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Original Article

Digital Health Technology in Asthma: A Comprehensive Scoping Review

Giselle Mosnaim, MD, MS[a], Guilherme Safioti, MD[b], Randall Brown, MD, MPH[c], Michael DePietro, MD[c], Stanley J. Szefler, MD[d], David M. Lang, MD[e], Jay M. Portnoy, MD[f], Don A. Bukstein, MD[g], Leonard B. Bacharier, MD[h], and Rajan K. Merchant, MD, FACAAI[i] *Evanston, Ill; West Chester, Pa; Aurora and Cleveland, Colo; Kansas City, Mo; Greenfield, Wis; Nashville, Tenn; Woodland, Calif; and Amsterdam, The Netherlands*

What is already known about this topic? Digital technology provides an opportunity to improve and individualize asthma self-management significantly across a variety of intervention types; however, the impact of different digital intervention characteristics has yet to be assessed.

What does this article add to our knowledge? Significant heterogeneity exists in study designs, patient populations, and outcomes measurement for digital interventions; more alignment is needed to measure impacts accurately on different dimensions of care and to guide future successful interventions.

How does this study impact current management guidelines? This scoping review does not directly affect current guidelines for asthma self-management, but it is hoped that it will inform the design of future digital intervention studies.

BACKGROUND: A variety of digital intervention approaches have been investigated for asthma therapy during the past decade, with different levels of interactivity and personalization and a range of impacts on different outcome measurements.
OBJECTIVE: To assess the effectiveness of digital interventions in asthma with regard to acceptability and outcomes and evaluate the potential of digital initiatives for monitoring or treating patients with asthma.
METHODS: We evaluated digital interventions using a scoping review methodology through a literature search and review. Of 871 articles identified, 121 were evaluated to explore intervention characteristics, the perception and acceptability of digital interventions to patients and physicians, and effects on asthma outcomes. Interventions were categorized by their level of interactivity with the patient.
RESULTS: Interventions featuring non-individualized content sent to patients appeared capable of promoting improved adherence to inhaled corticosteroids, but with no identified improvement in asthma burden; and data-gathering interventions appeared to have little effect on adherence or asthma

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Conflicts of interest: G. Mosnaim currently receives research grant support from Teva, Sanofi-Regeneron, Genentech, and Alk-Abello; received research grant support from AstraZeneca, GlaxoSmithKline, and Propeller Health; owned stock in Electrocore; and served as a consultant and/or member of a scientific advisory board for GlaxoSmithKline, Sanofi-Regeneron, Teva, Novartis, Astra Zeneca, Boehringer Ingelheim, and Propeller Health. G. Safioti, R. Brown, and M. DePietro are employees of Teva Pharmaceuticals. S. J. Szefler has consulted for AstraZeneca, Boehringer-Ingelheim, GlaxoSmithKline, Novartis, Propeller Health, Regeneron, and Sanofi; has received research support from the National Institutes of Health, the National Heart, Lung, and Blood Institute, Propeller Health, the Colorado Department of Public Health and Environment Colorado Cancer, and Cardiovascular and Pulmonary Disease Program. D. M. Lang is currently past president of AAAAI; serves as a member of the Editorial Board for *Allergy and Asthma Proceedings*; is Topic Editor for DynaMed; is associate editor for *J Asthma*; and is delegate to National Quality Forum representing the American Academy of Allergy, Asthma & Immunology. J. M. Portnoy has received honoraria as a speaker from Thermo Fisher and has consulted for BioCryst. D. A. Bukstein has received honoraria as a speaker from AstraZeneca, Genentech, Novartis, Teva, Regeneron, and ALK. L. B. Bacharier reports personal fees from GlaxoSmithKline, Genentech, Novartis, Merck, DBV Technologies, Teva, Boehringer Ingelheim, AstraZeneca, WebMD/Medscape, Sanofi, Regeneron, Vectura, and Circassia; and receives royalties from Elsevier. R. K. Merchant has received honoraria from Teva, Sanofi, and AstraZeneca for participation in advisory boards; and has served as speaker and consultant for Propeller Health; and his spouse is an employee of and holds stock options in Horizon Therapeutics.
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Abbreviations used
ACT- Asthma Control Test
HCP- Health care professional
ICS- Inhaled corticosteroids
SABA- Short-acting β-agonist
SMS- Short message service

burden. Evidence of improvement in both adherence and patients' impairment due to asthma were seen only with interactive interventions involving two-way responsive patient communication. Digital interventions were generally positively perceived by patients and physicians. Implementation was considered feasible, with certain preferences for design and features important to drive use.
CONCLUSIONS: Digital health interventions show substantial promise for asthma disease monitoring and personalization of treatment. To be successful, future interventions will need to include both inhaler device and software elements, combining accurate measurement of clinical parameters with careful consideration of ease of use, personalization, and patient engagement aspects. **© 2021 The Authors. Published by Elsevier Inc. on behalf of the American Academy of Allergy, Asthma & Immunology. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).** **(J Allergy Clin Immunol Pract 2021;9:2377-98)**

Key words: *Asthma; eHealth; Connectivity; Inhalers; Adherence; Monitoring; Disease control; Perception; Acceptability; Feasibility*

INTRODUCTION

Rationale

Asthma continues to be a significant chronic disease burden, with estimated patient numbers approaching 350 million globally.[1] Asthma is a major source of direct and indirect economic cost in addition to reduced quality of life and premature death in patients of all ages, including children.[2] Several areas of unmet clinical need are associated with conventional asthma management; while medications such as inhaled short-acting β-agonists (SABA) and inhaled corticosteroids (ICS) are efficacious, considerable long-term commitment to asthma self-management on behalf of the patient is required for therapeutic success.

Asthma self-management includes advice and education on self-monitoring and a defined asthma management plan supported by regular professional review. Self-management is recognized as an effective method to improve asthma control and quality of life and reduce unscheduled consultations and hospitalizations across diverse demographic groups.[3] For the patient, adherence to medication regimens is a key element of successful asthma management, in conjunction with wide-ranging factors including disease perception, patient education and understanding of symptoms, comorbidities, inhaler technique, access to medications, and health care professional (HCP) support.[4] On the part of clinicians, implementation of evidence-supported management guidelines for assessment, monitoring, patient education, control of environmental factors, and pharmacologic treatment is a key factor, although adherence to such guidelines varies among different physician groups.[5,6]

Several areas of asthma self-management could be improved using digital technology, including disease disparity, medication adherence, patient—clinician communication, personalized patient education, and passive monitoring of patient characteristics and behaviors that could prompt timely intervention. Technological innovations have the potential to support patients with disease self-management, allow for remote management by health care providers, and make future asthma management more proactive.[7]

Researchers have explored a variety of different digital asthma approaches including passive education, interactive websites, and electronic medication monitoring devices. Given the increasing prevalence of asthma worldwide and patient dependence on traditional inhaler devices to manage the disease, the inclusion of more advanced technology as a part of asthma self-management will be an essential next step to improving therapy for respiratory diseases. Lockdown and social distancing as a result of the COVID-19 pandemic have caused increased uptake and reliance on videoconferencing and telemedicine in various therapy areas.[8] Increased familiarity with telemedicine provides an opportunity for remote monitoring and disease management, particularly in areas where access to HCPs is challenging.

Given the wealth of available literature and heterogeneity of digital technologies used to varying degrees of success, we performed a scoping review to assess the available research in this field. Scoping reviews provide a preliminary assessment of the size and scope of available literature on a topic and characterize the nature of published studies to provide an overview of large, heterogeneous bodies of literature. Furthermore, scoping reviews provide a platform for more precise systematic reviews to look at specific research questions. This scoping review therefore seeks to evaluate the different options that have been explored and assess the future utility of digital health technology in asthma.

Objective

This study aimed to evaluate the current and potential future usability, acceptability, uptake, effectiveness, and adoption of digital health technology for treating or monitoring asthma using a scoping review methodology. The potential future reach and durability of these technologies will also be considered.

METHODS

Scoping review approach

We conducted a systematic scoping review based on the methodology described[9] and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews guidelines,[10] including identifying the research question, identifying relevant studies, selecting the study, charting data, collating, and summarizing and reporting the results. The purpose of a scoping review is to give a broad overview of the available literature without being directed toward a single discrete research question.

Sources and searches

We searched PubMed, Embase, and the Cochrane Library for January 2010 to June 2019 using the search terms and criteria in Table E1 (in this article's Online Repository at www.jaci-inpractice.org), adapted for each database, to identify asthma studies that assessed the effect of digital health technology interventions on patient outcomes, including symptoms, adherence, and medication use or therapy regimen. We also included studies that incorporated the acceptability of digital interventions to patients and HCPs and the

TABLE I. Classification of different intervention types

Intervention category	Intervention types
Generalized studies (not patient-specific or bidirectional): content given *to* patient	• Automated/speech recognition and SMS dose and pharmacy-refill reminders • Noninteractive education or motivational coaching by telephone, text, e-mail and other digital means (eg, simple access to static content)
Patient-specific, noninteractive studies (unidirectional): data collected *from* or sent *to* patient	• Decision support tool for randomized controlled trial enrollment • Device monitoring: noninhaler digital parameter tracking (eg, lung function) not resulting in immediate or ongoing asthma management feedback to patient (ie, data collection to inform health care professional at next visit) • Individualized static education and/or motivation • Digital questionnaires (by SMS/Web/phone) including ecological momentary association for data collection only (ie, not informing therapy) • Inhaler only: data collected on device from digital inhalers or adherence monitors but not fed back to patient for self-management • Inhaler platform: data collected from digital inhalers and a Web or app platform but not fed back to patient for self-management • Platform only: online digital chat platform (by Web or mobile app) providing nonindividualized education
Patient-specific interactive studies including telehealth and video counseling: bidirectional interaction	• Interactive education or motivational coaching • Device monitoring: noninhaler digital parameter tracking (eg, lung function, inhaler technique) with feedback to patient (usually by smartphone app) • Digital inhalers with electronic adherence monitors and individualized patient feedback • Digital inhaler studies with accompanying individualized asthma management Web or app platform • Interactive asthma management platforms that support self-management by collecting symptoms or Asthma Control Test/other data and give responses to guide patient's asthma treatment • Telemedicine interventions by phone, video, or SMS

SMS, short message service.

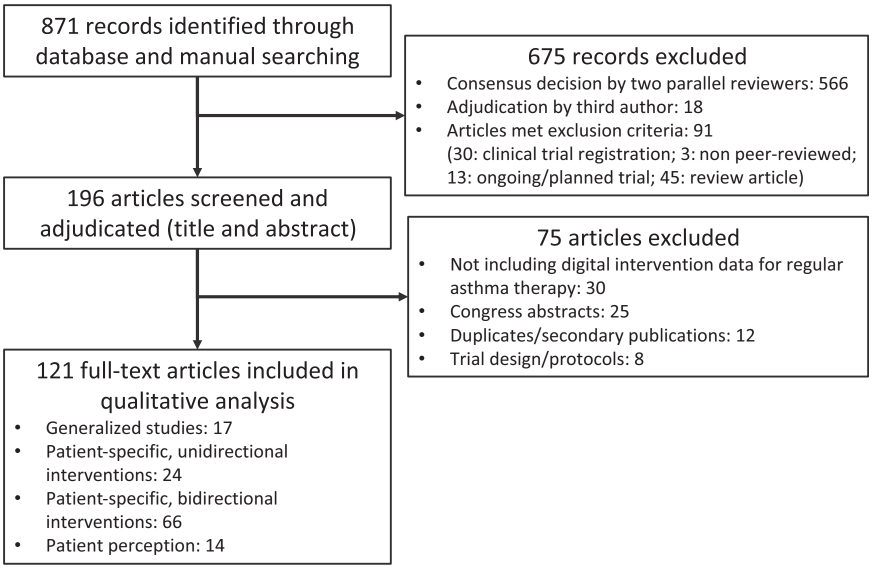

FIGURE 1. Articles selected for analysis.

feasibility of their wider uptake. Congress abstracts were excluded from the results. Database searches were supplemented by manual searches and references as appropriate.

Nonrelevant articles and duplicates were excluded; the titles and abstracts of remaining citations were reviewed by two authors (G.S. and G.M.) in parallel; a third author (R.K.M.) adjudicated discrepancies. Full-text articles were then obtained and a second round of screening was conducted (two reviewers worked in parallel and adjudication was performed by a third reviewer) and further articles were excluded as necessary. Articles were assessed for the type of digital health technology employed, study design, size of the study, and outcomes assessed.

Data extraction and synthesis

The full text of the selected articles was used to identify the types of technology used. Interventions were grouped (Table I) according to their primary characteristic (in which interventions contained more than one aspect), specifically, according to their level of interactivity with the patient. Interventions in which non-individualized information was sent to patients on an automated

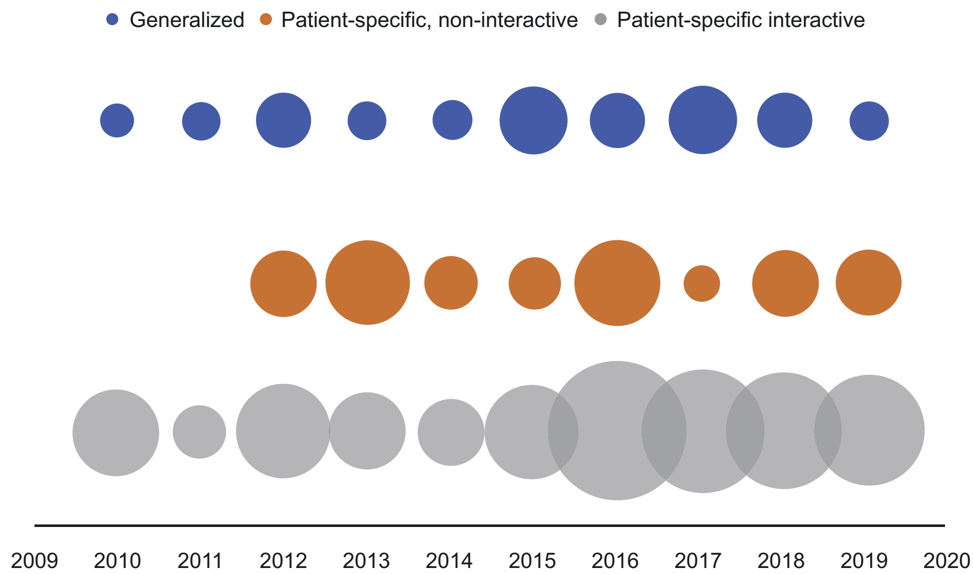

FIGURE 2. Bubble plot showing relative numbers of publications for different intervention categories by year.

basis (eg, short message service (SMS)-based dose reminders and automated pharmacy prescription refill calls, or access to noninteractive, non—patient specific digital educational material) were termed ‘generalized studies’. Interventions in which individualized information was gathered from or sent to patients (eg, parameter monitoring by a device with no feedback to the patient, or provision of patient-specific education) were termed ‘patient-specific, noninteractive studies’. Interventions composed of an interactive relationship with the patient, in which insights based on data collected from the patient or resulting from patient behavior were fed back to the patient to assist with asthma management on a personalized basis (eg, an asthma management platform responding to adherence data from a digital inhaler or questionnaire feedback from the patient) were termed ‘patient-specific interactive studies’. Within these broad intervention categories, studies were further grouped according to the type of technology involved (Table I).

Details of the studies performed (eg, subject characteristics, sample size, randomization) and outcomes, including adherence, asthma control or impairment and health care use were captured in a standardized table format as part of the data charting process. Adherence outcomes were assessed for being subjective (ie, reliant on questionnaire data or patient recollection) or objective (ie, monitored automatically as a result of medication use, including one study that calculated adherence from electronic medical records).

To assess the impact of the different intervention categories, we identified studies in which a positive effect (vs no effect or a negative effect) was reported with the intervention in three domains: adherence to ICS (and long-acting β_2-agonist) therapy, impairment caused by asthma (most commonly assessed by Asthma Control Test [ACT] score, but including changes in symptoms and quality of life when reported), and health care resource use (urgent consultations, emergency department visits, or hospitalizations). Because of heterogeneity in data reporting, to include as many studies as possible in our broad overview, we considered statistically significant, numerical, and anecdotal reports of benefit as evidence of positive effects in each of these three domains. Counts for studies reporting positive versus no effect or negative effects were then summarized.

Articles that reported patient and HCP perceptions of digital technologies were assessed separately, and relevant observations were extracted.

RESULTS

Selection of sources of evidence

Our selection process identified 121 articles for inclusion in this scoping review (Figure 1); 17 articles described generalized studies, 23 described patient-specific, noninteractive interventions, and 66 described patient-specific interactive interventions. Figure 2 shows a bubble plot of the number of articles for each intervention category published each year. During the past 5 years, interactive interventions were investigated more frequently than noninteractive initiatives, possibly because of the increased availability of mobile Internet access and personal smart devices. Fourteen articles were identified that investigated patients’ and clinicians’ perceptions of digital interventions.

Table II lists the number of studies reporting positive effects on outcomes for different intervention types.

Generalized studies

There were 17 generalized interventions, eight of which employed reminders or automated phone calls for medication doses or pharmacy fills, and nine that provided asthma education or asthma management motivation (n = 9). Most were randomized (n = 12) and most had an intervention period of 3 or more months (n = 15) (Table III).

Six of the studies described a change in adherence with the intervention; all of these reported a positive effect (6 positive vs 0 no effect or negative). Adherence in these studies was measured using both subjective (n = 3) and objective (n = 3) approaches.

TABLE II. Outcomes reporting for intervention categories and types

		Adherence		Asthma impairment		Health care use	
Intervention	Articles, n	Positive	No effect	Positive	No effect	Positive	No effect
Generalized studies	17	6	0	3	7	0	5
Reminders and pharmacy fill	8	6	0	0	5	0	3
EM	9	0	0	3	2	0	2
Patient-specific, noninteractive, unidirectional	24	2	4	2	4	0	2
Decision support	1	0	0	1	0	0	0
Digital questionnaire	9	0	1	1	1	0	1
Device monitoring	8	0	1	0	1	0	0
EM	2	1	1	0	0	0	0
Inhaler only	2	1	0	0	1	0	0
Inhaler platform	1	0	0	0	0	0	0
Platform only	1	0	1	0	1	0	1
Patient-specific interactive, bidirectional	66	17	8	31	15	12	14
EM	2	0	1	1	1	0	1
Inhaler only*	2	1	0	1	0	0	1
Inhaler platform	14	5	0	5	2	3	0
Platform only	32	9	6	15	9	5	8
Telemedicine	14	2	1	8	3	4	3
Device monitoring	2	0	0	1	0	0	1

EM, education and/or motivation.
*The study by Chan et al[11] was not included in positive/negative calculations because it was the same study as Chan et al.[12]

Few studies of generalized interventions reported a positive effect on asthma impairment (3 positive vs 7 no effect or negative), and none reported meaningful improvements in health care use (0 positive vs 5 no effect or negative) (Table II and Figure 3).

Patient-specific, noninteractive, unidirectional interventions

Of the 24 studies using patient-specific, noninteractive, unidirectional interventions, most focused on either digital questionnaire-based studies (n = 9) or device monitoring studies (without feedback to the patient; n = 8). Thirteen studies were randomized and 11 were single-arm. Nine interventions lasted for less than 3 months (Table IV).

Overall, few studies reported positive effects; only two studies found benefit in each of the adherence and asthma impairment domains and none reporting improvements in health care use (Table II and Figure 3). Positive effects on adherence were noted in one study of education provision and one involving adherence tracking with an automated reminder call; moreover, positive effects on asthma impairment resulted from one study involving a smartphone symptom and ACT diary with additional education and motivation, and one study in which a decision support algorithm was used to enter patients into different randomized controlled trials.

Patient-specific interactive, bidirectional interventions

Patient-specific, bidirectional interactive interventions were the largest group of interventions (n = 66). Most often, these entailed an asthma management platform (n = 32), a digital inhaler combined with an asthma management platform (n = 14), or a telemedicine-based intervention (n = 14). Most studies (n = 45) were randomized, and 15 of the interventions lasted less than 3 months (including two with the study period not stated) (Table V).

Reported positive effects outweighed no effect for both adherence (17 vs 8 studies, respectively) and asthma impairment (31 vs 15 studies, respectively) (Table II and Figure 3). Adherence was measured subjectively (n = 18) and objectively (n = 14) in a similar number of studies. Twelve studies found reductions in health care use, although a similar number (n = 14) found no effect.

This was the only intervention category within which improvements in both adherence and asthma impairment were reported more often than not and were seen consistently across the three most-studied intervention types.

Acceptability and feasibility of interventions

When reported, all types of digital interventions were considered to be acceptable or favorable to patients or their caregivers and feasible to implement, although this aspect was not rigorously investigated in articles reporting intervention results.[13,14,16-19,22-24,26,28,43,56,87,105,108,109,111,115,117] Digital inhaler systems were described as feasible to implement[31,61,62,65,69-71] and acceptable to most patients.[11,31,61,70,118] Similarly, digital asthma management platforms were reported to be both feasible[52,57,82,84,93,119] and acceptable.[75,76,92,96,100-102,107] One study reported low use of a Web portal that was not specifically targeted to symptomatic asthma patients.[81]

Although patients were generally satisfied with digital devices and were willing to use them, alerts were sometimes perceived as unwelcome if they were received at inopportune times.[35] Non-inhaler devices (including Fitbits (Google LLC, San Francisco, CA) to track activity levels and sleep, and devices designed to assess lung function) were also considered acceptable by patients.[35,52,54]

TABLE III. Generalized studies

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
13	Adults only	4510	NS	Reminder	Refill	SA	2 y	Significant but small improvement	–	No change in ED visits or hospitalizations
14	Adolescent or younger	1187	NS	Reminder	Refill	R	24 mo	Significant improvement in ICS adherence at 24 mo	–	No difference in ED visits, primary care visits or hospitalizations
15	Adults only	100	NS	Reminder	SMS reminder	SA	5 y	–	No difference in ACT scores between groups	–
16	Adolescents and adults	64	NS	Reminder	SMS reminder	R	6 mo	2.75% increase in adherence each month, but improvements were not sustained	No significant difference between arms	ED visits and hospitalizations for asthma were rare
17	Adolescent or younger	89	NS	Reminder	SMS reminder plus static education	R	3 wk	Significant improvement in self-reported 7-d adherence	No significant change in ACT	–
18	Adults only	26	Mild, moderate, severe	Reminder	SMS reminder	R	12 wk	Significant increase vs control	–	–
19	Adolescents and adults	12	NS	Reminder	SMS reminder	R	3 mo	–	No significant change in mean self-reported asthma control	–
20	Adults only	8517	NS	Reminder	Refill	R	18 mo	Modest but significant increase in ICS adherence	No significant change in asthma control	No significant effect on acute asthma health care use
21	Adolescent or younger	359	NS	EM	Static education to prompt physician questioning	R	1 y	–	–	–
22	Adults only	655	NS	EM	Static education by DVD for breathing retraining	R	12 mo	–	No significant improvement in symptom scores	–
23	Adults only	150	NS	EM	SMS education	R	13 mo	–	–	No significant difference in incidence of ED visits between groups
24	Adolescent or younger	64	NS	EM	Static EM, updated at intervals	R	3 mo	–	Significant increase in cACT	–
25	Adults only	330	NS	EM	Static education to encourage written asthma plan use	R	12 mo	–	No statistically significant change in ACQ scores	No significant change in ED or non-emergency health care professional visits

26	Adults only	144	NS	EM	Static video education during face-to-face visits	SA	1 mo	—	Significant improvement in ACT score	—
27	Adults only	34	NS	EM	Static Web-based education	SA	1 y	—	—	—
28	Adolescent or younger	50	NS	EM	Static Web-based education	SA	2 wk	—	—	—
29	Adults only	51	NS	EM	Static Web-based education	R	3 months	—	Significant improvements in self-reported asthma symptoms and control	—

(c)ACT, (childhood) Asthma Control Test; *ACQ*, Asthma Control Questionnaire; *ED*, emergency department; *EM*, education and/or motivation; *ICS*, inhaled corticosteroid; *SA*, single-arm; *NS*, not specified; *R*, randomized; *SMS*, short message service.

Cost-effectiveness

Only one[112] of the five studies to comment on cost-effectiveness[13,22,109,112,116] found that the digital intervention was not cost-effective, although formal investigations of cost-effectiveness were not performed. A smart nebulizer system was associated with decreased costs of additional treatments associated with asthma, such as antibiotics and corticosteroids.[64] Web-based monitoring of asthma control was deemed likely to be cost-effective after an analysis of an economic model.[39]

Perceptions of digital health technology

Fourteen articles commented on perceptions regarding digital interventions,[95,119-131] and all intervention types were widely considered to be acceptable and useful across groups of patients, prescribers, and families.

Patients' uptake of smartphone apps was affected by perceived need (ie, favorable if asthma not considered to be well-controlled)[125]; for smartphone app uptake in general, ease of access (ie, downloading) was considered important. Although social media could attract many initial downloads, long-term engagement was more successful with face-to-face recruitment by practices.[124]

Adolescents thought that smartphone apps should be designed to be visually simple, easy to use, informative, and customizable, and include familiar components (eg, alerts that appeared and sounded like their usual messaging apps), and they were open to using apps for support and information.[121,122,130,131] They preferred time-based to event-based reminders[44] and favored video and peer-chat functionality in addition to medication reminders.[119] They were also sensitive to design choices that were too childish for their age range, but appreciated gamification of asthma management.[121-123]

Adolescent patients and pharmacists had a positive attitude toward interactive mobile health interventions,[119] and adults and adolescents were receptive toward educational and directive SMS messaging; adolescents were also in favor of sending messages to a support person (ie, parent or guardian).[125] Tablet- and smartphone-based asthma questionnaires were acceptable to patients and useful in certain situations (eg, when HCP time was limited, or in rural areas).[126] Patients and caregivers were supportive of interactive Web-based education provision based on patient information and preferences, and of augmented reality inhaler technique training.[128]

Patients considered that smart devices and inhalers should be easy to use and convenient in terms of size and portability.[95,127]

Clinicians valued the concept of intervisit improvement of adherence and lung function data and considered adherence data to be especially important, with a preference for ICS adherence data. Rescue inhaler information was considered valuable to access if patients were overusing them, because this could indicate a need to adjust the ICS regimen. The opportunity to use a patient's data to illustrate how adherence affected symptoms or impairment during consultations was also appreciated.[120]

Some interesting concerns for clinicians included liability for acting on real-time data collection between visits when they could not respond, a preference to see data only before patient visits, and validation of data accuracy and security when devices could be shared.[120,132]

DISCUSSION

In this scoping review, we surveyed a wide variety of approaches to implementing digital technology to improve patient

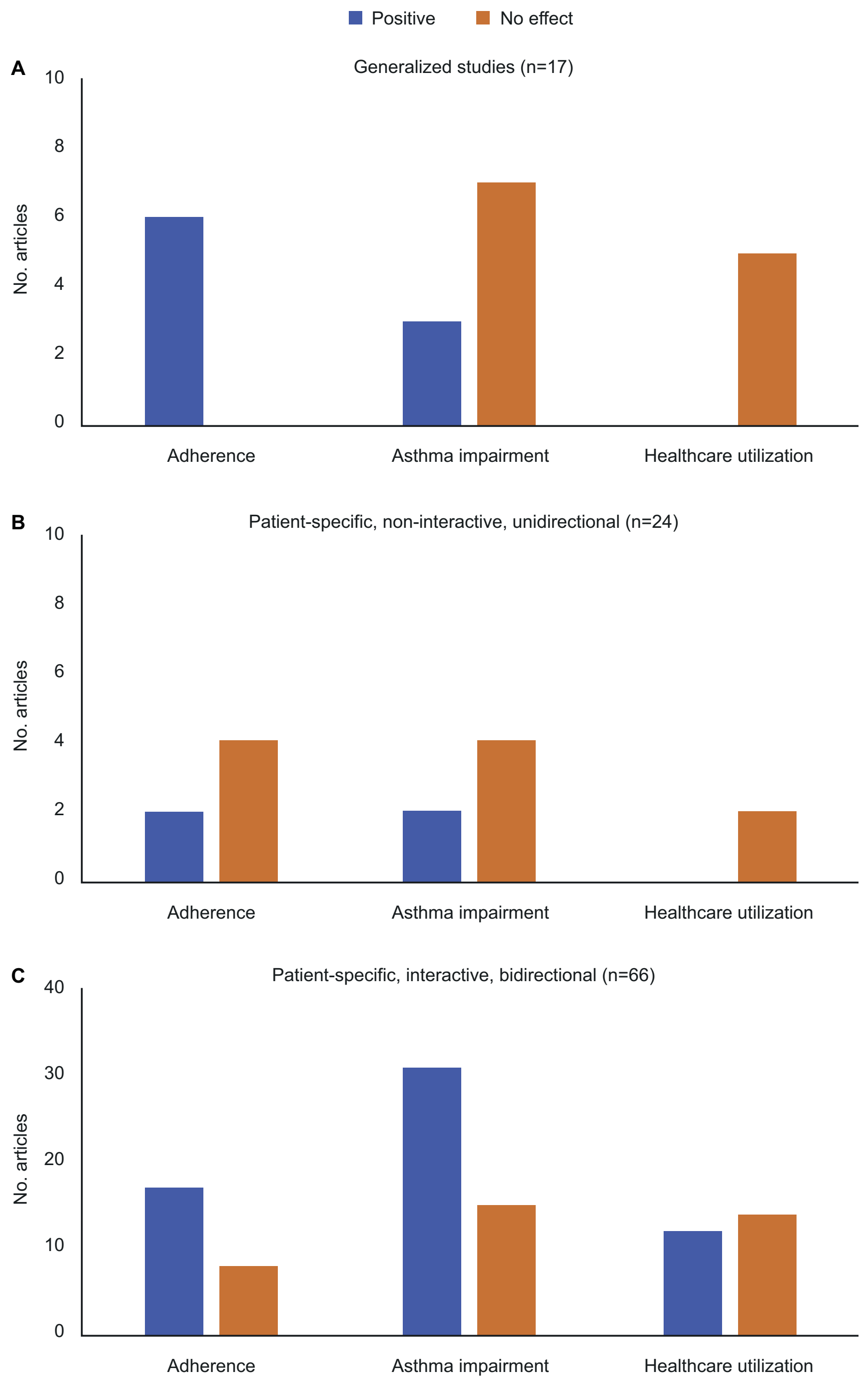

FIGURE 3. Balance of articles reporting positive effect versus no effect on adherence, asthma impairment, and health care use: A Generalized studies (n = 17). B Patient-specific, noninteractive, unidirectional interventions (n = 24). C Patient-specific interactive, bidirectional interventions (n = 66).

outcomes from asthma therapy. Such interventions usually focus on improving patient's adherence to their treatment regimen, through dose and prescription-fill reminder systems, behavior change as a result of education and motivation, or increased access to health care professionals and asthma advice through telemedicine or interactive asthma management platforms. We considered the interventions identified by our literature search based on their interactivity with patients, and whether data communication was unidirectional (data sent either from or to the patient) or bidirectional (data received from the patient prompting a response from the intervention). In terms of study outcomes, we looked for evidence of improvement with the various interventions in terms of patients' adherence to ICS regimens, improvements in impairment owing to asthma, and improvements in health care use (by reductions in unplanned or emergency consultations).

TABLE IV. Patient-specific, noninteractive, unidirectional interventions

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
30	Adolescent or younger	1143	NS	Decision support	Computerized randomized controlled trial decision support	R	16 wk	Change in adherence during therapy not reported	Significant increase in proportion of participants gaining good control	—
31	Adolescent or younger	41	NS	Device monitoring	Propeller Health platform only for data collection	R	30 d	Similar average daily adherence between intervention and control groups	Mean change in cACT similar between intervention and control groups	—
32	Adults only	239	Severe	Device monitoring	INCA adherence and inhaler technique only for data collection	SA	3 mo	Change in adherence during therapy not reported	—	—
33	Adults only	184	NS	Device monitoring	INCA adherence and inhaler technique for periodic assessment	R	3 mo	Change in adherence during therapy not reported; adherence via dose counter was significantly lower than by objective monitoring	Adherence was predictive of asthma exacerbations	—
34	Adults only	200	NS	Device monitoring	Smart spirometer only for data collection	SA	2 mo	—	—	—
35	Adolescent or younger	32	NS	Device monitoring	PEFR monitoring by SMS and digital peak flow meter, cold symptom monitoring by SMS	SA	3 wk	—	—	—
36	Adults only	111	NS	Device monitoring	Adherence monitor only for data collection	R	24 wk	Change in adherence during therapy not reported; consistent overestimation of self-reported adherence vs digitally monitored	—	—
37	Adolescent or younger	90	NS	Device monitoring	Adherence monitor only for data collection	SA	3 mo	Change in adherence during therapy not reported, ethnicity correlated with adherence	—	—
38	Adults only	123	NS	Device monitoring	INCA adherence and inhaler technique only for data collection	SA	2-4 wk	Overall change in adherence during therapy not reported; significant correlation between adherence and socioeconomic class, education. Inclusion of inhaler technique errors significantly reduced adherence by dose counter	—	—
39	Adolescent or younger	272	NS	Digital questionnaire	Cost-effectiveness data for Lv et al[23]; Web-based ACT used to adjust treatment periodically	R	4 mo	—	ACT used to adjust treatment	—

(continued)

TABLE IV. *(Continued)*

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
40	Adolescent or younger	272	NS	Digital questionnaire	See also Beerthuizen et al[39]; Web-based ACT used to adjust treatment periodically	R	1 y	—	No significant change in ACT in Web intervention group	No significant differences between groups in hospitalizations or steroid courses
41	Adolescent or younger	84	NS	Digital questionnaire	ADAM iPod cough monitoring and smartphone asthma diary for data collection only	SA	7 d	—	—	High cough counts were associated with higher use of health care services, hospitalizations, and office visits
42	Adolescent or younger	53	NS	Digital questionnaire	Automated telephone EMA	SA	1 mo	Change in adherence during therapy not reported	Change in ACT during therapy not reported	—
43	Adolescents and adults	410	NS	Digital questionnaire	ACT by SMS	R	5 ± 1 wk	—	Significant improvements in ACT were detectable using SMS reporting	—
44	Adults only	16	NS	Digital questionnaire	EMA by SMS with automated prompts for data collection	SA	2 wk	Change in adherence during therapy not reported	Change in symptoms during therapy not reported	—
45	Adolescent or younger	228	NS	Digital questionnaire	Web-based symptom diary for data collection only	R	4 wk	Change in adherence during therapy not reported	Change in ACT and cACT score during therapy not reported	—
46	Adolescent or younger	50	Moderate	Digital questionnaire	Smartphone app symptom diary plus EM	R	3 mo	No significant difference in self-reported medication adherence between groups with additional education/motivation	Significant improvement in cACT	—
47	All ages	7593	Mild, moderate, severe	Digital questionnaire	Regular data surveys from asthma patients	SA	6 mo	Change during study not reported	Change during study not reported	—
48	Adolescent or younger	68	NS	EM	Individualized static education	R	13 wk	No significant difference in adherence at wk 5 and 10	—	—
49	Adolescents and adults	216	NS	EM	Tailored static EM	R	9 mo	Significant improvement in adherence but less than clinically relevant level	—	—

50	Adolescent or younger	81	NS	Inhaler only	Adherence monitor for data collection only	SA	12 mo	Change in adherence during therapy not reported; median adherence was 87% and relatively constant in most patients	Asthma control during 12-mo study period was high and lung function was normal	—
51	Adults only	50	NS	Inhaler only	Automated interactive call plus electronic dose tracker	R	10 wk	32% improvement in adherence over 10 wk	No difference in ACT	—
52	Adolescent or younger	82	NS	Inhaler platform	kHealth platform and digital phenotyping: unidirectional; data available only to HCP	SA	1 or 3 mo	Effect of intervention on controller adherence during study not reported; poor adherence associated with poor asthma control	Effect of intervention on ACT during study not reported; poor adherence associated with poor asthma control	—
53	Adults only	67	NS	Platform only	WeChat platform with education and HCP interaction	R	3 mo	No significant difference in medication adherence between groups	No significant difference in improvement of asthma control between intervention and control groups	No significant difference between groups

(c)ACT, (childhood) Asthma Control Test; *EM*, education/motivation; *EMA*, ecological momentary association; *HCP*, health care professional; *ICS*, inhaled corticosteroid; *PEFR*, peak expiratory flow rate; *SA*, single-arm; *NS*, not specified; *R*, randomized; *SMS*, short message service.

Generalized dose and prescription reminders and non-personalized education and motivation were effective in improving adherence, but not impairment owing to asthma. Although subjective measurement of adherence is thought to overestimate adherence compared with objective measurement,[33,36] both types of adherence measurement were employed across these generalized studies; it is possible that adherence improvements were not sustained long enough to make a meaningful impact on asthma impairment. The patient-specific, noninteractive interventions included several different intervention types, but few reported positive impacts on either adherence or asthma impairment. However, the most-studied category of intervention, patient-specific interactive bidirectional interventions, reported the greatest number of improvements in adherence and asthma impairment. These benefits were largely found in studies of the most interactive interventions, those using interactive telemedicine, or those using an interactive management platform, with or without a digital inhaler. Each of these intervention types provides a high level of interactivity and instant feedback for patients through either live HCP consultation (telemedicine) or responses to monitored data or questionnaires (digital platforms with or without digital inhalers). Correlating patients' own asthma experiences (through ACT scores or other measured parameters) with their asthma management behaviors (eg, ICS adherence, trigger avoidance) may be a powerful engagement tool to motivate and educate patients about the need to stay on top of managing their condition.

We were able to identify broad trends in adherence and changes in asthma impairment among different intervention categories. The included studies generally did not find differences in health care use with interventions, either because it was not studied or because the incidence of emergency department visits or other unscheduled consultations was generally low.

All types of digital health interventions were well-received and acceptable to patients, caregivers, and clinicians. It is intuitive to think that digital interventions would be easily scalable to large populations and therefore be cost-effective, but currently there are few formal cost-effectiveness studies to confirm this assumption. In particular, the translation of improved adherence to improved symptom control and reduced health care use is not guaranteed, although several studies noted reductions in reliever or oral steroid use and reductions in unscheduled primary care visits. There may also be difficulties in transitioning coding and billing practices to accommodate digital interventions.

The progression of digital health monitoring and associated interventions in asthma still faces significant challenges. It is clear that a successful intervention must be able to combine objective monitoring with active patient engagement and education or motivation to maintain behaviors helpful to asthma therapy, and we have yet to develop an ideal system in this respect. Although there is further opportunity to incorporate digital interventions into patient care with respect to linking to patients' electronic health records and using data monitoring to trigger further HCP interventions, there is also the possibility of providing regular patient support through education about inhaler technique, avoidance of asthma triggers, and environmental monitoring and advice (eg, warnings related to high pollen count or air pollution), which could be equally important in reducing asthma burden.

The extensive implementation of digital interventions is attractive from the perspective of real-time population health monitoring as well as the increased opportunity and ability to

TABLE V. Patient-specific interactive, bidirectional interventions

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
54	Adolescent or younger	22	NS	Device monitoring	Vortex whistle and smartphone app for PEV	SA	1 mo	—	—	—
55	Adults only	72	All	Device monitoring	FEV measurement with smartphone asthma monitoring app	R	6 mo	—	Significant improvement in asthma control	No significant differences in unscheduled health care visits
56	Adults only	44	NS	EM	Individualized education in response to assignments	SA	6 wk	—	Significant increase in mean ACT score (greater than MID) at 3 mo after intervention	—
57	Adults only	51	Mod	EM	Interactive website for education and improving adherence	R	3 mo	No significant difference between groups	No significant difference in ACQ between groups	No significant difference between groups in HCP contact or steroid prescriptions
11	Adolescent or younger	220	NS	Inhaler only	Reliability data for Chan et al[12]; Adherence monitor with or without reminders	R	Not stated	—	Significant perceived and objective improvement in asthma control in conjunction with Chen et al[90]	—
12	Adolescent or younger	220	NS	Inhaler only	See also Chan et al[11]; adherence monitor with or without reminders	R	6 mo	Significant improvement in adherence with the reminder function in poorly adherent population at baseline; adherence then decline over 6 mo	Significant improvement in cACT vs control	No difference in frequency of ED visits
58	Adults only	39	NS	Inhaler platform	Adherence monitor and AMP platform	R	3 mo	Baseline adherence and adherence vs control not reported. Slight reduction in adherence in intervention group during study	Greater improvement from baseline to 3 mo for intervention compared with control group	—
59	All ages	495	NS	Inhaler platform	Propeller Health platform monitoring of SABA use	R	12 mo	—	Significant improvements in ACT in initially uncontrolled adults only; significantly larger decrease in SABA use vs routine care	—
60	Adolescent or younger	77	NS	Inhaler platform	Adherence monitor with periodic feedback	R	12 mo	Significantly higher adherence in intervention group over 12 mo	No significant difference in improvement of asthma control between intervention and control groups	Significantly fewer hospital admissions in intervention group

61	Adolescent or younger	14	Moderate to severe	Inhaler platform	Adherence monitor with motivational interviewing and feedback	SA	3 mo	Change in adherence during therapy not reported	Borderline significant improvement in ACT ($P = .05$)	–
62	Adolescent or younger	7	NS	Inhaler platform	Adherence monitor and smartphone app	SA	12 wk	Not performed owing to low patient numbers	–	–
63	All ages	224	NS	Inhaler platform	Propeller Health platform monitoring of SABA and ICS use	SA	1 y	–	–	Significant reduction in asthma-related ED visits, and combined ED and hospitalization events
64	Adolescent or younger	65	NS	Inhaler platform	Smart nebulizer with smartphone app for HCP contact	R	12 wk	Statistically significantly higher adherence at all time points vs control	–	Significantly lower frequency of ED visits, respiratory infections, antibiotics or systemic steroid use, and therapeutic cost vs control
65	Adolescent or younger	12	NS	Inhaler platform	Adherence monitor with smartphone app	SA	Not stated	Clinically significant improvement during pilot study	–	–
66	Adults only	30	NS	Inhaler platform	Adherence monitor for SABA use and interactive Web interface	SA	4 mo	–	Small but statistically significant improvement in ACT scores	–
67	Adolescents and adults	120	NS	Inhaler platform	Adherence monitor for SABA use and interactive Web interface	SA	1 mo	Rescue medication monitored rather than ICS	Significant reduction in SABA use during study	–
68	Adolescent or younger	12	NS	Inhaler platform	Adherence monitor and smartphone app	SA	8 wk	Patients meeting target ICS adherence ($\geq$50%) increased from 8% to 58% at wk 8	58% of patients reached MID for ACT scores	–
69	Adolescents and adults	143	Moderate to severe	Inhaler platform	Adherence monitor and Web interface	R	6 mo	Significant increase in adherence in groups receiving reminders and feedback	No significant difference in ACT between groups	–
70	Adults only	32	NS	Inhaler platform	Adherence monitor for data collection with customizable reminders	SA	3 wk	Change in adherence during therapy not reported	–	–
71	All ages	497	NS	Inhaler platform	Adherence monitor with interactive smartphone app	SA	12 mo	Rescue medication monitored rather than ICS	Significant increase in symptom-free days over 12 mo	–

(continued)

TABLE V. *(Continued)*

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
72	Adults only	138	NS	Platform only	breathe mobile health platform	R	12 mo	Self-reported controller use increased before clinic visits	Post hoc analysis associated high ACT scores with app use	—
73	Adults only	408	NS	Platform only	Online asthma care tool	R	12 mo	No significant difference between groups	Significant improvement in total ACT score with intervention	No significant difference between groups
74	Adults only	60	NS	Platform only	Interactive smartphone app	SA	4 mo	—	Significant increase in ACT	—
75	Adults only	100	NS	Platform only	Online MAP asthma educational and monitoring portal	R	6 mo	—	ACT evaluated but not reported separately	No significant difference in hospitalizations
76	Adults only	327	All	Platform only	POPET interactive smartphone app	R	6 mo	—	Significant improvements in ACT and proportion of well-controlled patients	Significant reduction in unplanned hospital visits and ED visits
77	Adolescent or younger	152	Mild to moderate	Platform only	Asthma management smartphone app	R	12 mo	Statistically significant higher treatment adherence vs control group	Statistically significantly higher cACT scores and fewer exacerbations vs control	—
78	Adolescent or younger	193	NS	Platform only	AsthmaCare smartphone asthma management app	R	6 mo	—	—	Significant reduction in urgent care visits, but not ED visits or hospitalizations
79	Adolescent or younger	34	NS	Platform only	Smartphone AMP	R	6 mo	—	Overall, no changes in ACT and self-efficacy scores between groups; adolescents with uncontrolled asthma had improved ACT within intervention group	—
80	Adults only	103	NS	Platform only	Online asthma patient community	R	9 wk	No change in self-reported adherence	—	—
81	Adolescent or younger	237	All	Platform only	MyAsthma online asthma management portal	R	12 mo	Significant increase in asthma medication changes or refills for children with uncontrolled asthma after parental use of portal	—	Significantly more medication changes and primary care asthma visits with portal use
82	Adults only	44	NS	Platform only	snuCare smartphone AMP and PFM	R	8 wk	Significant improvement in adherence	—	—

83	Adults only	48	NS	Platform only	Interactive motivational interviewing and EMA	R	3 mo	Trend for fewer doses missed vs control, but not statistically significant	Trend for improved ACT vs control, but not statistically significant	—
84	Adolescent or younger	58	NS	Platform only	Interactive smartphone app	R	6 mo	Significant improvement in patients with low (<75%) baseline adherence	—	No significant change in ED or acute visits during study
85	Adolescent or younger	20	NS	Platform only	Smartphone AMP	SA	8 wk	—	Significant increase in ACT for participants with uncontrolled asthma at baseline	—
86	Adults only	21	Moderate to severe	Platform only	Online P'ASMA asthma management portal	R	4 wk	No significant difference between groups	No significant difference between groups	—
87	Adolescent or younger	26	Moderate to severe	Platform only	EM by phone plus tailored SMS	R	3 mo	Reduced barriers to adherence	Clinically meaningful improvement in symptoms with medium to large effect sizes over 3 mo	—
88	Adults only	89	Moderate to severe	Platform only	Smartphone asthma diary with management feedback	R	6 mo	—	Asthma symptom scores used to adjust therapy	Significantly fewer patients with unscheduled ED visits
89	Adults only	120	NS	Platform only	SMS monitoring with HCP feedback as necessary	R	3 mo	—	No significant difference between groups	No significant difference between groups
90	Adults only	424	NS	Platform only	SMS monitoring with HCP feedback as necessary	R	3 mo	—	No significant difference between groups	No significant difference in ED visits or hospitalizations between groups after 5 wk
91	Adults only	80	NS	Platform only	CARAT smartphone app for asthma monitoring with e-mail feedback	R	6 mo	No difference between groups for medication adherence	No significant difference between groups	—
92	Adolescent or younger	40	NS	Platform only	CHANGE Asthma smartphone app with education and AMP	R	4 mo	—	No significant difference in cACT between groups	—
93	Adolescent or younger	234	NS	Platform only	ADAPT interactive smartphone app including CARAT	R	6 mo	Significant improvement in self-reported adherence patients with poor baseline adherence with or without uncontrolled asthma; no significant difference overall	No significant difference in CARAT score between groups	—

(continued)

TABLE V. *(Continued)*

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
94	Adolescent or younger	87	NS	Platform only	ADAPT interactive smartphone app including CARAT	R	6 mo	No significant change in self-reported adherence	Change in CARAT score during therapy not reported	—
95	Adolescent or younger	15	NS	Platform only	mASMAA interactive SMS asthma diary system	SA	2 wk	Anecdotal reports of improved adherence	Anecdotal reports of improved control over asthma symptoms	—
96	Adults only	107	NS	Platform only	Web platform for asthma monitoring, AMP and HCP contact	R	30 mo	—	Significant and sustained (≥30 mo) improvement in asthma control via AQLQ and ACQ	—
97	Adolescent or younger	24	All	Platform only	Web-based peak flow and symptom tracker with feedback	SA	2-15 mo	—	Significant reduction in number of wheezing episodes	Significant reduction in doctor or clinic visits
98	Adolescent or younger	90	All	Platform only	Web-based peak flow and symptom tracker with education, AMP and feedback	R	1 y	No significant difference in self-reported medication adherence between groups	Significant improvement in ACQ scores but not sustained beyond 12 mo	—
99	Adults only	200	Moderate	Platform only	Web-based peak flow and symptom tracker with AMP and feedback	R	1 y	—	Significant improvement in ACQ for patients with partly controlled or uncontrolled asthma only	—
100	Adults only	106	NS	Platform only	Web-based AMP with SMS feedback	R	12 mo	Change in adherence during therapy not reported	No significant difference in ACT between groups	No significant difference in hospitalizations or ED visits between groups
101	Adolescent or younger	24	NS	Platform only	AsthmaCare smartphone asthma management app	SA	30 d	Increased adherence in 85% of subjects	—	—
102	Adults only	22	NS	Platform only	Web-based AMP and symptom/peak flow diary with feedback	SA	8 d	Change in adherence during therapy not reported	Significant improvement in CACG symptom benchmarks	No significant difference in urgent health care visits
103	Adolescents	422	All	Platform only	Web-based platform with tailored feedback to questions	R	12 mo	—	Significant reduction in symptom days	No difference in frequency of ED visits

104	Adults only	51	Moderate to severe	Telemed	EM by phone plus static education	SA	9 mo	31.4% of 35 subjects indicated improved adherence	Change in ACT statistically significant, but less than MID	No difference in ED visits or hospitalizations between baseline and end of study
105	Adolescent or younger	400	NS	Telemed	Telemed visits	R	1 school y	—	Significant improvement in symptom-free days per 2 wk	Reduced likelihood of ED visit or hospitalization for asthma
106	Adolescent or younger	210	NS	Telemed	Online virtual asthma clinic	R	16 mo	—	Significant improvement in cACT but not ACT, in children and adolescents, respectively	No significant difference between groups
107	Adults only	100	NS	Telemed	Telemed and SMS asthma monitoring	R	12 mo	—	Statistically, but not clinically, significant increase in ACT score for intervention and control (between-group interaction not reported)	No hospitalizations during study
108	All ages	20	NS	Telemed	Telemed education	SA	1 y	—	Increase in proportion of well-controlled patients by ACT score	—
109	Adolescent or younger	210	NS	Telemed	Telemed visits	R	16 mo	—	Significant increase in cACT but no difference in ACT for teenagers, after 16 mo	Online asthma management was associated with fewer outpatient clinic visits
110	Adolescent or younger	50	Severe	Telemed	Telemonitoring of FEV_1 and intervention if necessary	R	12 mo	—	No significant difference between groups for exacerbations	—
111	Adolescent or younger	48	NS	Telemed	Telemed evaluation compared with face-to-face	SA	7 mo	—	—	—
112	Adults only	422	NS	Telemed	Telemed EM	R	2 y	—	Significantly improved ACT scores after 2 y	Significant reduction in asthma-related hospitalization
113	Adolescent or younger	362	NS	Telemed	Telemed EM	R	1 y	—	Significant reduction in proportion of children with poorly controlled asthma	Urgent care events decreased in both groups with no significant difference between groups

(continued)

TABLE V. *(Continued)*

Reference	Patient age group	n	Asthma severity	Intervention type	Intervention details	Study type	Study period	Effect on ICS adherence with intervention	Effect on asthma impairment or symptoms with intervention	Effect on health care use and/or hospitalization with intervention
114	Adolescent or younger	393	NS	Telemed	Telemed EM	R	6 mo	Significant increase in caregiver-reported adherence but no significant difference in asthma medication ratio	No statistically significant difference between groups in reported symptom-free days	—
115	Adults only	30	NS	Telemed	Telemed education and inhaler technique	SA	2 wk	—	—	—
116	Adolescent or younger	295	NS	Telemed	Telemed education	R	1 y	—	—	Significant reduction in ED visits and hospitalizations during follow-up
117	Adults only	98	NS	Telemed	Telemed education	R	3 mo	Within-group improvement in adherence in intervention group	No significant between-group difference in ACT; within-group improvement in intervention group	—

AMP, asthma management plan; *(c)ACT*, (childhood) Asthma Control Test; *ACQ*, Asthma Control Questionnaire; *AQLQ*, Asthma Quality of Life Questionnaire; *EM*, education or motivation; *EMA*, ecological momentary association; *FEV*, forced expiratory volume; *HCP*, health care professional; *ICS*, inhaled corticosteroid; *MID*, minimal important difference; *PEFR*, peak expiratory flow rate; *PEV*, peak expiratory volume; *SA*, single-arm; *NS*, not specified; *R*, randomized; *SABA*, short-acting β-agonist; *SMS*, short message service; *Telemed*, telemedicine intervention.

improve individual asthma outcomes through treatment personalization and daily disease management. Data analysis may also assist the understanding of relations and causal mechanisms among patient characteristics, environment, and asthma symptoms and exacerbations, ultimately leading to the development of patient digital phenotypes.

However, beyond the challenge of developing suitable technologies, considerable financial, technological, and political barriers still need to be overcome. The development of artificial intelligence protocols to interpret and apply the huge amount of monitoring data involved will be important. There will also be a considerable emphasis on the infrastructure necessary to incorporate continuous monitoring into patients' overall health care to support physicians. Such a fundamental change in the organization and delivery of health care will also have significant effects on liability for physicians making artificial intelligence-augmented decisions.[133,134] Large-scale personal health data collection naturally generates concern regarding data security and use, and patients and physicians must be confident about how their data will be used, who will have access to it, and the extent to which individual patients will own their data.[135]

Regardless of pharmacological therapy, consultations can already be implemented regularly by videoconference, which is especially important for patients with reduced mobility or reduced free time, or in remote locations; videoconferencing could also be used to provide support between face-to-face appointments. In the context of a pandemic such as COVID-19, reducing face-to-face contact between clinicians and selected patients has been a necessity. The use of telemedicine and video consultation was implemented as an elegant solution to this challenge for patient assessment and education, both of which can be delivered remotely.[136,137] One related effect of the current pandemic situation is a large-scale uptake of videoconference technology for work and social contact in the general population, which could help acclimatize patients and physicians to accessing and providing health care in this way. We consider it likely that many of the benefits of telemedicine realized during the pandemic, initially through necessity, will continue to gain increasing acceptance and form an integral part of respiratory care in the future.[137,138]

Limitations

Conclusions from this scoping review are limited by heterogeneity in terms of the wide variety of study designs and outcome measures and the different ways of implementing similar interventions for patient-independent and patient-dependent initiatives. In addition, study heterogeneity limited our interpretation of different outcomes for the same intervention category (eg, the changes observed in adherence were not necessarily measured in the same studies as changes in ACT). The ACT was the most common measure of asthma burden and is a subjective measure of patients' perception of impairment resulting from asthma, rather than a measure of risk for an asthma exacerbation. Changes in asthma exacerbations were not commonly used as a primary outcome measure, possibly because the expected number of exacerbations in study populations was not sufficiently frequent to make this a useful end point.

Because patients were generally monitored for no more than 12 months (and commonly only 3 or 6 months), the long-term effects of the various interventions are unknown. Studies also typically did not account for seasonality or incorporate environmental information (such as aeroallergen or air pollution levels). Most of the studies analyzed did not specify participants' asthma severity at baseline and lacked stratification by asthma severity. An abundance of studies also reported outcomes only at single specific time points or as a single assessment for the whole study period, rather than as change over time associated with a specific intervention.

The relation between asthma controller adherence and health care use is an important issue, but one that is challenging to study. In addition to the acknowledged problems with the accuracy of self-reported adherence,[48,139,140] in a general population of treated asthma patients who are not under close clinical supervision, it would be expected that the frequency of emergency or unplanned clinical consultation would be low, and therefore statistically significant changes would be difficult to detect. The studies identified for this review rarely assessed health care use systematically, and few reported on both adherence and health care use. Furthermore, correlating changes in adherence with changes in use outcomes is confounded by several patient-related and sociobehavioral factors including symptom severity, ethnicity, level of educational achievement, household income, and attitude toward treatment.[141]

Therefore, the fact that reductions in health care use were not reported with digital asthma interventions in the studies discussed in this review does not mean that these interventions are not associated with benefit in terms of health care resource use in the real world. The patient populations, intervention assessments, and data collection methods might not have been capable of detecting health care use changes accurately, even where these may have occurred. Further research into the effects of adherence on health care use is undoubtedly needed, and considerable effort will be required to account for these factors in the design of future studies assessing digital interventions. Furthermore, future research into digital technology as a part of asthma interventions would benefit from a convention on standard approaches to outcomes and their measurement to enhance similarity in the ways in which we assess asthma treatment.

CONCLUSIONS

Digital health interventions are acceptable to asthma patients and clinicians, and the relative ubiquity of mobile Internet- and Bluetooth-connected devices in everyday life makes real-time monitoring of asthma treatment and symptoms extremely feasible. However, an effective digital intervention must fulfill several important design criteria. Both inhaler devices and software should be intuitive and easy to use, and hardware should be unobtrusive with accurate and objective measurement of adherence and other parameters, and be seamlessly integrated with software providing convenient assessment of symptoms and asthma control. Software should be designed to educate and maintain patients' engagement (at a variety of different ages), provide clear communication of hardware- and software-measured parameters for access by patients and clinicians, and be customizable by patients to fit into their lives and routines. Motivating patients to take an active role in managing their condition and maintaining their interest in doing so is of paramount importance in designing a successful future digital intervention.

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REFERENCES

1. The Global Asthma Report 2018. Auckland, New Zealand: Global Asthma Network; 2018.
2. Levy ML. The national review of asthma deaths: what did we learn and what needs to change? Breathe (Sheff) 2015;11:14-24.
3. Pinnock H, Parke HL, Panagioti M, Daines L, Pearce G, Epiphaniou E, et al. Systematic meta-review of supported self-management for asthma: a healthcare perspective. BMC Med 2017;15:64.
4. Gruffydd-Jones K. Unmet needs in asthma. Ther Clin Risk Manag 2019;15:409-21.
5. Akinbami LJ, Salo PM, Cloutier MM, Wilkerson JC, Elward KS, Mazurek JM, et al. Primary care clinician adherence with Asthma Guidelines: the National Asthma Survey of Physicians. J Asthma 2020;57:543-55.
6. Cloutier MM, Salo PM, Akinbami LJ, Cohn RD, Wilkerson JC, Diette GB, et al. Clinician agreement, self-efficacy, and adherence with the guidelines for the diagnosis and management of asthma. J Allergy Clin Immunol Pract 2018;6:886-894.e4.
7. Morrison D, Mair FS, Yardley L, Kirby S, Thomas M. Living with asthma and chronic obstructive airways disease: using technology to support self-management – an overview. Chron Respir Dis 2017;14:407-19.
8. Mann DM, Chen J, Chunara R, Testa PA, Nov O. COVID-19 transforms health care through telemedicine: evidence from the field. J Am Med Inform Assoc 2020;27:1132-5.
9. Pham MT, Rajić A, Grieg JD, Sargeant JM, Papadopoulos A, McEwan SA. A scoping review of scoping reviews: advancing the approach and enhancing the consistency. Res Synth Methods 2014;5:371-85.
10. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med 2018;169:467-73.
11. Chan AHY, Stewart AW, Harrison J, Black PN, Mitchell EA, Foster JM. Electronic adherence monitoring device performance and patient acceptability: a randomized control trial. Expert Rev Med Devices 2017;14:401-11.
12. Chan AH, Stewart AW, Harrison J, Camargo CA, Black PN, Mitchell EA. The effect of an electronic monitoring device with audiovisual reminder function on adherence to inhaled corticosteroids and school attendance in children with asthma: a randomised controlled trial. Lancet Respir Med 2015;3:210-9.
13. Cvietusa PJ, Goodrich GK, Shoup JA, Steffen DA, Tacinas C, Wagner NM, et al. Implementing health care technology research into practice to improve adult asthma management. J Allergy Clin Immunol Pract 2019;7:908-14.
14. Bender BG, Cvietusa PJ, Goodrich GK, Lowe R, Nuanes HA, Rand C, et al. Pragmatic trial of health care technologies to improve adherence to pediatric asthma treatment: a randomized clinical trial. JAMA Pediatr 2015;169:317-23.
15. Lee SH, Song WJ, Park HW, Kang MG, Kim SH, Park HK, et al. Multifaceted interventions to reduce acute exacerbations in elderly asthmatics. Asia Pac Allergy 2018;8:e1.
16. Britto MT, Rohan JM, Dodds CM, Byczkowski TL. A randomized trial of user-controlled text messaging to improve asthma outcomes: a pilot study. Clin Pediatr (Phila) 2017;56:1336-44.
17. Johnson KB, Patterson BL, Ho YX, Chen Q, Nian H, Davison CL, et al. The feasibility of text reminders to improve medication adherence in adolescents with asthma. J Am Med Inform Assoc 2016;23:449-55.
18. Strandbygaard U, Thomsen SF, Backer V. A daily SMS reminder increases adherence to asthma treatment: a three-month follow-up study. Respir Med 2010;104:166-71.

19. Britto MT, Munafo JK, Schoettker PJ, Vockell AL, Wimberg JA, Yi MS. Pilot and feasibility test of adolescent-controlled text messaging reminders. Clin Pediatr (Phila) 2012;51:114-21.
20. Vollmer WM, Feldstein A, Smith DH, Dubanoski JP, Waterbury A, Schneider JL, et al. Use of health information technology to improve medication adherence. Am J Manag Care 2011;17:SP79-87.
21. Sleath B, Carpenter DM, Davis SA, Watson CH, Lee C, Loughlin CE, et al. Improving youth question-asking and provider education during pediatric asthma visits. Patient Educ Couns 2018;101:1051-7.
22. Thomas M, Bruton A, Little P, Holgate S, Lee A, Yardley L, et al. A randomised controlled study of the effectiveness of breathing retraining exercises taught by a physiotherapist either by instructional DVD or in face-to-face sessions in the management of asthma in adults. Health Technol Assess 2017;21:1-162.
23. Lv Y, Zhao H, Liang Z, Dong H, Liu L, Zhang D, et al. A mobile phone short message service improves perceived control of asthma: a randomized controlled trial. Telemed J E Health 2012;18:420-6.
24. Cowden JD, Wilkerson-Amendell S, Weathers L, Gonzalez ED, Dinakar C, Westbrook DH, et al. The talking card: randomized controlled trial of a novel audio-recording tool for asthma control. Allergy Asthma Proc 2015;36:e86-91.
25. Lau AY, Arguel A, Dennis S, Liaw ST, Coiera E. Why didn't it work?" Lessons from a randomized controlled trial of a Web-based personally controlled health management system for adults with asthma. J Med Internet Res 2015;17:e283.
26. Kim YH, Yoo KH, Yoo JH, Kim TE, Kim DK, Park YB, et al. The need for a well-organized, video-assisted asthma education program at Korean primary care clinics. Tuberc Respir Dis (Seoul) 2017;80(2):169-78.
27. Lipszyc JC, Gotzev S, Scarborough J, Liss GM, Gupta S, Tarlo SM. Evaluation of the efficacy of a web-based work-related asthma educational tool. J Asthma 2016;53:1071-5.
28. Hughes M, Murphy M. Evaluation of a pilot national online asthma e-learning program for secondary school students. Issues Compr Pediatr Nurs 2014;37:136-46.
29. Burns P, Jones SC, Iverson D, Caputi P. AsthmaWise — a field of dreams? The results of an online education program targeting older adults with asthma. J Asthma 2013;50:737-44.
30. Kercsmar CM, Sorkness CA, Calatroni A, Gergen PJ, Bloomberg GR, Gruchalla RS, et al. A computerized decision support tool to implement asthma guidelines for children and adolescents. J Allergy Clin Immunol 2019;143:1760-8.
31. Kenyon CC, Gruschow SM, Quarshie WO, Griffis H, Leach MC, Zorc JJ, et al. Controller adherence following hospital discharge in high risk children: a pilot randomized trial of text message reminders. J Asthma 2019;56:95-103.
32. Sulaiman I, Seheult J, MacHale E, Boland F, O'Dwyer SM, Rapcan V, et al. A method to calculate adherence to inhaled therapy that reflects the changes in clinical features of asthma. Ann Am Thorac Soc 2016;13:1894-903.
33. Killane I, Sulaiman I, MacHale E, Breathnach A, Taylor TE, Holmes MS, et al. Predicting asthma exacerbations employing remotely monitored adherence. Healthc Technol Lett 2016;3:51-5.
34. Hernández CR, Fernández MN, Sanmartín AP, Roibas CM, Domínguez LC, Rial MIB, et al. AF validation of the portable Air-Smart Spirometer. PLoS One 2018;13:e0192789.
35. Gahleitner F, Legg J, Holland E, Pearson S, Roberts G. The validity and acceptability of a text-based monitoring system for pediatric asthma studies. Pediatr Pulmonol 2016;51:5-12.
36. Patel M, Perrin K, Pritchard A, Williams M, Wijesinghe M, Weatherall M, et al. Accuracy of patient self-report as a measure of inhaled asthma medication use. Respirology 2013;18:546-52.
37. Vasbinder E, Dahhan N, Wolf B, Zoer J, Blankman E, Bosman D, et al. The association of ethnicity with electronically measured adherence to inhaled corticosteroids in children. Eur J Clin Pharmacol 2013;69:683-90.
38. Sulaiman I, Seheult J, MacHale E, D'Arcy S, Boland F, McCrory K, et al. Irregular and ineffective: a quantitative observational study of the time and technique of inhaler use. J Allergy Clin Immunol Pract 2016;4:900-909.e2.
39. Beerthuizen T, Voorend-van Bergen S, van den Hout WB, Vaessen-Verberne AA, Brackel HJ, Landstra AM, et al. Cost-effectiveness of FENO-based and web-based monitoring in paediatric asthma management: a randomised controlled trial. Thorax 2016;71:607-13.
40. Voorend-van Bergen S, Vaessen-Verberne AA, Brackel HJ, Landstra AM, van den Berg NJ, Hop WC, et al. Pijnenburg Monitoring strategies in children with asthma: a randomised controlled trial. Thorax 2015;70:543-50.
41. Rhee H, Belyea MJ, Sterling M, Bocko MF. Evaluating the validity of an automated device for asthma monitoring for adolescents: correlational design. J Med Internet Res 2015;17:e234.
42. Mulvaney SA, Ho YX, Cala CM, Chen Q, Nian H, Patterson BL, et al. Assessing adolescent asthma symptoms and adherence using mobile phones. J Med Internet Res 2013;15:e141.
43. Uysal MA, Mungan D, Yorgancioglu A, Yildiz F, Akgun M, Gemicioglu B, et al. Asthma control test via text messaging: could it be a tool for evaluating asthma control? J Asthma 2013;50:1083-9.
44. MacDonell K, Gibson-Scipio W, Lam P, Naar-King S, Chen X. Text messaging to measure asthma medication use and symptoms in urban African American emerging adults: a feasibility study. J Asthma 2012;49:1092-6.
45. Voorend-van Bergen S, Vaessen-Verberne AA, Landstra AM, Brackel HJ, van den Berg NJ, Caudri D, et al. Monitoring childhood asthma: web-based diaries and the asthma control test. J Allergy Clin Immunol 2014;133:1599-1605.e2.
46. Montalbano L, Ferrante G, Cilluffo G, Gentile M, Arrigo M, La Guardia D, et al. Targeting quality of life in asthmatic children: the MyTEP pilot randomized trial. Respir Med 2019;153:14-9.
47. Chan YY, Wang P, Rogers L, Tignor N, Zweig M, Hershman SG, et al. The Asthma Mobile Health Study, a large-scale clinical observational study using ResearchKit. Nat Biotechnol 2017;35:354-62.
48. Mosnaim G, Li H, Martin M, Richardson D, Belice PJ, Avery E, et al. The impact of peer support and mp3 messaging on adherence to inhaled corticosteroids in minority adolescents with asthma: a randomized, controlled trial. J Allergy Clin Immunol Pract 2013;1:485-93.
49. Petrie KJ, Perry K, Broadbent E, Weinman J. A text message programme designed to modify patients' illness and treatment beliefs improves self-reported adherence to asthma preventer medication. Br J Health Psychol 2012;17:74-84.
50. Klok T, Kaptein AA, Duiverman EJ, Brand PL. It's the adherence, stupid (that determines asthma control in preschool children)! Eur Respir J 2014;43:783-91.
51. Bender BG, Apter A, Bogen DK, Dickinson P, Fisher L, Wamboldt FS, et al. Test of an interactive voice response intervention to improve adherence to controller medications in adults with asthma. J Am Board Fam Med 2010;23:159-65.
52. Jaimini U, Thirunarayan K, Kalra M, Venkataraman R, Kadariya D, Sheth A. "How is my child's asthma?" Digital phenotype and actionable insights for pediatric asthma. JMIR Pediatr Parent 2018;1:e11988.
53. Cao Y, Lin S-H, Zhu D, Xu F, Chen Z-H, Shen H-H, et al. WeChat public account use improves clinical control of cough-variant asthma: a randomized controlled trial. Med Sci Monit 2018;24:1524-32.
54. Mikalsen IB, Nassehi D, Øymar K. Vortex whistle and smart phone application for peak flow recordings in asthmatic children: a feasibility study. Telemed J E Health 2019;25:1077-82.
55. Zairina E, Abramson MJ, McDonald CF, Li J, Dharmasiri T, Stewart K, et al. Telehealth to improve asthma control in pregnancy: a randomized controlled trial. Respirology 2016;21:867-74.
56. Speck AL, Hess M, Baptist AP. An electronic asthma self-management intervention for young African American adults. J Allergy Clin Immunol Pract 2016;4:89-95.e2.
57. Morrison D, Wyke S, Saunderson K, McConnachie A, Agur K, Chaudhuri R, et al. Findings from a pilot Randomised trial of an Asthma Internet Self-management Intervention (RAISIN). BMJ Open 2016;6:e009254.
58. Weinstein AG, Singh A, Laurenceau JP, Skoner DP, Maiolo J, Sharara R, et al. A pilot study of the effect of an educational Web application on asthma control and medication adherence. J Allergy Clin Immunol Pract 2019;7:1497-506.
59. Merchant RK, Inamdar R, Quade RC. Effectiveness of population health management using the Propeller Health Asthma Platform: a randomized clinical trial. J Allergy Clin Immunol Pract 2016;4:455-63.
60. Morton RW, Elphick HE, Rigby AS, Daw WJ, King DA, Smith LJ, et al. STAAR: a randomised controlled trial of electronic adherence monitoring with reminder alarms and feedback to improve clinical outcomes for children with asthma. Thorax 2017;72:347-54.
61. Kenyon CC, Chang J, Wynter SA, Fowler JC, Long J, Bryant-Stephens TC. Electronic adherence monitoring in a high-utilizing pediatric asthma cohort: a feasibility study. JMIR Res Protoc 2016;5:e132.
62. Cushing A, Manice MP, Ting A, Parides MK. Feasibility of a novel mHealth management system to capture and improve medication adherence among adolescents with asthma. Patient Prefer Adherence 2016;10:2271-5.
63. Merchant R, Szefler SJ, Bender BG, Tuffli M, Barrett MA, Gondalia R, et al. Impact of a digital health intervention on asthma resource utilization. World Allergy Organ J 2018;11:28.
64. Zhou Y, Lu Y, Zhu H, Zhang Y, Li Y, Yu Q. Short-term effect of a smart nebulizing device on adherence to inhaled corticosteroid therapy in Asthma Predictive Index-positive wheezing children. Patient Prefer Adherence 2018;12:861-8.

65. Grossman B, Conner S, Mosnaim G, Albers J, Leigh J, Jones S, et al. Application of Human Augmentics: a persuasive asthma inhaler. J Biomed Inform 2017;67:51-8.
66. Van Sickle D, Magzamen S, Truelove S, Morrison T. Remote monitoring of inhaled bronchodilator use and weekly feedback about asthma management: an open-group, short-term pilot study of the impact on asthma control. PLoS One 2013;8:e55335.
67. Barrett MA, Humblet O, Marcus JE, Henderson K, Smith T, Eid N, et al. Effect of a mobile health, sensor-driven asthma management platform on asthma control. Ann Allergy Asthma Immunol 2017;119:415-21.
68. Mosnaim G, Li H, Martin M, Richardson D, Belice PJ, Avery E, et al. A tailored mobile health intervention to improve adherence and asthma control in minority adolescents. J Allergy Clin Immunol Pract 2015;3: 288-290.e1.
69. Foster JM, Usherwood T, Smith L, Sawyer SM, Xuan W, Rand CS, et al. Inhaler reminders improve adherence with controller treatment in primary care patients with asthma. J Allergy Clin Immunol 2014;134:1260-1268.e3.
70. Kuipers E, Poot CC, Wensing M, Chavannes NH, de Smet PA, Teichert M. Self-Management Maintenance Inhalation Therapy With eHealth (SELFIE): observational study on the use of an electronic monitoring device in respiratory patient care and research. J Med Internet Res 2019;21:e13551.
71. Barrett M, Combs V, Su JG, Henderson K, Tuffli M, Simrall G, et al. AIR Louisville: addressing asthma with technology, crowdsourcing, cross-sector collaboration, and policy. Health Affairs 2018;37:525-34.
72. Morita PP, Yeung MS, Ferrone M, Taite AK, Madeley C, Stevens Lavigne A, et al. A patient-centered mobile health system that supports asthma self-management (breathe): design, development, and utilization. JMIR Mhealth Uhealth 2019;7:e10956.
73. Pool AC, Kraschnewski JL, Poger JM, Smyth J, Stuckey HL, Craig TJ, et al. Impact of online patient reminders to improve asthma care: a randomized controlled trial. PLoS One 2017;12:e0170447.
74. Cook KA, Modena BD, Simon RA. Improvement in asthma control using a minimally burdensome and proactive smartphone application. J Allergy Clin Immunol Pract 2016;4:730-737.e1.
75. Ahmed S, Ernst P, Bartlett SJ, Valois MF, Zaihra T, Paré G, et al. The effectiveness of Web-based asthma self-management system, My Asthma Portal (MAP): a pilot randomized controlled trial. J Med Internet Res 2016;18:e313.
76. Cingi C, Yorgancioglu A, Cingi CC, Oguzulgen K, Muluk NB, Ulusoy S, et al. The "physician on call patient engagement trial" (POPET): measuring the impact of a mobile patient engagement application on health outcomes and quality of life in allergic rhinitis and asthma patients. Int Forum Allergy Rhinol 2015;5:487-97.
77. Lv S, Ye X, Wang Z, Xia W, Qi Y, Wang W, et al. A randomized controlled trial of a mobile application-assisted nurse-led model used to improve treatment outcomes in children with asthma. J Adv Nurs 2019;75:3058-67.
78. Stukus DR, Farooqui N, Strothman K, Ryan K, Zhao S, Stevens JH, et al. Real-world evaluation of a mobile health application in children with asthma. Ann Allergy Asthma Immunol 2018;120:395-400.e1.
79. Perry TT, Marshall A, Berlinski A, Rettiganti M, Brown RH, Randle SM, et al. Smartphone-based vs paper-based asthma action plans for adolescents. Ann Allergy Asthma Immunol 2017;118:298-303.
80. Koufopoulos JT, Conner MT, Gardner PH, Kellar I. A Web-based and mobile health social support intervention to promote adherence to inhaled asthma medications: randomized controlled trial. J Med Internet Res 2016;18:e122.
81. Fiks AG, DuRivage N, Mayne SL, Finch S, Ross ME, Giacomini K, et al. Adoption of a portal for the primary care management of pediatric asthma: a mixed-methods implementation study. J Med Internet Res 2016;18:e172.
82. Kim MY, Lee SY, Jo EJ, Lee SE, Kang MG, Song WJ, et al. Feasibility of a smartphone application based action plan and monitoring in asthma. Asia Pac Allergy 2016;6:174-80.
83. Kolmodin MacDonell K, Naar S, Gibson-Scipio W, Lam P, Secord E. The Detroit Young Adult Asthma Project: pilot of a technology-based medication adherence intervention for African-American emerging adults. J Adolesc Health 2016;59:465-71.
84. Wiecha JM, Adams WG, Rybin D, Rizzodepaoli M, Keller J, Clay JM. Evaluation of a web-based asthma self-management system: a randomised controlled pilot trial. BMC Pulm Med 2015;15:17.
85. Burbank AJ, Lewis SD, Hewes M, Schellhase DE, Rettiganti M, Hall-Barrow J, et al. Mobile-based asthma action plans for adolescents. J Asthma 2015;52:583-6.
86. Araújo L, Jacinto T, Moreira A, Castel-Branco MG, Delgado L, Costa-Pereira A. Clinical efficacy of web-based versus standard asthma self-management. J Investig Allergol Clin Immunol 2012;22:28-34.
87. Seid M, D'Amico EJ, Varni JW, Munafo JK, Britto MT, Kercsmar CM, et al. The in vivo adherence intervention for at risk adolescents with asthma: report of a randomized pilot trial. J Pediatr Psychol 2012;37:390-403.
88. Liu WT, Huang CD, Wang CH, Lee KY, Lin SM, Kuo HP. A mobile telephone-based interactive self-care system improves asthma control. Eur Respir J 2011;37:310-7.
89. Prabhakaran L, Chee WY, Chua KC, Abisheganaden J, Wong WM. The use of text messaging to improve asthma control: a pilot study using the mobile phone short messaging service (SMS). J Telemed Telecare 2010;16:286-90.
90. Lathy P, Neo LP, Gan CC, Tham LM, Ng C, Yap CW, et al. Effectiveness of the ecare programme: a short message service (SMS) for asthma monitoring. Ann Acad Med Singap 2018;47:233-6.
91. Kuipers E, Wensing M, de Smet P, Teichert M. Self-management research of asthma and good drug use (SMARAGD study): a pilot trial. Int J Clin Pharm 2017;39:888-96.
92. Real FJ, Beck AF, DeBlasio D, Zackoff M, Henize A, Xu Y, et al. Dose Matters: a smartphone application to improve asthma control among patients at an urban pediatric primary care clinic. Games Health J 2019;8:357-65.
93. Kosse RC, Bouvy ML, de Vries TW, Koster ES. Effect of a mHealth intervention on adherence in adolescents with asthma: a randomized controlled trial. Respir Med 2019;149:45-51.
94. Kosse RC, Bouvy ML, Belitser SV, de Vries TW, van der Wal PS, Koster ES. Effective engagement of adolescent asthma patients with mobile health-supporting medication adherence. JMIR Mhealth Uhealth 2019;7:e12411.
95. Rhee H, Miner S, Sterling M, Halterman JS, Fairbanks E. The development of an automated device for asthma monitoring for adolescents: methodologic approach and user acceptability. JMIR Mhealth Uhealth 2014;2:e27.
96. van Gaalen JL, Beerthuizen T, van der Meer V, van Reisen P, Redelijkheid GW, Snoeck-Stroband JB, et al. Long-term outcomes of internet-based self-management support in adults with asthma: randomized controlled trial. J Med Internet Res 2013;15:e188.
97. Arnold RJ, Stingone JA, Claudio L. Computer-assisted school-based asthma management: a pilot study. JMIR Res Protoc 2012;1:e15.
98. Rikkers-Mutsaerts ER, Winters AE, Bakker MJ, van Stel HF, van der Meer V, de Jongste JC, et al. Internet-based self-management compared with usual care in adolescents with asthma: a randomized controlled trial. Pediatr Pulmonol 2012;47:1170-9.
99. van der Meer V, van Stel HF, Bakker MJ, Roldaan AC, Assendelft WJ, Sterk PJ, et al. Weekly self-monitoring and treatment adjustment benefit patients with partly controlled and uncontrolled asthma: an analysis of the SMASHING study. Respir Res 2010;11:74.
100. Poureslami I, Shum J, Lester RT, Tavakoli H, Dorscheid DR, FitzGerald JM. A pilot randomized controlled trial on the impact of text messaging check-ins and a web-based asthma action plan versus a written action plan on asthma exacerbations. J Asthma 2018;16:1-13.
101. Farooqui N, Phillips G, Barrett C, Stukus D. Acceptability of an interactive asthma management mobile health application for children and adolescents. Ann Allergy Asthma Immunol 2015;114:527-9.
102. Licskai C, Sands TW, Ferrone M. Development and pilot testing of a mobile health solution for asthma self-management: asthma action plan smartphone application pilot study. Can Respir J 2013;20:301-6.
103. Joseph CL, Ownby DR, Havstad SL, Saltzgaber J, Considine S, Johnson D, et al. Evaluation of a web-based asthma management intervention program for urban teenagers: reaching the hard to reach. J Adolesc Health 2013;52:419-26.
104. Rasulnia M, Burton BS, Ginter RP, Wang TY, Pleasants RA, Green CL, et al. Assessing the impact of a remote digital coaching engagement program on patient-reported outcomes in asthma. J Asthma 2018;55:795-800.
105. Halterman JS, Fagnano M, Tajon RS, Tremblay P, Wang H, Butz A, et al. Effect of the School-Based Telemedicine Enhanced Asthma Management (SB-TEAM) program on asthma morbidity: a randomized clinical trial. JAMA Pediatr 2018;172:e174938.
106. van den Wijngaart LS, Roukema J, Boehmer ALM, Brouwer ML, Hugen CAC, Niers LEM, et al. A virtual asthma clinic for children: fewer routine outpatient visits, same asthma control. Eur Respir J 2017;50:1700471.
107. Nemanic T, Sarc I, Skrgat S, Flezar M, Cukjati I, Marc Malovrh M. Telemonitoring in asthma control: a randomized controlled trial. J Asthma 2019;56: 782-90.
108. Brown W, Scott D, Friesner D, Schmitz T. Impact of telepharmacy services as a way to increase access to asthma care. J Asthma 2017;54:961-7.
109. Van Den Wijngaart LS, Kievit W, Roukema J, Boehmer AL, Brouwer ML, Hugen CA, et al. The virtual asthma clinic for children: a cost-effectiveness analysis. Pediatr Pulmonol 2016;51:S65.

110. Deschilde A, Béghin L, Salleron J, Iliescu C, Thumerelle C, Santos C, et al. Home telemonitoring (forced expiratory volume in 1 s) in children with severe asthma does not reduce exacerbations. Eur Respir J 2012;39:290-6.
111. Gattu R, Scollan J, DeSouza A, Devereaux D, Weaver H, Agthe AG. Telemedicine: a reliable tool to assess the severity of respiratory distress in children. Hosp Pediatr 2016;6:476-82.
112. Patel MR, Song PXK, Sanders G, Nelson B, Kaltsas E, Thomas LJ, et al. A randomized clinical trial of a culturally responsive intervention for African American women with asthma. Ann Allergy Asthma Immunol 2017;118:212-9.
113. Garbutt JM, Banister C, Highstein G, Sterkel R, Epstein J, Bruns J, et al. Telephone coaching for parents of children with asthma: Impact and lessons learned. Arch Pediatr Adolesc Med 2010;164:625-30.
114. Perry TT, Halterman JS, Brown RH, Luo C, Randle SM, Hunter CR, et al. Results of an asthma education program delivered via telemedicine in rural schools. Ann Allergy Asthma Immunol 2018;120:401-8.
115. Nelson P, Young HN, Knobloch MJ, Griesbach SA. Telephonic monitoring and optimization of inhaler technique. Telemed J E Health 2011;17:734-40.
116. Coughey K, Klein G, West C, Diamond JJ, Santana A, McCarville E, et al. The child asthma link line: a coalition-initiated, telephone-based, care coordination intervention for childhood asthma. J Asthma 2010;47:303-9.
117. Young HN, Havican SN, Griesbach S, Thorpe JM, Chewning BA, Sorkness CA. Patient and phaRmacist telephonic encounters (PARTE) in an underserved rural patient population with asthma: results of a pilot study. Telemed J E Health 2012;18:427-33.
118. McKibben S, De Simoni A, Bush A, Thomas M, Griffiths C. The use of electronic alerts in primary care computer systems to identify the over-prescription of short-acting beta2-agonists in people with asthma: a systematic review. NPJ Prim Care Resp Med 2017;27:30.
119. Kosse RC, Bouvy ML, de Vries TW, Koster ES. Evaluation of a mobile health intervention to support asthma self-management and adherence in the pharmacy. Int J Clin Pharm 2019;41:452-9.
120. Hollenbach JP, Cushing A, Melvin E, McGowan B, Cloutier MM, Manice M. Understanding clinicians' attitudes toward a mobile health strategy to childhood asthma management: a qualitative study. J Asthma 2017;54:754-60.
121. Roberts C, Sage A, Geryk L, Sleath B, Carpenter D. Adolescent preferences and design recommendations for an asthma self-management app: mixed-methods study. JMIR Form Res 2018;2:e10055.
122. Sage A, Roberts C, Geryk L, Sleath B, Tate D, Carpenter D. A self-regulation theory-based asthma management mobile app for adolescents: a usability assessment. JMIR Hum Factors 2017;4:e5.
123. Elias P, Rajan NO, McArthur K, Dacso CC. InSpire to promote lung assessment in youth: evolving the self-management paradigms of young people with asthma. Med 2 0 2013;2:e1.
124. Hui CY, McKinstry B, Walton R, Pinnock H. A mixed method observational study of strategies to promote adoption and usage of an application to support asthma self-management. J Innov Health Inform 2019;25:243-53.
125. Doyle R, Albright K, Hurley LP, Chávez C, Stowell M, Dircksen S, et al. Patient perspectives on a text messaging program to support asthma management: a qualitative study. Health Promot Pract 2019;20:585-92.
126. Gupta S, Lam Shin Cheung V, Kastner M, Straus S, Kaplan A, Boulet LP, et al. Patient preferences for a touch screen tablet-based asthma questionnaire. J Asthma 2019;56:771-81.
127. Merchant R, Inamdar R, Henderson K, Barrett M, Su JG, Riley J, et al. Digital health intervention for asthma: patient-reported value and usability. JMIR Mhealth Uhealth 2018;6:e133.
128. McWilliams A, Reeves K, Shade L, Burton E, Tapp H, Courtlandt C, et al. Patient and family engagement in the design of a mobile health solution for pediatric asthma: development and feasibility study. JMIR Mhealth Uhealth 2018;6:e68.
129. Foster JM, Reddel HK, Usherwood T, Sawyer SM, Smith L. Patient-perceived acceptability and behaviour change benefits of inhaler reminders and adherence feedback: a qualitative study. Respir Med 2017;129:39-45.
130. Roberts CA, Geryk LL, Sage AJ, Sleath BL, Tate DF, Carpenter DM. Adolescent, caregiver, and friend preferences for integrating social support and communication features into an asthma self-management app. J Asthma 2016;53:948-54.
131. Burnay E, Cruz-Correia R, Jacinto T, Sousa AS, Fonseca J. Challenges of a mobile application for asthma and allergic rhinitis patient enablement-interface and synchronization. Telemed J E Health 2013;19:13-8.
132. Foster J, Reddel HK. Adherence monitoring and inhaler reminders benefit GPs and patients in family practice settings. Am J Respir Crit Care Med 2018;201:A4832.
133. Callens S, Galot A, Lamas E. Legal aspects of personal health monitoring. Stud Health Technol Inform 2013;187:55-63.
134. Van Biesen W, Decruyenaere J, Sideri K, Cockbain J, Sterckx S. Remote digital monitoring of medication intake: methodological, medical, ethical and legal reflections. Acta Clin Belg 2019;23:1-8.
135. Campbell JL, Eyal N, Muslimenta A, Haberer JE. Ethical questions in medical electronic adherence monitoring. J Gen Intern Med 2016;31:338-42.
136. Shaker MS, Oppenheimer J, Grayson M, Stukus D, Hartog N, Hsieh EWY, et al. COVID-19: pandemic contingency planning for the allergy and immunology clinic. J Allergy Clin Immunol Pract 2020;8:1477-88.
137. Portnoy J, Waller M, Elliott T. Telemedicine in the era of COVID-19. J Allergy Clin Immunol Pract 2020;8:1489-91.
138. Portnoy J, Pandya A, Waller M, Elliott T. Telemedicine and emerging technologies for health care in allergy/immunology. J Allergy Clin Immunol 2020;145:445-54.
139. Spector SL, Kinsman R, Mawhinney H, Siegel SC, Rachelefsky GS, Katz RM, et al. Compliance of patients with asthma with an experimental aerosolized medication: implications for controlled clinical trials. J Allergy Clin Immunol 1986;77:65-70.
140. Kaye L, Gondalia R, Gonzalez C, Adams B, Zhu L, Quan P, et al. Electronic medication monitoring vs self-reported use of inhaled corticosteroids and short-acting $beta_2$-agonists in adult patients with uncontrolled asthma. J Allergy Clin Immunol 2020;145:AB59.
141. Apter AJ, Boston RC, George M, Norfleet AL, Tenhave T, Coyne JC, et al. Modifiable barriers to adherence to inhaled steroids among adults with asthma: it's not just black and white. J Allergy Clin Immunol 2003;111:1219-26.