy population	Nonhealthcare setting	1.5 months + 1 month	IG1: Instant messaging App (WhatsApp), IG2: Email
Morikawa ²⁵ , 2011, Japan	41 (22, 19), 0 (0.00%)	47.74	HTN	Nonhealthcare setting: worksite	1 month + 0 month	Digital self-monitoring sodium device + Email (Primary type: the device)
Nakadate ²⁶ , 2018, Japan	50 (28, 22), 35 (70.00%)	53.54	HTN + Healthy adults	Nonhealthcare setting: home	3 months + 0 month	Digital self-monitoring sodium device
Riches ¹³ , 2021, UK	47 (31, 16), 30 (63.83%)	65.00	HTN	Nonhealthcare + healthcare setting	1.5 months + 0.5 month	App developed for sodium reduction (SaltSwap) + SMS (Primary type: SaltSwap)
Takada ²⁷ , 2018, Japan	158 (79, 79), 105 (66.46%)	62.45	HTN + Healthy adults	Nonhealthcare + healthcare setting	1 month + 0 month	Digital self-monitoring sodium device
Thattong ²⁸ , 2020, Thailand	67 (32, 35), NA	40.94	HTN	Nonhealthcare setting: worksite	2 months + 0.5 month	Instant messaging App (LINE)
Toft ²⁹ , 2020, Denmark	112 (63, 24), 46 (52.87%)	40.68	Healthy population	Nonhealthcare setting	4 months + 0 month	Telephone call + Email (Primary type: telephone call)
Wiriyatanakorn ³⁰ , 2021, Thailand	90 (45, 45), 49 (54.44%)	62.90	HTN	Healthcare setting	2 months + 0 month	Digital self-monitoring sodium device
Yokokawa ³¹ , 2020, Thailand	753 (374, 379), 367 (48.74%)	66.25	HTN + Healthy population	Healthcare setting	3 months + 9 months	Digital self-monitoring sodium device
Yuan ³² , 2019, China	168 (84, 84), 72 (42.86%)	57.50	HTN	Nonhealthcare + healthcare setting	6 months + 0 month	Instant messaging App (WeChat) + Telephone call + SMS (Primary type: WeChat)

App application, CG control group, HTN hypertension, IG intervention group, NA not available, No. number, SMS short message service, UK the United Kingdom, USA the United States of America. Note: Primary technology type was defined as the most frequently used or the predominant technology used in the intervention.

Seven types of technological tools were identified: mobile apps developed for sodium reduction ($n = 6$)^{12,13,19,21,23,24,33}, telephone calls ($n = 6$)^{18,20–22,29,32}, digital self-monitoring sodium devices ($n = 5$)^{25–27,30,31}, instant messaging apps ($n = 4$)^{12,24,28,32}, emails ($n = 4$)^{21,24,25,29}, SMS ($n = 3$)^{13,32,33}, and videos ($n = 2$)^{20,33}. Eight RCTs used partially technology-supported interventions with face-to-face components^{12,13,18,20,29–32}. Nine RCTs used an individual-based delivery mode^{13,19,22–25,28,32,33}, followed by group-based mode ($n = 4$)^{12,18,30,31}, dyad-based mode ($n = 3$, all were participant-family dyads)^{20,27,29}, and mixed mode ($n = 2$)^{21,26}. Six RCTs involved participants' family members^{12,20,21,26,27,29}. Different intervention frequencies were found, including \leq weekly ($n = 7$)^{22–24,26,28,32,33}, using mobile apps developed for sodium reduction when food shopping ($n = 4$)^{13,19,21,33}, $>$ weekly ($n = 3$)^{12,18,24}, and four not identified^{20,27,29,31}. Dietitians were the most common professionals delivering interventions ($n = 5$)^{20,22,27,30,31}, followed by nurses ($n = 4$)^{13,18,20,32}, nutritionists ($n = 2$)^{18,29}, physicians ($n = 1$)²⁷, healthcare assistants ($n = 1$)¹³, research assistants ($n = 1$)²⁸, and trained teachers ($n = 1$)¹². Only six RCTs employed theoretical frameworks^{13,18–20,27,29}. Three self-estimation methods for sodium intake were identified: mobile apps developed for sodium reduction ($n = 6$)^{12,13,19,21,23,33}, self-monitoring sodium devices ($n = 5$)^{25–27,30,31}, and salt-restriction spoons/scales ($n = 2$)^{18,32}. Ten studies included an inactive control group (e.g., general health education without focusing on sodium reduction or no treatment)^{12,18,19,21,24,25,28,29,31,32}, while eight studies had an active control group (e.g., salt reduction advice leaflet)^{13,20,22,23,26,27,30,33}. Intervention groups had a sodium reduction ranging from -2.77 gm/24 h to $+0.32$ gm/24 h, indicating the sodium reduction percentages from -46.94% to $+8.85\%$ (median -14.95% ; mean -14.56% [SD 11.99]).

Regarding BCT identification, 35 BCTs from 13 groupings were identified in the intervention groups from 18 included RCTs (Supplementary Table 2.1 and Table 2.2). BCTs identified per RCT ranged from 5 to 24 (median 10.00; mean 11.68 [SD 4.84]). The five most frequently identified BCTs were 4.1 'instruction on how to perform the behavior' ($n = 18$), 6.1 'demonstration of the behavior' ($n = 17$), 8.1 'behavioral practice/rehearsal' ($n = 17$), 8.3 'habit formation' ($n = 15$), 1.1 'goal setting(behavior)' ($n = 12$), 1.4 'action planning' ($n = 12$), 2.2 'feedback on behavior' ($n = 10$), and 5.1 'information about health consequences' ($n = 10$) (Supplementary Table 2.3).

Risk of bias assessment

Overall quality judgments rated 33% of RCTs with a low risk of bias ($n = 6$)^{12,13,21,29,30,33}, 50% with some concerns of bias ($n = 9$)^{19,20,22–27,31}, and 17% with a high risk of bias ($n = 3$) (Supplementary Fig. 2)^{18,28,32}. A high risk of bias was identified in 6 RCTs in Domain 2 (deviation from intended interventions) and 1 RCT in Domain 3 (missing outcome data).

Meta-analysis of the 24HUNa, SBP, and DBP

Technology-supported behavior change interventions significantly reduced 24HUNa (MD -0.39 gm/24 h, 95% CI -0.50 to -0.27 ; $I^2 = 24\%$; Fig. 2), at a rate equivalent to a salt reduction of 0.98 gm/24 h (95% CI -1.25 to -0.68) compared to active or inactive control conditions^{12,13,18–24,26,27,29–33}. The effect size of 24HUNa was $g = -0.32$ (95% CI to -0.42 to -0.21), representing a small to medium effect based on the absolute value of g . No publication bias was detected by the Begg test ($p = 0.13$) and the Egger test ($p = 0.18$). SBP significantly decreased following the intervention (MD -2.67 mmHg, 95% CI -4.06 to -1.29 ; $I^2 = 40\%$; Fig. 3)^{12,13,19,21,22,25,27,29–33}, with a small to medium effect based on the absolute value of g ($g = -0.22$, 95% CI -0.29 to -0.15). The Begg test ($p = 0.20$) and the Egger test ($p = 0.13$) did not discover publication bias. A significant decrease was also found in DBP (MD -1.39 mmHg, 95% CI -2.31 to -0.48 ; $I^2 = 31\%$; Fig. 4)^{12,13,22,25,27,29–33}, with a small effect based on the absolute value of g ($g = -0.15$, 95% CI -0.25 to -0.0). Neither the Begg test ($p = 0.22$) nor the Egger test ($p = 0.08$) indicated publication bias.

Overall, sensitivity analyses supported the robustness of the effects on 24HUNa, SBP, and DBP. The intervention effects were not significantly changed after excluding RCTs with high risk of bias regarding 24HUNa (MD -0.36 gm/24 h, 95% CI -0.47 to -0.26 and $g = -0.32$, 95% CI -0.43 to

-0.20), SBP (MD -2.33 mmHg, 95% CI -3.29 to -1.38 and $g = -0.20$, 95% CI -0.28 to -0.13), and DBP (MD -1.23 mmHg, 95% CI -2.05 to -0.40 and $g = -0.13$, 95% CI -0.24 to -0.03).

Subgroup analysis and meta-regression of the 24HUNa

The results of subgroup analyses are reported in Supplementary Table 3. Intervention frequency significantly affected the effects on 24HUNa ($p = 0.03$), with more frequent interventions (\leq weekly) achieving a larger effect than less frequent interventions ($>$ weekly). Additionally, applying BCT 6.1 'demonstration of the behavior' ($p = 0.04$) and 8.1 'behavioral practice/rehearsal' ($p = 0.04$) resulted in significantly greater reductions in 24HUNa, compared to not using these techniques. No significant differences were detected in other subgroups of intervention characteristics. However, relatively but not significantly larger effect sizes of 24HUNa were shown in the following subgroups: normative participants ($g = -0.57$), use of instant messaging apps ($g = -0.53$), multidisciplinary professionals for intervention delivery ($g = -0.35$), dyad-based intervention delivery mode ($g = -0.50$), family member involvement ($g = -0.33$), entirely technology-supported interventions ($g = -0.37$), healthcare setting ($g = -0.34$), using digital self-monitoring sodium devices as the method of self-estimating sodium intake ($g = -0.37$), individually applying the BCTs of 1.1 'goal setting(behavior)' ($g = -0.32$), 2.3 'self-monitoring of behavior' ($g = -0.34$), 2.6 'biofeedback' ($g = -0.37$), 3.2 'social support (practical)' ($g = -0.35$), 8.3 'habit formation' ($g = -0.36$), and 9.1 'credible source' ($g = -0.33$).

Meta-regressions suggested that sample size, proportion of female participants, mean age, intervention duration, follow-up duration, and number of BCTs identified in each RCT were not associated with 24HUNa reduction (Supplementary Table 4).

Discussion

This is the first meta-analysis to evaluate the effects of technology-supported behavior change interventions for reducing sodium intake on 24HUNa, SBP, and DBP and identify the BCTs used in behavior change interventions for sodium intake reduction. Subgroup analyses showed that intervention frequency and the BCTs of 6.1 'demonstration of the behavior' and 8.1 'behavioral practice/rehearsal' were significantly associated with the effect on 24HUNa. Other effective intervention characteristics in reducing 24HUNa, such as primary technology type and intervention delivery mode, were also identified.

Significant 24HUNa reduction was observed (MD -0.39 gm/24 h) in this meta-analysis. The result is comparable to a finding from a meta-analysis (MD -0.46 gm/24 h), in which included interventions were primarily delivered in a face-to-face format⁹. This suggests that technology-supported behavior change interventions can serve as an effective alternative to traditional face-to-face interventions. Reducing sodium intake by 0.39 gm/24 h by behavior change has considerable public health implications. It was estimated that a 0.4 gm/24 h sodium reduction would substantially reduce 9 million CVD events and save 4 million lives in the Chinese population by 2030³⁴. The significant reductions of 2.67 mmHg in SBP and 1.39 mmHg in DBP identified in this meta-analysis are comparable to the findings of a recent meta-analysis, which found that health education interventions significantly reduced SBP and DBP by 2.8 and 2.1 mmHg, respectively⁴. Similarly, another meta-analysis found sodium reduction via dietary modifications reduced 2.9 mmHg in SBP and 1.2 mmHg in DBP³⁵. The similar magnitudes of BP reduction in this study suggest that technology-supported interventions are as efficacious as face-to-face-delivered interventions in controlling BP. These effects on 24HUNa, SBP, and DBP are robust, as confirmed by the leave-one-out sensitivity analysis and excluding RCTs with a high risk of bias. It is important to note that the effects on 24HUNa and BP reduction in this meta-analysis represent post-intervention effects. These effects were assessed over relatively short intervention durations (mean 2.8 months and median 2 months), without assessment of longer-term follow-up effects. Future RCTs are needed to evaluate and report the long-term effects on 24HUNa and BP. Although technology-supported interventions can supplement current sodium

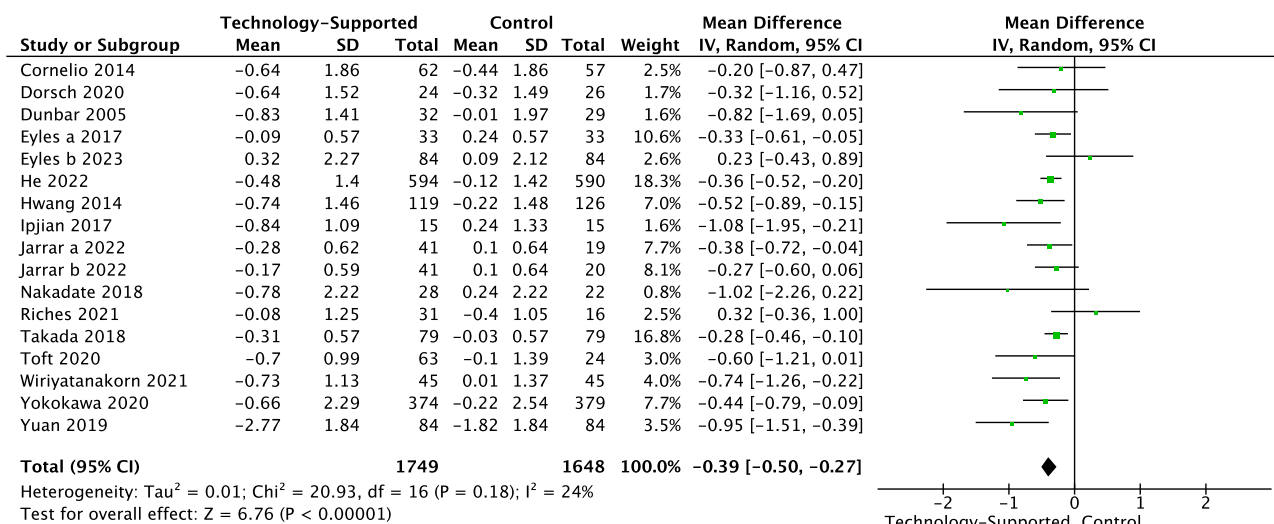


Fig. 2 | Forest plot of 24-h urinary sodium. The unit of 24-h urinary sodium (24HUNa) was 'gm/24 h'. The 'Mean' (change score or change from baseline) of 24HUNa within each group was calculated by subtracting the baseline mean from

the post-intervention mean. The 'Mean Difference' refers to the comparison of mean values between two groups. Post-intervention data was used in the meta-analysis as the majority of studies did not assess outcomes during follow-up periods.

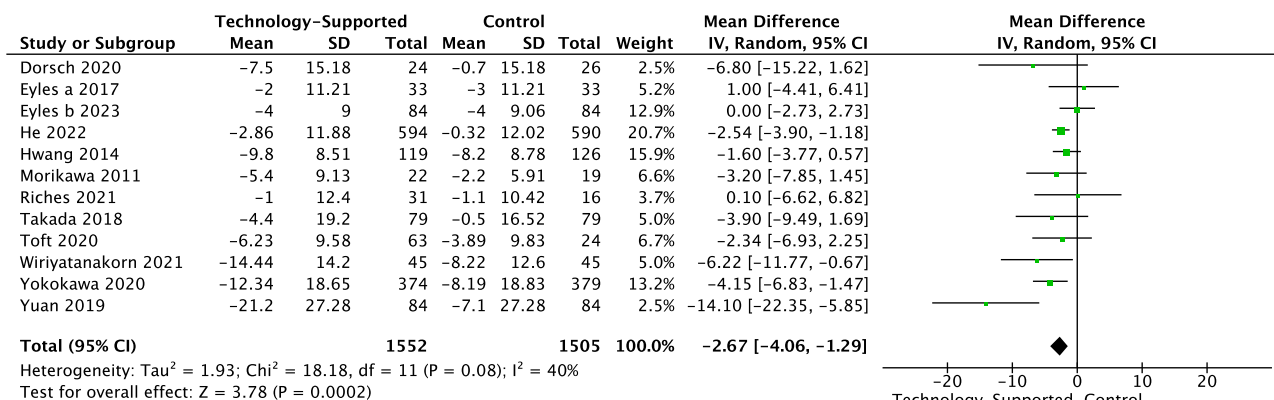


Fig. 3 | Forest plot of systolic blood pressure. The unit of systolic blood pressure (SBP): mmHg. The 'Mean' (change score or change from baseline) of SBP within each group was calculated by subtracting the baseline mean from the post-

intervention mean. The 'Mean Difference' refers to the comparison of mean values between two groups. Post-intervention data was used in the meta-analysis as the majority of studies did not assess outcomes during follow-up periods.

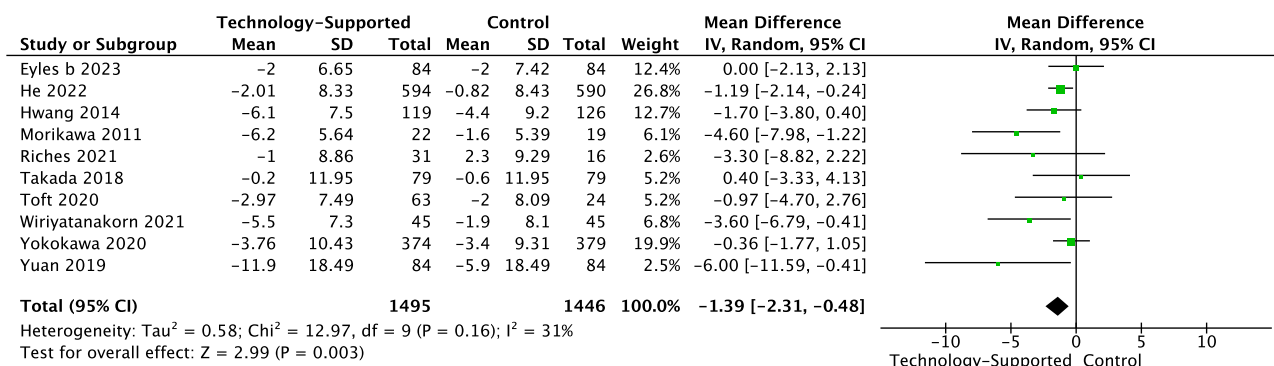


Fig. 4 | Forest plot of diastolic blood pressure. The unit of diastolic blood pressure (DBP): mmHg. The 'Mean' (change score or change from baseline) of DBP within each group was calculated by subtracting the baseline mean from the post-

intervention mean. The 'Mean Difference' refers to the comparison of mean values between two groups. Post-intervention data was used in the meta-analysis as the majority of studies did not assess outcomes during follow-up periods.

reduction efforts, the average proportion of sodium reduction (14.56%) in the intervention group found in this review would not be sufficient to reach the WHO's goal of a 30% reduction in the population's sodium intake by 2030. Future research should explore the integration of technology-supported interventions into the sodium reduction initiatives recommended by the WHO, such as food reformulation and front-of-pack nutrition labeling initiatives^{7,11}. By incorporating these technological advancements, it is possible to amplify the effects of current multi-faceted sodium reduction initiatives, ultimately resulting in more significant synergistic health benefits. For instance, leveraging technology such as widely used instant messaging apps (e.g., WhatsApp and WeChat) to distribute educational content on sodium reduction could enhance awareness among the broader population and foster greater acceptance of low-sodium products resulting from food reformulation⁷. This approach can also improve their comprehension and use of front-of-pack nutrition labels, empowering them to make informed choices about low-sodium foods^{7,11}. Given the widespread accessibility of technology such as smartphones, this approach can be readily applied to patients in healthcare settings as well as to community-dwelling individuals in non-healthcare environments. Consequently, the technology-supported strategy not only bolsters individual efforts to reduce sodium intake but also reinforces the effectiveness of the food industry and governmental efforts in such food reformulation and nutrition labeling initiatives.

Effective intervention characteristics identified in this review provide evidence for guiding the development of future interventions. Significant 24HUNa reductions were found among hypertensive, normative participants, and a combination of both, suggesting the feasibility of using technology-supported interventions for hypertensive patients and the general population. Regardless of the delivery mode, whether as individuals, dyads, or groups—all modes were effective in reducing 24HUNa. Dyad-based interventions (i.e., participant-family dyads) were likely to have a greater effect size ($g = -0.50$) than individual-based ($g = -0.30$) and group-based ($g = -0.24$) interventions. This result is consistent with another subgroup analysis in this study, which found that involving family members in participants' sodium reduction had a relatively larger effect size ($g = -0.33$) compared to interventions in which family members did not participate ($g = -0.28$). One possible reason is that individual sodium intake is affected by social environment (e.g., a family's eating habits³⁶). Involving family members to support individual sodium reduction, such as changing the family's eating habits or the home chef's cooking behavior, might be a promising strategy to reduce sodium intake^{20,37}. Technology-supported interventions were also effective in reducing 24HUNa in healthcare ($g = -0.34$) and non-healthcare settings ($g = -0.30$), irrespective of the presence of face-to-face intervention components, suggesting the potential for technology-supported interventions to be used as a standalone approach for reducing sodium intake. Compared to partially technology-supported interventions ($g = -0.29$), entirely technology-supported interventions were found to produce a stronger effect ($g = -0.37$) and may be less resource-consuming. Thus, implementing technology-supported interventions in different sub-populations and settings can be an effective public health approach in primary prevention and secondary management of excessive sodium intake.

Effective reductions in 24HUNa were observed regarding different technology types, including instant messaging apps ($g = -0.53$), telephone calls ($g = -0.33$), apps developed for sodium reduction ($g = -0.21$), and digital self-monitoring sodium devices ($g = -0.37$). Among these types, interventions delivered via instant messaging apps, such as WhatsApp and WeChat, had a relatively larger effect size on sodium reduction. Instant message-delivered interventions, which can be delivered through various formats (e.g., text, image, or voice) and cater to the participants' preferred time and frequency, provide participants with more personalized and real-time feedback from health professionals, leading to improved outcomes^{38,39}. Notably, interventions delivered weekly or less than weekly had a significantly larger effect size ($g = -0.48$, more frequent) over more than weekly ($g = -0.25$, less frequent) and are recommended for future trials. As sodium

intake is highly associated with daily diet consumption^{1,40}, interventions that are delivered more frequently may serve as a constant reminder for individuals to adopt healthier sodium intake behaviors in their daily lives, potentially leading to better sodium reduction outcomes. Except for more frequent delivery, innovative methods of self-estimation of sodium intake, such as apps developed for sodium reduction ($g = -0.21$) and digital self-monitoring sodium devices ($g = -0.37$) can also be applied in the intervention. As approximately 55% of the population is unaware of their daily sodium intake and tends to underestimate it^{41,42}, providing individuals with more accurate feedback on their sodium intake can help them understand their sodium intake conditions and make informed decisions to initiate, adjust, or maintain their sodium reduction behavior¹⁵. Dietitians, nurses, nutritionists, and physicians can independently practice ($g = -0.31$) or collaborate in a multidisciplinary team ($g = -0.35$) to reduce individuals' sodium intake, which later potentially results in a greater effect size on sodium reduction. A meta-analysis also highlighted the importance of involving healthcare professionals in achieving better outcomes in sodium reduction interventions⁸.

Compared to without BCT 6.1 'demonstration of the behavior' ($g = 0.27$), using BCT 6.1 ($g = -0.33$) was significantly associated with larger reductions in 24HUNa, where providing observable samples, such as a cookbook of low-sodium recipes¹⁸ or photographs of high-sodium food²⁹, facilitated participants to imitate the desired behavior by increasing their knowledge and skills to reduce sodium intake¹⁷. BCT 8.1 'behavioral practice/rehearsal' ($g = -0.33$) was also significantly associated with 24HUNa reduction compared to without BCT 8.1 ($g = 0.27$), where participants practiced the desired behavior to improve their self-efficacy on sodium reduction^{17,43}. The results should be interpreted with caution, considering that the two significantly effective BCTs were identified across 15 studies, compared to only one study that did not employ these techniques. Only one original RCT clearly stated the BCTs used¹⁵, and only 35 out of the 93 BCTs were identified, implying that BCTs are not widely explored in behavior change interventions for sodium reduction. Future trials aimed at changing behavior for sodium reduction may employ effective BCTs identified in this study and explore other BCTs.

This review adhered to PRISMA guidelines with a rigorous analysis of the overall effects, including publication bias examination, sensitivity analysis, and excluding RCT with high risks of bias. This review included only RCTs where the sodium intake was evaluated by 24HUNa, which provides an objective appraisal of the evidence on sodium reduction. The focus was exclusively on behavior modifications related to sodium intake, without examining interventions that included other HTN-related lifestyle modifications. This approach minimized the potential influence of confounding variables or moderators on BP reduction and provided a more targeted assessment of the effect of sodium intake behavior change on BP reduction.

This study has several limitations. The participant numbers in some subgroups were not evenly distributed. The results of subgroup analyses should be interpreted with caution as statistical tests may not detect significant differences between subgroups, or the results may be biased toward the larger subgroup. Insufficient intervention description in some original RCTs, especially on BCTs, limited subsequent analyses of the intervention characteristics associated with 24HUNa.

In conclusion, our systematic review and meta-analysis showed that technology-supported behavior change interventions for reducing sodium intake are effective in reducing 24HUNa, SBP, and DBP at post-intervention in adults. Further trials need to test the effective characteristics, such as intervention frequency (\leq weekly), technology (instant messaging apps), delivery mode (participant-family dyad), and long-term effects on sodium and BP reduction.

Methods

The systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines⁴⁴ (PRISMA, Supplementary Table 5) and was registered on the International Prospective

Register of Systematic Reviews (PROSPERO registration number: CRD42022357905).

Search strategy

Both English-language (PubMed, Cochrane Library, and Embase) and Chinese-language databases (Wan Fang and China National Knowledge Infrastructure) were searched for relevant articles written in English or Chinese published between 1 January 2000 and 13 April 2023. Medical subject headings (MeSH) and keywords related to ‘technology’, ‘sodium’, ‘salt’, and ‘reduction’ were used for the literature search. A manual search of reference lists was also conducted (Supplementary Table 6).

Study selection

The eligibility criteria based on population, intervention, comparison, outcomes, and study (PICOS) were applied. Population: adults (≥ 18 years). Participants with chronic kidney disease were excluded as the WHO’s sodium intake recommendation is not applicable to all these patients⁴⁵. Intervention: technology-supported interventions targeting to change individuals’ sodium intake behavior by partially (i.e., combined with face-to-face intervention components) or entirely utilizing technological tools, such as telephone, video, web/mobile apps, and digital devices. Interventions that addressed modifications to both sodium intake behavior and other HTN risk factors (e.g., physical inactivity) were excluded. Comparison: participants in the control groups received either active control⁴⁶ (e.g., sodium reduction education conducted contemporaneously with the intervention group) or inactive control (e.g., usual/standard treatment or no treatment). Outcomes: the original RCTs must report 24-h urinary sodium (24HUNa), which is the gold standard for estimating daily sodium intake⁴⁷, regardless of whether it was estimated from 24-h urine or spot urine samples and reported together with BP readings. Study: RCTs, excluding review, abstract, and protocol papers.

Data extraction

The RCTs were independently assessed by two reviewers (Y.Y.Y. and C.M.L.) for eligibility, information extraction, and quality assessment. Disagreements during these processes were resolved by a third reviewer (L.J.J.).

The extracted information: author, year, country, sample size, number and proportion of female participants, mean age, participants’ health status, intervention setting, intervention duration, follow-up duration, technology type, primary technology type (defined as the most frequently used or the predominant technology used in the intervention), urine sample type, intervention delivery mode (defined as individual-based, dyad-based, or group-based interventions, which interventions were delivered to 1, 2, or ≥ 3 participants, respectively⁴⁸), number of family members involved, intervention frequency, intervention delivery professional, partially technology-supported or entirely technology-supported, method of self-estimation of sodium intake, and proportion of sodium reduction in the intervention groups (calculated by: $100\% * [24\text{HUNa at post-intervention} - 24\text{HUNa at baseline}] / 24\text{HUNa at baseline}$ ⁴⁹).

The BCTs used in the original RCTs were identified by Michie’s BCT Taxonomy (BCTTv1)¹⁶, which contains 93 BCTs with unique codes and definitions. Intervention contents in the intervention groups were mapped to BCTTv1. The coding of each BCT was based on whether it was explicitly described in the intervention and assigned a ‘+’ if the content description met the corresponding definition. The BCTs were first identified by one reviewer (Y.Y.Y.), then double-checked and confirmed by another reviewer (C.M.L.).

All units of 24HUNa were converted to ‘gm/24 h for meta-analysis’⁴⁷. Post-intervention data was used in the meta-analysis as the majority of RCTs did not assess outcomes during follow-up periods. The change score was calculated by subtracting the baseline mean from the post-intervention mean within each group⁴⁹ and used in the meta-analysis. Corresponding SDs were calculated from the sample size, standard errors, confidence intervals, or *t*, *z*, or *p* values⁴⁹. If the SD could not be computed from the

aforementioned values, the correlation coefficients were computed instead⁴⁹. Due to the unavailability of similar meta-analyses to refer to in calculating coefficients, data from a single RCT that aimed to reduce participants’ sodium intake by changing their sodium intake behavior through a mobile app were used to compute the correlation coefficients, as this RCT was reported in considerable detail, including change scores and SD needed to compute the correlation coefficients¹². The correlation coefficients used to calculate SD of 24HUNa, SBP, and DBP were 0.5, 0.8, and 0.7, respectively. Sensitivity analyses were performed using different correlation coefficients to examine the robustness of the overall estimates⁴⁹.

Risk of bias assessment

The quality of included RCTs was assessed by the Cochrane risk-of-bias tool for randomized trials (ROB2)⁵⁰, which categorizes risk of bias as low, some concerns, or high.

Meta-analysis

Random-effect models with the inverse variance method were applied to pool estimated effects on 24HUNa (primary outcome), SBP, and DBP. The estimates were reported as mean difference (MD), 95% confidence interval (CI), and I^2 statistics. Standardized mean difference (SMD), estimated using adjusted Hedges’*g*, was used to determine effect size magnitude⁵¹. In this review, a negative *g* indicates the intervention group mean is lower than the control mean⁵², with the absolute value of $g = 0.2, 0.5, \text{ and } 0.8$ for small, medium, and large effects, respectively⁵³. Publication bias was evaluated by the Egger and Begg tests⁵⁴, and if identified, the estimated effects were adjusted by the trim and fill method⁵⁵. Sensitivity analysis was performed by the leave-one-out method to verify the robustness of the estimated effects⁴⁹. Review Manager (version 5.4) and R Studio (‘metafor’ package, version 2022.07.1) were used for the meta-analysis. A *p*-value of < 0.05 (two-sided) was considered statistically significant.

Subgroup analysis and meta-regression

The subgroup analyses were conducted: BP of participants (hypertensive vs. normative vs. hypertensive+normative)⁴⁹, primary technology type (instant messaging app vs. telephone call vs. app developed for sodium reduction vs. digital self-monitoring sodium device)^{49,11}, intervention delivery professional (multidisciplinary vs. unidisciplinary), intervention delivery mode (individual- vs. dyad- vs. group-based)⁴⁸, family members involved (yes vs. no)⁵⁶, partially or entirely technology-supported (partially vs. entirely)⁵⁷, intervention frequency (\leq weekly vs. $>$ weekly)^{4,11}, intervention settings (nonhealthcare vs. healthcare vs. nonhealthcare+healthcare), method of self-estimation of sodium intake (app developed for sodium reduction vs. digital self-monitoring sodium device vs. salt-restriction spoon/scale), urine sample used for estimating sodium intake (24-h urine vs. spot urine), control group (active control vs. inactive control)⁴⁶, and whether the BCT was used (yes vs. no)¹⁴. The BCTs identified in at least five original RCTs were eligible for subgroup analyses to avoid inflation of the results from BCTs that were only sporadically used in the original RCTs¹⁴. Meta-regression was performed on continuous variables, including sample size, the proportion of female participants, mean age⁵⁸, intervention duration⁵⁸, follow-up duration⁵⁸, and the number of BCTs identified in each RCT. Both subgroup analysis and meta-regression were also used to investigate potential sources of substantial heterogeneity when $I^2 \geq 50\%$ ⁴⁹.

Data availability

Y.Y.Y. has full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. All study materials are available from the corresponding author upon reasonable request.

Code availability

The code used for the analyses in R Studio (version 2022.07.1, ‘metafor’ package) is available upon reasonable request from the corresponding author.

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- Author contributions**
Y.Y.Y. and L.J.J. were responsible for conceptualization. Y.Y.Y., C.M.L., and L.J.J. completed the literature search, article screening, data extraction, and quality appraisal. Y.Y.Y. conducted data analysis and wrote the original draft. All authors contributed to data interpretation, reviewing, and editing of the final paper. All authors approved the final paper.
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- Correspondence** and requests for materials should be addressed to Jung Jae Lee.
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