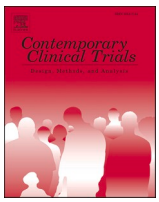
Contemporary Clinical Trials 138 (2024) 107454

Contents lists available at ScienceDirect

Contemporary Clinical Trials

journal homepage: www.elsevier.com/locate/conclintrial



Promoting fluid intake to increase urine volume for kidney stone prevention: Protocol for a randomized controlled efficacy trial of the *sip*^{IT} intervention

David E. Conroy [a,*], James Marks [b], Alyssa Cutshaw [a], Nilam Ram [c], Edison Thomaz [d], Necole M. Streeper [b]

[a] Department of Kinesiology, The Pennsylvania State University, University Park, PA 16802, USA
[b] Department of Urology, The Pennsylvania State University, Hershey, PA 17033, USA
[c] Department of Communication and Psychology, Stanford University, Palo Alto, CA 94305, USA
[d] Department of Electrical and Computer Engineering, University of Texas, Austin, TX 78712, USA

ARTICLE INFO

Keywords:
Urology
Behavioral intervention
Mobile health
Hydration
Prevention

ABSTRACT

Background: Risk of kidney stone recurrence can be reduced by increasing fluid intake and urine production but most patients fail to adhere to recommended clinical guidelines. Patients have indicated that common barriers to fluid intake include a lack of thirst, forgetting to drink, and not having access to water. We developed the *sip*^{IT} intervention to support patients' fluid intake with semi-automated tracking (via a mobile app, connected water bottle and a smartwatch clockface that detects drinking gestures) and provision of just-in-time text message reminders to drink when they do not meet the hourly fluid intake goal needed to achieve the recommended volume. This trial evaluates the efficacy of *sip*^{IT} for increasing urine output in patients at risk for recurrence of kidney stones.

Method/design: Adults with a history of kidney stones and lab-verified low urine production (<2 L/day) will be randomly assigned to receive either usual care (education and encouragement to meet fluid intake guidelines) or usual care plus the *sip*^{IT} intervention. The primary outcome is 24-h urine volume; secondary outcomes include urinary supersaturations, past week fluid intake, and experienced automaticity of fluid intake. Outcomes will be assessed at baseline, 1 month, 3 months, and 12 months.

Conclusions: The *sip*^{IT} intervention is the first to prompt periodic fluid intake through integration of just-in-time notifications and semi-automated tracking. If *sip*^{IT} is more efficacious than usual care, this intervention provides an innovative treatment option for patients needing support in meeting fluid intake guidelines for kidney stone prevention.

1. Introduction

Approximately 9% of American adults have kidney stones [1]. Stones cause tremendous suffering, an average of 1.2 million emergency department visits/year, and direct medical costs that exceed $10 billion annually [2,3]. With five-year recurrence rates being as high as 40%, a core prevention guideline is to increase fluid intake enough to produce >2.5 L of urine daily [4,5]. This goal corresponds to the top quintile of 24-h urine volumes observed in the Nurses' Health Study and Health Professionals Follow-up Study [6,7]; however, the American Urological Association guidelines also note that, "there is no definite threshold for urine volume and increased risk (the relationship is continuous and may not be linear)" (p. 9). [4] The available evidence from clinical trials and observational studies indicates that, even without reaching the 2.5 L 24-h urine volume goal specified in the guidelines, increasing fluid intake more than halves risk of recurrent stone episodes [8–14]. Indeed, observational studies indicate that increasing fluid intake reduces stone recurrence rates by 50–60% [13]. Based on the prevailing evidence, usual care for preventing kidney stones involves clinicians educating patients about prevention guidelines and advising them to increase fluid intake and advising patients to adhere to guidelines [15].

Unfortunately, patients' adherence to fluid intake guidelines is

* Corresponding author.
E-mail address: conroy@psu.edu (D.E. Conroy).

https://doi.org/10.1016/j.cct.2024.107454
Received 19 November 2023; Received in revised form 11 January 2024; Accepted 19 January 2024
Available online 20 January 2024

typically <50% [16,17]. Patients are widely aware of recommendations to increase fluid intake but the effects of usual care on urine output are modest (M = +0.35 L/day) and most patients lapse [15,16,18]. Consequently, 10-year recurrence rates for stones can be as high as 80%, with an overall mean time to first recurrence of 8.8 years, and more frequent recurrence among patients with more metabolically-active etiology [19,20].

One reason for these treatment failures is that usual care does not address the barriers patients report. Most patients describe relying on thirst to cue fluid intake, but not being thirsty enough to meet fluid intake guidelines [18,21,22]. In the absence of interoceptive cues, patients must rely on effortful self-regulation of drinking. However, in the face of many other goals and competing demands for attention, they often report forgetting to drink [18,21,22]. There is a pressing need to develop and evaluate tools that patients with kidney stones can use to improve self-regulation of fluid intake and adherence to fluid intake guidelines, and that specifically address the barriers faced in their daily lives (e.g., lack of thirst, forgetting to drink) [18,21–23].

Another reason for the treatment failures of usual care is that patients receive minimal support outside of the clinic when they are struggling to drink enough fluids. Patients have expressed interest in strategies that provide just-in-time support for fluid intake, such as self-monitoring tools, reminders to drink (regularly-timed or lapse-contingent), and connected water bottles [18,21]. These strategies increase opportunities to drink, activate goals as needed, and provide feedback on goal discrepancies that increase effort [24–26]. Mobile apps for self-monitoring and connected water bottles for tracking fluid intake exist commercially, but there is little evidence about the efficacy of these tools for increasing adherence to stone prevention guidelines [27–31].

We developed the *sip*^{IT} intervention to provide patients support for pursuing fluid intake goals in daily life and to facilitate their transition from effortful regulation of fluid intake (which is difficult to sustain for extended periods) to more automatic regulation (which supports long-term adherence) [32]. Drawing on just-in-time intervention development principles [33], *sip*^{IT} combines semi-automated tracking of fluid intake with lapse-contingent reminders to drink (see Fig. 1). Semi-automated tracking was selected because patients drink a variety of fluids in a variety of ways in their daily lives (e.g., from cups, water bottles, straws, drinking fountains) and no single method can capture every drink event. Manual self-tracking has a long history in behavior modification, but it is burdensome and difficult to sustain. Automated tracking via connected water bottles reduces burden, but does not capture drinks from other containers (and some straw-based devices are recommended only for use with water). More recently, we used data from inertial sensors on the wrist to detect drinking gestures [34]. Embedding that classifier in a smartwatch can capture drinks with the instrumented (often non-dominant) hand, but will not capture drinks from the other (often dominant) hand or drinks that do not require the prototypical hand and arm movement (e.g., leaning over to drink from a water fountain). Combining multiple methods increases the likelihood of detecting drinking events [35] – information that supports a tailoring variable that triggers lapse-contingent reminder messages. At the start of a daily monitoring period, a timer for achieving a small fluid intake goal is set. Fluid intake is monitored by the semi-automated tracking system and, once a patient reaches their fluid intake goal for that period, the timer is reset. When the timer is not reset by achieving the goal and expires, the system sends a text message to remind the participant to drink. Reminder messages are presumed to be disruptive and aversive (particularly if they are received frequently). Thus, the system leverages the principle of negative reinforcement to shape behavior and form a habit for frequent fluid intake throughout the day. Negative reinforcement involves withdrawing an aversive consequence when a desired behavior is enacted and provides a reward to condition the behavior in that context [36], defined here as the time between drinking events. By reinforcing an internal timer for fluid intake, *sip*^{IT} aims to create a new temporal cue that can complement thirst as an internal cue for fluid intake.

In two previously-conducted single-group studies, the *sip*^{IT} intervention was effective. In the first study, patients using *sip*^{IT} reported reductions in key barriers to fluid intake and increases in experienced automaticity (habit strength) for drinking water [32]. In the second study, with a simpler version using the bottle and app only, patients who used *sip*^{IT} for one month increased 24-h urine volume [37]. Although promising, those studies did not have control groups, and thus did not rule out the possibility that the behavior changes resulted from naturally-occurring changes in barriers, experienced automaticity, or 24-h urine volume. A rigorous trial with controls is needed to determine the efficacy of *sip*^{IT} for supporting patients with kidney stones.

2. Methods

2.1. Trial design

We propose a two-arm randomized controlled trial to answer the question, "Does *sip*^{IT} increase 24-hour urine volume more than usual care over a 3-month period?" Given that the *sip*^{IT} system is new and its effects on clinical outcomes are unknown, the appropriate comparator is one with low formidability, in this case, usual care. Stone formation and passage varies, and recurrence may not occur for years (mean time to first symptomatic recurrence is 8.8 years [19]). Thus, our primary outcome is 24-h urine volume, a surrogate endpoint based on prevention guidelines [4,5]. We will evaluate our primary outcome at 3 months, with an intermediate assessment at 1 month and a follow-up to evaluate maintenance after 12 months of intervention. The 12-month assessment is planned because long-term maintenance of increased urine output is important for effective prevention and it is important to understand whether intervention fatigue weakens *sip*^{IT} effects over time.

2.2. Participants and recruitment strategies

Adults with a history of kidney stones and low urine production will be recruited for this trial. Inclusion criteria include (a) kidney stone diagnosis within the past 5 years, (b) 24-h urine volumes ≤2.0 L/day, (c) age ≥ 18 years, (d) own smartphone with iOS or Android operating system, (e) willingness to complete the study protocol including being randomized to treatment groups, using a smartwatch, connected water bottle, and mobile app for the study every day for 1 year, and receiving text message reminders to drink, (f) fluent in English, and (g) capable of providing informed consent. Participants were excluded if they (a) had a prior diagnosis of a cystine stone (due to increased fluid intake

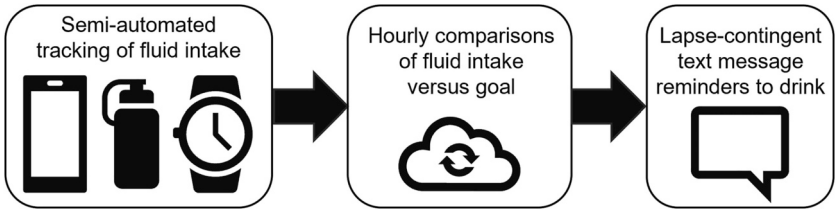


Fig. 1. Components of the *sip*^{IT} digital tools include the HidrateSpark mobile application, HidrateSpark PRO connected water bottle, and Fitbit Sense smartwatch.

recommendations of 4.5–5 L/day), (b) were pregnant or planning to become pregnant in the next 12 months, (c) were concurrently participating in another study involving fluid intake or diet, (d) planned to have surgery or relocate outside the area within the next year, (e) had any comorbidities that would preclude high fluid intake (e.g., congestive heart failure, bariatric surgery, GI tract ostomy, short gut syndrome, chronic diarrhea including patients with ulcerative colitis/Crohn's disease, hyponatremia) or accurate 24-h urine collection (e.g., severe urinary incontinence), (f) were undergoing active medical treatment that would impair protocol compliance, (g) were chronically using lithium, or (h) had any psychiatric conditions that would impair compliance with the study protocol.

Three recruitment strategies will be used. First, staff will review electronic health records for patients in the Penn State Health Urology Clinics and approach candidate patients about the trial during clinic visits. Second, clinicians at a Mt. Nittany Health urology clinic will refer patients who are candidates for the trial to staff for screening. Finally, we will use i2b2 via TriNetx to identify patients in the Penn State Health electronic health records with ICD-10 code N20.0 and mail recruitment letters.

2.3. Sample size and power estimates

We plan to enroll 216 participants in the proposed trial, with the expectation that at least 188 will complete the 3-month primary endpoint assessment. Statistical power analysis using G*Power3 suggested that a sample of $N = 188$ would support detection of small-to-medium sized effects (Cohen's $f = 0.125$, power ≥ 0.80) at the 3-month primary endpoint, assuming a Type-1 error rate of 0.05 (adjusted to $\alpha = 0.0026$ for 19 planned tests of six main effects [group, time, age, sex, stones history, notification frequency], nine 2-way interactions involving either group, time, or both], and four 3-way interactions [involving group X time and each of the four remaining main effects]) [38]. Planning for attrition and preservation of statistical power, we will oversample by 15% ($N = 216$).

2.4. Intervention

Participants will be randomized (1:1 allocation) to receive either usual care or the *sip*^{IT} intervention. The statistician will generate 22 randomization sequences in blocks of 10 using the *psych* package in R and transmit them directly to a supporting project coordinator who does not interact with participants in this trial for input the sequence into a Research Electronic Data Capture (REDCap) database [39,40]. Allocations will be masked from all investigators other than the statistician (who has no interaction with participants) and project staff who interact with the participants during enrollment and assessments.

Usual care consists of education about and encouragement to meet daily fluid intake guidelines. Education is delivered by staff via a handout that staff reviewed with each participant individually (see Supplementary Appendix).

The ***sip*^{IT} intervention** supplements usual care with digital tools to support fluid intake. The *sip*^{IT} digital tools combine semi-automated tracking with lapse-contingent text message reminders to drink. The semi-automated tracking tools shown in Fig. 2 include the HidrateSpark mobile app for manual entry of drinks, a HidrateSpark PRO connected water bottle that can be used with any fluid type and automatically senses changes in weight to infer fluid intake, and a Fitbit Sense smartwatch with a clockface that detects drinking gestures. The HidrateSpark bottle and Fitbit watch transmitted data to the HidrateSpark and Fitbit apps, respectively, using Bluetooth. Those mobile applications transmit data to the HidrateSpark and Fitbit servers. Application programming interfaces (APIs) transmit data from the HidrateSpark and Fitabase servers to the *sip*^{IT} intervention server. Participants provide 12-h windows for when they are willing to receive lapse-contingent reminder messages each day. At the beginning of the daily messaging window, a 60-min timer started. As soon as incoming data indicates that a participant reached their goal for the hour, the timer is reset. Whenever the timer reaches zero (indicating that a participant had not met their fluid intake goal in the past hour), the intervention server triggers delivery of a lapse-contingent reminder to drink message, specifically a small image file like the samples shown in Fig. 3 (selected at random without replacement within participant from a library of 114 total images).

Fig. 2. Hardware used by participants as a part of the *sip*^{IT} semi-automated tracking system. Photo credit: HidrateSpark.

2.5. Outcome measures

The **primary outcome** will be 24-h urine volumes assessed at baseline and months 1, 3 (primary) and 12. A certified laboratory will ship each participant a collection kit and participants will be instructed to complete the collection on a day they will not need to leave their home. Staff will train participants to start the collection after their first morning urination and to end it the following day at 24 h. Samples will be picked up from participants' residence by a commercial shipper and returned to the laboratory for analysis. The laboratory will screen urine creatinine levels outside of normal limits for sex and body weight to identify improper collection practices (e.g., under- or over-collection) [41,42]. Month 1, 3 and 12 samples with urine creatinine that differs from baseline >30% will trigger collection of a second 24-h urine.

The **secondary outcomes** from the urine collection include supersaturations of common stone-forming salts (calcium oxalate, calcium phosphate, uric acid), and creatinine concentrations. Experienced automaticity of fluid intake will be assessed using the 4-item Self-Report Behavioral Automaticity Index from the Self-Report Habit Index [43,44]. The stem for each item will be, "Drinking tap or bottled water…" and participants will rate each item on a scale ranging from 1

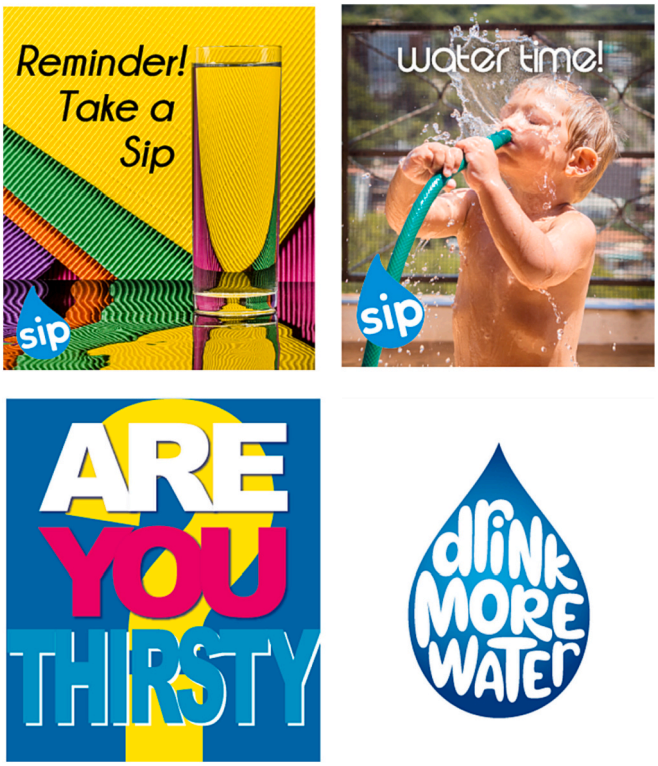


Fig. 3. Sample images sent via text messages as lapse-contingent reminders to drink.

(strongly disagree) to 7 (strongly agree). Past-week fluid intake will be rated using the BEV-Q-15 [45–47]. Participants will rate the frequency and amount of daily consumption for 15 common beverages.

Biological moderator variables include age, sex assigned at birth, height, weight, weight gain by 12 months, waist circumference, body mass index (BMI), medication use, stone type, treatment history, and recurrence. Protocols in the PhenX Toolkit will be used as available [48]. Age and sex will be assessed at baseline. Height and weight will be measured in person by staff (in duplicate) using a stadiometer and a digital scale at baseline, month 3 and month 12. BMI will be calculated as kg/m^2 and standard adult cutpoints will be used to classify underweight (<18.5 kg/m^2), normal weight (18.5–24.9 kg/m^2), overweight (25–29.9 kg/m^2) or obesity (>30.0 kg/m^2). Waist circumference will be assessed by staff at baseline and months 3 and 12 using a tape measure at the midpoint between the lowest rib and iliac crest. Electronic health records will be reviewed at baseline and months 3 and 12 to capture medication use, stone recurrence, stone type, and stone treatment. Patients will also self-report on stone passing (that did not involve seeking medical attention) and medication use at each assessment occasion.

Behavioral moderator variables assessed in the *sip*^{IT} intervention group specifically quantify engagement with the *sip*^{IT} digital tools throughout the 12-month intervention period. Self-monitoring will be recorded as the daily frequency and volume of manual entries in the HidrateSpark app. Bottle use will be recorded as the daily volume consumed from the HidrateSpark connected water bottle. Drinking gestures will be recorded as the daily frequency of drinking events detected by the custom smartwatch clockface. Reminder frequency will be assessed as the daily frequency of reminder messages sent.

2.6. Procedures

Fig. 4 summarizes the trial protocol approved by the Institutional Review Board (#00015540) and registered on clinicaltrials.gov (NCT05196113). Staff will describe the trial to prospective

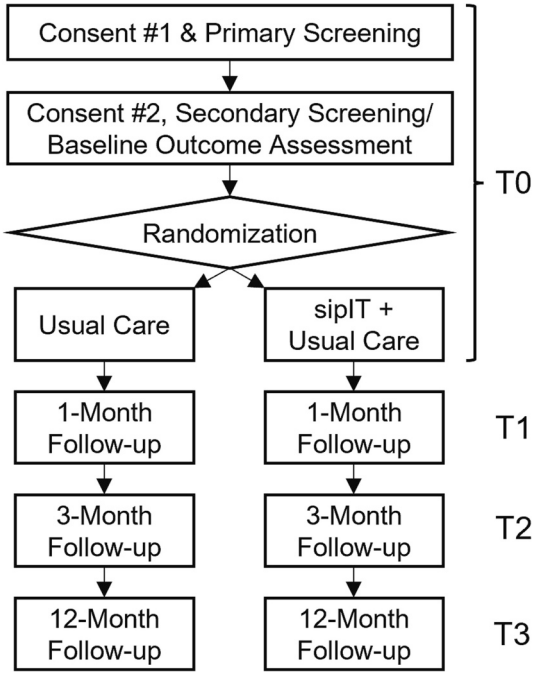


Fig. 4. Schematic of the *sip*^{IT} efficacy trial protocol.

participants and conduct preliminary screening for eligibility. Provisionally-eligible participants will provide verbal informed consent for secondary screening. Study staff will review 24-h urine collection procedures with participants and participants will receive a 24-h urine collection kit from a certified laboratory. Patients who completed a 24-h urine collection in the past 3 months using the same laboratory will not need to complete a repeat collection for screening. Eligible participants will be scheduled for a baseline lab visit.

During the baseline lab visit, the participant will provide verbal informed consent for the trial and complete REDCap questionnaires on a computer. Staff will collect anthropometric measurements, health and behavioral history and enter those data in REDCap. The participant's randomly-assigned treatment allocation will be revealed via the REDCap randomization module. Staff will provide and review an educational handout with all patients, assign a goal of consuming 100 fl oz./day, and encourage participants to meet that goal. For participants in the control group, staff will schedule the intermediate outcome assessment. For participants in the intervention group, staff will provide a HidrateSpark PRO (21 oz) connected water bottle and a Fitbit Sense smartwatch. Staff will help participants install the Fitbit and HidrateSpark mobile apps on their smartphone, authenticate their devices to a study account, and train participants how to use each device to support their fluid intake goal. Staff will review a web-based dashboard and contact participants to troubleshoot if data are not received from them for three consecutive days.

Approximately two weeks before the 1-, 3- and 12-month 24-h urine outcome assessments, staff will confirm participant mailing addresses for shipping a 24-h urine collection kit and repeat the remote urine collection procedures from baseline. Participants will be encouraged to repeat the assessments on the same day of week as the baseline assessment. Two staff members will download and manually enter urine panel results into the REDCap database. Participants will be compensated for completing assessments once lab results are received.

Additionally, participants will complete in-person visits at both 3- and 12-months. During these visits, participants will complete online questionnaires on the computer. Staff will collect anthropometric measurements, health and behavioral history, and enter those data in REDCap. During the 12-month in-person visit, staff will also complete a

voice recorded end-of-study interview to evaluate user experience and obtain feedback for refining the *sip*^{IT} system (interview guide included as Supplementary File). Participants randomly assigned to the usual care group will receive a smartwatch and connected water bottle upon completion of the study.

2.7. Safety monitoring

The investigators will meet with an external safety monitor quarterly to review data integrity and participant safety.

2.8. Data analysis

Outcome data will be analyzed using the intent-to-treat principle. Additional analyses will be conducted using contemporary missing data handling approaches [49]. Missing data will be handled by evaluating the pattern of missingness (including differential dropout between groups), determining plausibility of missing at random assumptions, identifying relevant controls needed to reduce missing data-related bias in analytic models, and invoking full information maximum likelihood estimation where reasonable [50].

The primary outcome analysis will evaluate the efficacy of *sip*^{IT} vs usual care for increasing urine volume in patients with a history of kidney stones. Urine volume is a continuous variable and expected to be normally distributed. Prior to analysis, we will examine the distribution and, if necessary, transform the outcome to comply with assumptions of the analytic approach. The main hypothesis associated with Aim 1 will be tested using a repeated-measures analysis of variance with Time as a within-person factor (baseline, 1 month, 3 month) and Group as a between-person factor. Of greatest interest for determining intervention effects is the Group X Time interaction. Models that control for age and sex will be parameterized and estimated in a Bayesian multilevel modeling framework using weakly informative priors. After checks for convergence (e.g., R-hat, mixing of chains), statistical inferences and evaluation of hypotheses will be based on 95% credible intervals and probabilities of direction using posterior parameter distributions constructed from at least 5000 montecarlo samples.

Parallel models will be constructed to evaluate effects of the intervention on 3-month urine supersaturation of stone-forming salts, 3-month experienced automaticity, 3-month past-week fluid intake, and 12-month follow-up data for each of those variables. Finally, biological and behavioral moderators of intervention effects will be identified by extending the repeated measures ANOVA model described above with the additional predictors. Of specific interest are the sign and strength of the Moderator X Group X Time interaction terms after controlling for main effects and relevant two-way interaction terms [51].

3. Discussion

This trial will provide a rigorous test of a first-in-kind intervention to support fluid intake and habit formation in patients with kidney stones, *sip*^{IT}. This intervention introduces several innovations to the fields of behavioral medicine and urology. First, *sip*^{IT} is one of the few interventions designed around the idea of semi-automated tracking [52]. Connected water bottles and companion mobile apps are increasingly available to consumers for automated and manual tracking and have gained attention based on their potential for supporting patients [18,27,53]. However, each of these tools has blind spots caused by the diversity of drinking containers that people use daily and the burden of manually tracking fluid intake. A recent trial found no difference in urine output between groups using a connected water bottle for automated tracking alone or an app for manual tracking alone [53]. Given the limitations of these two individual methods for capturing in situ drinking behavior, *sip*^{IT} has combined them and leveraged the inertial sensors in a smartwatch to detect drinking gestures. This approach increases the likelihood of detecting drinking events. Semi-automated tracking may be useful for improving monitoring in other behavior change contexts, including dietary behavior modification, physical activity promotion, and enhancing medication adherence [52].

Second, the *sip*^{IT} intervention is unique because it was explicitly designed to facilitate fluid intake habit formation [32]. *sip*^{IT} is grounded in a well-established habit formation framework (cue-behavior-reward [54]) but, in contrast to most digital tools which strive to increase engagement by providing more notifications, is distinguished by the innovative use of negative reinforcement instead of positive reinforcement following fluid intake. If decreasing notification frequency by limiting them to momentary lapses in goal pursuit is effective, this trial could provide an alternative model for promoting habit formation and behavioral adherence in other contexts.

This trial is one of the few behavioral intervention trials for preventing kidney stones. It complements the ongoing PUSH trial which evaluates the effects of a behavioral intervention on 2-year recurrence rates of symptomatic stones [55]. All participants in the PUSH trial receive connected water bottles and their companion mobile applications. Half are randomly assigned to receive a behavioral intervention involving personalized fluid intake prescriptions based on their urine output, financial incentives for achieving daily fluid intake goals and, as needed, structured problem solving to address barriers and low-touch interventions such as behavioral feedback, engaging support partners, and gamifying adherence feedback. The *sip*^{IT} intervention will be less expensive to deliver, and will estimate the average effect of digital tools and lapse-contingent reminders to drink on urine volume, fluid intake, and experienced automaticity for fluid intake.

If *sip*^{IT} increases fluid intake and urine output more than usual care, this trial could lead to practice-changing treatment for the prevention of kidney stones – and would also have great potential for addressing other pressing health problems caused by dehydration. Older adults in particular may benefit from such interventions because approximately 1 in 4 non-hospitalized older adults are estimated to be dehydrated due to low fluid intake, with elevated rates in long-term care residents [56]. Observational research has linked dehydration with impaired cognitive function in older adults [57–59]. An effective fluid intake intervention enables a shift to much-needed experimental tests of associations between dehydration and cognition.

An effective fluid intake intervention could also provide acute support during vulnerable periods caused by weather- or health-related dehydration. As extreme heat and heat strain becomes more common due to the climate crisis, effective countermeasures for preventing dehydration in vulnerable populations will be needed to reduce risk for cardiovascular and kidney problems [60,61]. For patients with pneumonia, dehydration more than doubles the risk of medium-term mortality in older adults [62]. For patients undergoing colonic resectioning and ileostomy, dehydration is a common cause of costly hospital readmissions [63]. Tools that support fluid intake during these vulnerable periods have potential to improve outcomes, reduce health care costs, and extend the lifespan.

Some limitations of the *sip*^{IT} trial should be noted. First, the sample is delimited to adults because kidney stones are less common in children and barriers to adherence may differ [64]. Second, this intervention would not provide a solution for the 15% of adults who do not own a smartphone [65]. Third, urine output is a proximal surrogate for risk and recurrence may be influenced by a variety of factors. Thus, supersaturations are assessed as secondary outcomes to provide a more complete portrait of how *sip*^{IT} impacts risk profiles. If *sip*^{IT} increases urine output, future work should evaluate the effects of *sip*^{IT} on radiographic evidence of stone growth and symptomatic stone recurrence. Finally, follow-up is limited to one-year but long-term adherence is likely needed to reduce recurrence risk.

In sum, this trial will provide a rigorous test of a behavioral intervention designed to address barriers to fluid intake identified by patients with kidney stones. The *sip*^{IT} intervention is innovative in its implementation of a semi-automated tracking system, provision of lapse-

contingent reminders to drink, and application of negative reinforcement to form habits for frequent fluid intake throughout the day. If successful, this intervention may be a potential solution for an array of dehydration-related health problems in addition to reducing risk factors associated with kidney stone recurrence.

Funding

Research reported in this publication was supported by the National Institute of Diabetes and Digestive and Kidney Diseases and the National Center for Advancing Translational Sciences of the National Institutes of Health under grants R01 DK124469 and UL1 TR002014, respectively. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

CRediT authorship contribution statement

David E. Conroy: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **James Marks:** Writing – review & editing, Project administration, Investigation. **Alyssa Cutshaw:** Writing – review & editing, Project administration, Investigation. **Nilam Ram:** Writing – review & editing, Methodology, Funding acquisition. **Edison Thomaz:** Writing – review & editing, Software, Methodology, Funding acquisition. **Necole M. Streeper:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

Acknowledgements

We would like to thank Dr. Tullika Garg, Kathy Lehman, Mary Myers, Kennedy Jackson and Deborah Brunke-Reese for their contributions to planning and conducting this trial, Fitabase and Purple Workshops for developing and maintaining software used in this trial, HidrateSpark for providing the image for Fig. 2, and Natalie Lueders for graphic design.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cct.2024.107454.

References

[1] C.D. Scales, A.C. Smith, J.M. Hanley, C.S. Saigal, Urologic Diseases in America Project, prevalence of kidney stones in the United States, Eur. Urol. 62 (2012) 160–165, https://doi.org/10.1016/j.eururo.2012.03.052.
[2] S.H. Eaton, J. Cashy, J.A. Pearl, D.M. Stein, K. Perry, R.B. Nadler, Admission rates and costs associated with emergency presentation of urolithiasis: analysis of the Nationwide Emergency Department Sample 2006–2009, J. Endourol. 27 (2013) 1535–1538, https://doi.org/10.1089/end.2013.0205.
[3] D.C. Miller, C.S. Saigal, M.S. Litwin, The demographic burden of urologic diseases in America, Urol. Clin. North Am. 36 (2009) 11–27, https://doi.org/10.1016/j.ucl.2008.08.004.
[4] M.S. Pearle, D.S. Goldfarb, D.G. Assimos, G. Curhan, C.J. Denu-Ciocca, B. R. Matlaga, M. Monga, K.L. Penniston, G.M. Preminger, T.M.T. Turk, J.R. White, American Urological Assocation, medical management of kidney stones: AUA guideline, J. Urol. 192 (2014) 316–324, https://doi.org/10.1016/j.juro.2014.05.006.
[5] A. Qaseem, P. Dallas, M.A. Forciea, M. Starkey, T.D. Denberg, Clinical guidelines Committee of the American College of Physicians, dietary and pharmacologic management to prevent recurrent nephrolithiasis in adults: a clinical practice guideline from the American College of Physicians, Ann. Intern. Med. 161 (2014) 659–667, https://doi.org/10.7326/M13-2908.
[6] G.C. Curhan, W.C. Willett, F.E. Speizer, D. Spiegelman, M.J. Stampfer, Comparison of dietary calcium with supplemental calcium and other nutrients as factors affecting the risk for kidney stones in women, Ann. Intern. Med. 126 (1997) 497–504, https://doi.org/10.7326/0003-4819-126-7-199704010-00001.
[7] G.C. Curhan, W.C. Willett, E.B. Rimm, M.J. Stampfer, Family history and risk of kidney stones, J. Am. Soc. Nephrol. 8 (1997) 1568–1573.
[8] A.L. Strauss, F.L. Coe, L. Deutsch, J.H. Parks, Factors that predict relapse of calcium nephrolithiasis during treatment: a prospective study, Am. J. Med. 72 (1982) 17–24, https://doi.org/10.1016/0002-9343(82)90566-6.
[9] M. Daudon, C. Hennequin, G. Boujelben, B. Lacour, P. Jungers, Serial crystalluria determination and the risk of recurrence in calcium stone formers, Kidney Int. 67 (2005) 1934–1943, https://doi.org/10.1111/j.1523-1755.2005.00292.x.
[10] H.A. Fink, T.J. Wilt, K.E. Eidman, P.S. Garimella, R. MacDonald, I.R. Rutks, M. Brasure, R.L. Kane, J. Ouellette, M. Monga, Medical management to prevent recurrent nephrolithiasis in adults: a systematic review for an American College of Physicians Clinical Guideline, Ann. Intern. Med. 158 (2013) 535–543, https://doi.org/10.7326/0003-4819-158-7-201304020-00005.
[11] M. Frank, A. De Vries, Prevention of urolithiasis. Education to adequate fluid intake in a new town situated in the Judean Desert mountains, Arch. Environ. Health 13 (1966) 625–630, https://doi.org/10.1080/00039896.1966.10664630.
[12] D.H. Hosking, S.B. Erickson, C.J. Van den Berg, D.M. Wilson, L.H. Smith, The stone clinic effect in patients with idiopathic calcium urolithiasis, J. Urol. 130 (1983) 1115–1118, https://doi.org/10.1016/s0022-5347(17)51711-5.
[13] L. Borghi, T. Meschi, F. Amato, A. Briganti, A. Novarini, A. Giannini, Urinary volume, water and recurrences in idiopathic calcium nephrolithiasis: a 5-year randomized prospective study, J. Urol. 155 (1996) 839–843.
[14] Y. Bao, X. Tu, Q. Wei, Water for preventing urinary stones, Cochrane Database Syst. Rev. 2 (2020), https://doi.org/10.1002/14651858.CD004292.pub4. CD004292.
[15] J.H. Parks, E.R. Goldfischer, F.L. Coe, Changes in urine volume accomplished by physicians treating nephrolithiasis, J. Urol. 169 (2003) 863–866, https://doi.org/10.1097/01.ju.0000044922.22478.32.
[16] W. Cheungpasitporn, S. Rossetti, K. Friend, S.B. Erickson, J.C. Lieske, Treatment effect, adherence, and safety of high fluid intake for the prevention of incident and recurrent kidney stones: a systematic review and meta-analysis, J. Nephrol. 29 (2016) 211–219, https://doi.org/10.1007/s40620-015-0210-4.
[17] E.J. Gordon, T.R. Prohaska, M. Gallant, L.A. Siminoff, Self-care strategies and barriers among kidney transplant recipients: a qualitative study, Chronic Illn. 5 (2009) 75–91, https://doi.org/10.1177/1742395309103558.
[18] N.M. Streeper, K. Lehman, D.E. Conroy, Acceptability of mobile health technology for promoting fluid consumption in patients with nephrolithiasis, Urology 122 (2018) 64–69, https://doi.org/10.1016/j.urology.2018.08.020.
[19] J.W. Sutherland, J.H. Parks, F.L. Coe, Recurrence after a single renal stone in a community practice, Miner. Electrolyte Metab. 11 (1985) 267–269.
[20] A. Trinchieri, F. Ostini, R. Nespoli, F. Rovera, E. Montanari, G. Zanetti, A prospective study of recurrence rate and risk factors for recurrence after a first renal stone, J. Urol. 162 (1999) 27–30, https://doi.org/10.1097/00005392-199907000-00007.
[21] N.M. Streeper, A. Dubnansky, A.B. Sanders, K. Lehman, E. Thomaz, D.E. Conroy, Improving fluid intake behavior among patients with kidney stones: a focus group to understand patients' experiences and acceptability of wearable sensors, Urology 133 (2019) 57–66, https://doi.org/10.1016/j.urology.2019.05.056.
[22] L.R. McCauley, A.J. Dyer, K. Stern, T. Hicks, M.M. Nguyen, Factors influencing fluid intake behavior among kidney stone formers, J. Urol. 187 (2012) 1282–1286, https://doi.org/10.1016/j.juro.2011.11.111.
[23] S. Tarplin, M. Monga, K.L. Stern, L.R. McCauley, C. Sarkissian, M.M. Nguyen, Predictors of reporting success with increased fluid intake among kidney stone patients, Urology 88 (2016) 49–56, https://doi.org/10.1016/j.urology.2015.10.024.
[24] L.E. Burke, J. Wang, M.A. Sevick, Self-monitoring in weight loss: a systematic review of the literature, J. Am. Diet. Assoc. 111 (2011) 92–102, https://doi.org/10.1016/j.jada.2010.10.008.
[25] P. Sheeran, J. Suls, A. Bryan, L. Cameron, R.A. Ferrer, W.M.P. Klein, A.J. Rothman, Activation versus change as a principle underlying intervention strategies to promote health behaviors, Ann. Behav. Med. 57 (2023) 205–215, https://doi.org/10.1093/abm/kaac045.
[26] S. Michie, M.M. van Stralen, R. West, The behaviour change wheel: a new method for characterising and designing behaviour change interventions, Implement. Sci. 6 (2011) 42, https://doi.org/10.1186/1748-5908-6-42.
[27] D.E. Conroy, A. Dubansky, J. Remillard, R. Murray, C.A. Pellegrini, S.M. Phillips, N.M. Streeper, Using behavior change techniques to guide selections of mobile applications to promote fluid consumption, Urology (2016), https://doi.org/10.1016/j.urology.2016.09.015.
[28] D.J. Stevens, K. McKenzie, H.W. Cui, J.G. Noble, B.W. Turney, Smartphone apps for urolithiasis, Urolithiasis 43 (2015) 13–19, https://doi.org/10.1007/s00240-014-0738-0.
[29] D.J. Kok, The preventive treatment of recurrent stone-formation: how can we improve compliance in the treatment of patients with recurrent stone disease? Urolithiasis 44 (2016) 83–90, https://doi.org/10.1007/s00240-015-0842-9.
[30] A.C. Small, S.L. Thorogood, O. Shah, K.A. Healy, Emerging mobile platforms to aid in stone management, Urol. Clin. North Am. 46 (2019) 287–301, https://doi.org/10.1016/j.ucl.2018.12.010.

[31] R. Cohen, G. Fernie, A. Roshan Fekr, Monitoring fluid intake by commercially available smart water bottles, Sci. Rep. 12 (2022) 4402, https://doi.org/10.1038/s41598-022-08335-5.
[32] D.E. Conroy, A.B. West, D. Brunke-Reese, E. Thomaz, N.M. Streeper, Just-in-time adaptive intervention to promote fluid consumption in patients with kidney stones, Health Psychol. 39 (2020) 1062–1069, https://doi.org/10.1037/hea0001032.
[33] I. Nahum-Shani, S.N. Smith, B.J. Spring, L.M. Collins, K. Witkiewitz, A. Tewari, S. A. Murphy, Just-in-time adaptive interventions (JITAIs) in mobile health: key components and design principles for ongoing health behavior support, Ann. Behav. Med. 52 (2018) 446–462, https://doi.org/10.1007/s12160-016-9830-8.
[34] K.S. Chun, A.B. Sanders, R. Adaimi, N. Streeper, D.E. Conroy, E. Thomaz, Towards a generalizable method for detecting fluid intake with wrist-mounted sensors and adaptive segmentation, in: Proceedings of the 24th International Conference on Intelligent User Interfaces, ACM, New York, NY, USA, 2019, pp. 80–85, https://doi.org/10.1145/3301275.3302315.
[35] R. Cohen, G. Fernie, A. Roshan Fekr, Fluid intake monitoring systems for the elderly: a review of the literature, Nutrients 13 (2021) 2092, https://doi.org/10.3390/nu13062092.
[36] B.F. Skinner, Science and Human Behavior, Macmillan, New York, 1953.
[37] N.M. Streeper, J.D. Fairbourn, J. Marks, E. Thomaz, N. Ram, D.E. Conroy, Feasibility of Mini sipIT behavioral intervention to increase urine volume in patients with kidney stones, Urology 179 (2023) 39–43, https://doi.org/10.1016/j.urology.2023.06.019.
[38] F. Faul, E. Erdfelder, A.-G. Lang, A. Buchner, G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behav. Res. Methods 39 (2007) 175–191.
[39] P.A. Harris, R. Taylor, R. Thielke, J. Payne, N. Gonzalez, J.G. Conde, Research electronic data capture (REDCap) - a metadata-driven methodology and workflow process for providing translational research informatics support, J. Biomed. Inform. 42 (2009) 377–381, https://doi.org/10.1016/j.jbi.2008.08.010.
[40] W. Revelle, Psych: Procedures for Psychological, Psychometric, and Personality Research, 2020.
[41] J.L. Ennis, J.R. Asplin, The role of the 24-h urine collection in the management of nephrolithiasis, Int. J. Surg. 36 (2016) 633–637, https://doi.org/10.1016/j.ijsu.2016.11.020.
[42] A.F. Alruwaily, C.A. Dauw, M.J. Bierlein, P. Yan, J.R. Asplin, K.R. Ghani, J.S. Wolf, J.M. Hollingsworth, How much information is lost when you only collect one 24-hour urine sample during the initial metabolic evaluation? J. Urol. 196 (2016) 1143–1148, https://doi.org/10.1016/j.juro.2016.04.074.
[43] B. Verplanken, S. Orbell, Reflections on past behavior: a self-report index of habit strength, J. Appl. Soc. Psychol. 33 (2003) 1313–1330, https://doi.org/10.1111/j.1559-1816.2003.tb01951.x.
[44] B. Gardner, C. Abraham, P. Lally, G.-J. de Bruijn, Towards parsimony in habit measurement: testing the convergent and predictive validity of an automaticity subscale of the self-report habit index, Int. J. Behav. Nutr. Phys. Act. 9 (2012) 102, https://doi.org/10.1186/1479-5868-9-102.
[45] V.E. Hedrick, J. Savla, D.L. Comber, K.D. Flack, P.A. Estabrooks, P.A. Nsiah-Kumi, S. Ortmeier, B.M. Davy, Development of a brief questionnaire to assess habitual beverage intake (BEVQ-15): sugar-sweetened beverages and total beverage energy intake, journal of the academy of, Nutr. Diet. 112 (2012) 840–849, https://doi.org/10.1016/j.jand.2012.01.023.
[46] V.E. Hedrick, D.L. Comber, K.E. Ferguson, P.A. Estabrooks, J. Savla, A.M. Dietrich, E. Serrano, B.M. Davy, A rapid beverage intake questionnaire can detect changes in beverage intake, Eat. Behav. 14 (2013) 90–94, https://doi.org/10.1016/j.eatbeh.2012.10.011.
[47] V.E. Hedrick, D.L. Comber, P.A. Estabrooks, J. Savla, B.M. Davy, The beverage intake questionnaire: determining initial validity and reliability, J. Am. Diet. Assoc. 110 (2010) 1227–1232, https://doi.org/10.1016/j.jada.2010.05.005.
[48] C.M. Hamilton, L.C. Strader, J.G. Pratt, D. Maiese, T. Hendershot, R.K. Kwok, J. A. Hammond, W. Huggins, D. Jackman, H. Pan, D.S. Nettles, T.H. Beaty, L. A. Farrer, P. Kraft, M.L. Marazita, J.M. Ordovas, C.N. Pato, M.R. Spitz, D. Wagener, M. Williams, H.A. Junkins, W.R. Harlan, E.M. Ramos, J. Haines, The PhenX Toolkit: get the most from your measures, Am. J. Epidemiol. 174 (2011) 253–260, https://doi.org/10.1093/aje/kwr193.
[49] J.W. Graham, Missing data analysis: making it work in the real world, Annu. Rev. Psychol. 60 (2009) 549–576, https://doi.org/10.1146/annurev.psych.58.110405.085530.
[50] J.L. Schafer, J.W. Graham, Missing data: our view of the state of the art, Psychol. Methods 7 (2002) 147–177.
[51] L.S. Aiken, S.G. West, Multiple Regression: Testing and Interpreting Interactions, Sage, Newbury Park, CA, 1991.
[52] E.K. Choe, S. Abdullah, M. Rabbi, E. Thomaz, D.A. Epstein, F. Cordeiro, M. Kay, G. D. Abowd, T. Choudhury, J. Fogarty, B. Lee, M. Matthews, J.A. Kientz, Semi-automated tracking: a balanced approach for self-monitoring applications, IEEE Pervas. Comput. 16 (2017) 74–84, https://doi.org/10.1109/MPRV.2017.18.
[53] H.C. Wright, L. Alshara, H. DiGennaro, Y.E. Kassis, J. Li, M. Monga, J. Calle, S. Sivalingam, The impact of smart technology on adherence rates and fluid management in the prevention of kidney stones, Urolithiasis 50 (2022) 29–36, https://doi.org/10.1007/s00240-021-01270-6.
[54] B. Gardner, A.L. Rebar, P. Lally, How does habit form? Guidelines for tracking real-world habit formation, Cogent Psychol. 9 (2022) 2041277, https://doi.org/10.1080/23311908.2022.2041277.
[55] C.D. Scales, A.C. Desai, J.D. Harper, H.H. Lai, N.M. Maalouf, P.P. Reese, G. E. Tasian, H.R. Al-Khalidi, Z. Kirkali, H. Wessells, Urinary Stone Disease Research Network, prevention of urinary stones with hydration (PUSH): design and rationale of a clinical trial, Am. J. Kidney Dis. 77 (2021) 898–906.e1, https://doi.org/10.1053/j.ajkd.2020.09.016.
[56] E. Parkinson, L. Hooper, J. Fynn, S.H. Wilsher, T. Oladosu, F. Poland, S. Roberts, E. Van Hout, D. Bunn, Low-intake dehydration prevalence in non-hospitalised older adults: systematic review and meta-analysis, Clin. Nutr. 42 (2023) 1510–1520, https://doi.org/10.1016/j.clnu.2023.06.010.
[57] S.K. Nishi, N. Babio, I. Paz-Graniel, L. Serra-Majem, J. Vioque, M. Fitó, D. Corella, X. Pintó, A. Bueno-Cavanillas, J.A. Tur, L. Diez-Ricote, J.A. Martinez, C. Gómez-Martínez, A. González-Botella, O. Castañer, A. Alvarez-Sala, C. Montesdeoca-Mendoza, M. Fanlo-Maresma, N. Cano-Ibáñez, C. Bouzas, L. Daimiel, M.Á. Zulet, J. L. Sievenpiper, K.L. Rodriguez, Z. Vázquez-Ruiz, J. Salas-Salvadó, Water intake, hydration status and 2-year changes in cognitive performance: a prospective cohort study, BMC Med. 21 (2023) 82, https://doi.org/10.1186/s12916-023-02771-4.
[58] H.J. Bethancourt, W.L. Kenney, D.M. Almeida, A.Y. Rosinger, Cognitive performance in relation to hydration status and water intake among older adults, NHANES 2011–2014, Eur. J. Nutr. (2019), https://doi.org/10.1007/s00394-019-02152-9.
[59] C.J. Edmonds, E. Foglia, P. Booth, C.H.Y. Fu, M. Gardner, Dehydration in older people: a systematic review of the effects of dehydration on health outcomes, healthcare costs and cognitive performance, Arch. Gerontol. Geriatr. 95 (2021) 104380, https://doi.org/10.1016/j.archger.2021.104380.
[60] O. Jay, A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R. S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, K. L. Ebi, Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities, Lancet 398 (2021) 709–724, https://doi.org/10.1016/S0140-6736(21)01209-5.
[61] K.L. Ebi, A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R. S. Kovats, W. Ma, A. Malik, N.B. Morris, L. Nybo, S.I. Seneviratne, J. Vanos, O. Jay, Hot weather and heat extremes: health risks, Lancet 398 (2021) 698–708, https://doi.org/10.1016/S0140-6736(21)01208-3.
[62] L. Hooper, A. Abdelhamid, S.M. Ajabnoor, C. Esio-Bassey, J. Brainard, T.J. Brown, D. Bunn, E. Foster, C.C. Hammer, S. Hanson, F.O. Jimoh, H. Maimouni, M. Sandhu, X. Wang, L. Winstanley, J.L. Cross, A.A. Welch, K. Rees, C. Philpott, Effects of fluid and drinking on pneumonia mortality in older adults: a systematic review and meta-analysis, Clin. Nutr. ESPEN 47 (2022) 96–105, https://doi.org/10.1016/j.clnesp.2021.11.021.
[63] I. Vogel, M. Shinkwin, S.L. van der Storm, J. Torkington, J.A. Cornish, P.J. Tanis, R. Hompes, W.A. Bemelman, Overall readmissions and readmissions related to dehydration after creation of an ileostomy: a systematic review and meta-analysis, Tech. Coloproctol. 26 (2022) 333–349, https://doi.org/10.1007/s10151-022-02580-6.
[64] G.E. Tasian, M. Ross, L. Song, J. Audrain-McGovern, D. Wiebe, S.G. Warner, B. Henderson, A. Patel, S.L. Furth, Ecological momentary assessment of factors associated with water intake among adolescents with kidney stone disease, J. Urol. 201 (2019) 606–614, https://doi.org/10.1016/j.juro.2018.07.064.
[65] A. Perrin, Mobile Technology and Home Broadband 2021, Pew Research Center, Washington, DC, 2021. https://www.pewresearch.org/internet/2021/06/03/mobile-technology-and-home-broadband-2021/ (accessed November 15, 2023).