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Mobile Health and Inhaler-Based Monitoring Devices for Asthma Management

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Abstract

Mobile health and web applications (apps), wearables, and other personal monitoring devices have tremendous potential to improve the management of asthma. Over 500 asthma-related apps, whether standalone or paired with sensors on inhalers, are currently available for health education, symptom recording, tracking of inhaler use, displaying environmental alerts and providing medication reminders. Benefits of these tools include the ability to longitudinally collect symptom, trigger, and inhaler usage data, allowing the detection of significant changes over time to help patients and their caregivers determine whether symptoms are worsening. In addition, data from external information sources, including weather, allergen and air quality reports can be integrated with user-specific data to enhance predictions on when patients may experience symptoms and/or need to avoid triggers. Barriers to adoption of asthma-related apps and inhaler-based devices include uncertain efficacy and effectiveness, potential high cost, sustained user engagement, and concerns about privacy. Moreover, ensuring the acceptability and utility of asthma management apps for individuals of all races/ethnicities, socioeconomic groups, ages, genders, and literacy levels is necessary. Based on studies thus far, mobile health apps and inhaler-based devices have great potential to serve as useful tools in the patient-doctor relationship and revolutionize asthma care.

Keywords

apps; asthma; inhaler; mobile health

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Introduction

Asthma, a chronic lung disease characterized by variable airflow limitation, affects 22 million Americans and costs the U.S. $81.9 billion annually.[1] No methods to prevent or cure asthma exist, but clinical therapy following established guidelines successfully controls symptoms in most patients.[2] Asthma management includes the identification and avoidance of triggers that worsen symptoms, and the proper use of appropriately prescribed inhaler medications. Patients do not always adhere to their asthma medication plans, with non-adherence estimates ranging between 30% and 70%.[3,4] Furthermore, patients who are adherent to their treatment plans may not use their inhalers appropriately, decreasing their effectiveness.[5-7] Thus, patient education, including guidance to improve inhaler technique, is an important aspect of asthma disease management.[8-13] Because asthma severity is determined partly based on frequency of symptoms and exacerbations, knowing whether patients are adhering to and properly using inhaler medications helps healthcare providers treat their patients with proper disease management strategies.[14] In addition to improving patient quality of life, improved asthma management is associated with reduced burden and costs to healthcare systems.[15,16]

Mobile health and web applications (apps), wearables, and other personal monitoring devices are becoming mainstream tools to assist patients in disease decision-making, with some models allowing patients to share data with healthcare providers.[17-19] Personal computer and smartphone use is widespread in the U.S., with over 77% of Americans owning smartphones in 2018.[20] Because of the ubiquity of internet-connected devices and the fact that smartphones are becoming the main source of contact for most people, the digital health marketplace has surged over the past decade.[21] Android and Apple devices are the main platforms used for app development, and Apple created two software frameworks fit specifically for developers of healthcare apps. ResearchKit (released March 2015) was designed to assist in medical research patient enrollment and data collection, and CareKit (released March 2016) was designed for patient-centered disease self-management (http://www.apple.com/researchkit/). As evidenced by the growth of asthma-related apps and devices, as well as publications related to their design and use, [17,22-24] there has been sustained interest in the use of asthma management apps and devices as a means to improve health outcomes and facilitate research studies. Here, we summarize mobile health and inhaler-based monitoring devices available for asthma management, discuss the promise and demonstrated utility of such tools, and review barriers that must be overcome to enable their widespread use for disease self-management and to improve health.

Synopsis of Asthma Mobile Health Applications

Many asthma apps have been produced over the past decade, offering functions that span health education, symptom tracking, environmental alerts, and medication reminders. The number of asthma apps continues to grow: we reported 209 English-language asthma-related apps in the Apple Store and/or Google Play in a 2015 review,[22] and that number is now over 500. The few current standalone asthma apps with research reporting their ability to improve asthma management are summarized in Table 1.

The Asthma Mobile Health Study, one of the first Apple ResearchKit apps tested to demonstrate the feasibility of using health apps, is one of the largest asthma mobile health tracking efforts.[25] In this study, 7,593 participants in the U.S. were monitored remotely by smartphone. Data gathered, which consisted of self-reported symptoms over a 6-month period, showed expected regional trends based on environmental characteristics (e.g., increased symptoms in regions with more pollen). Challenges encountered were broadly valuable to inform mobile health research efforts. Specifically, the initial enthusiasm of using the app decreased quickly over time, there was selection bias in those enrolling and providing information, and data security concerns limited some subjects' willingness to share data. For example, demonstrating high up-front enrollment with waning interest, 6,470 subjects responded to at least one question, but only 175 completed a 6-month milestone survey. The app used in this study was withdrawn when the study was completed.

The "Physician on call patient engagement trial" (POPET) was a clinical trial that measured the impact of a mobile patient engagement application on quality of life and health outcome measures for patients with allergic rhinitis and asthma.[26] The study enrolled 136 asthma patients and 12 physicians (6 ear, nose and throat and 6 chest specialists) in Turkey. Patients were provided with the POPET app, which allowed users to submit their overall health status on a 7-point scale with an emoticon, share a 140 character status update, send and receive messages, ask for immediate assistance with an urgent message option, track medication use with a diary, receive automated reminders according to the patient's prescribed treatment plan, and, for asthma patients, complete the Asthma Control Test (ACT) within 24 hours after enrollment and 3 months later. Physicians were allowed to view a list of their patients in order of severity of health status, respond to message with texts or likes, view all of their patients' input, and broadcast messages or multimedia simultaneously. The study found that patients who received intervention with POPET had improved clinical outcomes, including better controlled asthma and fewer unplanned hospitalizations and emergency department visits. Thus, digital communication was found to be an important tool for the future of healthcare.

Synopsis of Inhaler-Based Monitoring Devices

Because self-management in assessing symptoms and adhering to medication regimens are especially important, people with asthma may be particularly interested in apps that are paired with sensors on inhalers to offer help with symptom and inhaler use monitoring. Apps that include sensors on inhalers can also be used to benefit people broadly. For example, a recent report used integrated sensor data corresponding to rescue medication use with measures of particulate matter to quantify cost savings and illustrate decreased health care utilization that occurs with pollution reduction.[27] Currently available inhaler-based monitoring devices use various approaches to measure adherence, including capturing the time and date of medication use, recording audio during inhaler use, and providing telemonitoring based on remotely captured spirometry measures. Pharmaceutical companies are using some of these tools to monitor medication adherence during clinical studies and better understand circumstances surrounding medication use. Table 2 contains a summary of inhaler-based monitoring devices with apps paired to them, along with studies providing evidence that their use improved asthma management.

A sensor made by Propeller Health that attaches to both rescue and controller inhaler devices and can record date, time and number of puffs taken, is one of the most extensively evaluated. When paired with its app, data from the sensor can be matched with a person's location (obtained from a smartphone's GPS coordinates). The app also serves to record patient triggers and symptoms, and can integrate online data streams (e.g., weather) to provide comprehensive reports of data relevant to asthma management. In a 2013 pilot study, 30 individuals used these sensors along with their corresponding app for four months, resulting in preliminary evidence that asthma control could improve by use of this digital health platform.[28] A subsequent randomized control trial in 495 patients, with 245 receiving routine care and 250 receiving Propeller Health sensor-based feedback, found that those receiving sensor-based feedback had decreased daily short-acting beta agonist (SABA) use during the study period (up to 1 year per person), with an effect that was more pronounced among those participants who began the trial with uncontrolled asthma. The mean daily SABA per person for the study period was 0.25 in routine care arm versus 0.19 in intervention arm.[29] Although the decrease in SABA use was quite small and may not have clinical meaning, the ACT scores of adults who initially had uncontrolled asthma and received feedback were improved relative to those receiving usual care. Another report evaluated the Propeller Health digital platform that displayed results in a provider-facing web interface and found that asthma-related ED visits and hospitalizations decreased with platform use.[30] An additional study of 120 participants enrolled in a single-arm trial of the Propeller Health digital platform found that SABA use dropped by 39%, and symptom-free days increased by 12%.[31] Propeller Health has received eight U.S. Federal Drug Administration (FDA) approvals for its devices and apps since 2012, and is currently being used in a variety of studies, including collaborations with Novartis and GlaxoSmithKline.

The SmartTrack device, which pairs with the Hailie app, is a tool focused on improving medication adherence by recording the date and time of actuations, the total number of actuations used, and missed doses. The app displays long-term use and trends in activity and can provide reminder notifications so that a person uses their inhalers on schedule. Preliminary testing of the device in ten participants found that its reliability and utility for data upload, reminders, and display of medication use over time were acceptable.[32] A subsequent study of the SmartTrack device involving 220 participants, with an intervention consisting of ringtone reminders that rung twice daily and stopped when a person's correct dose was used (reminders were automatically stopped if the proper dose was taken within six hours before the set time), showed that the intervention group had 84% adherence by the end of the study, while the control group had 30% adherence.[33]

While SmartTrack is focused primarily on medication reminders and tracking of actuations, and Propeller Health also integrates geospatial information, the INhaler Compliance Assessment device (INCA) is an alternative tool that, in addition to adherence, can be used to assess proper inhaler technique. Specifically, INCA creates audio recordings as a person uses an inhaler device, and based on analysis of sound, can determine whether there was proper inhaler technique by measuring time-stamped failure to prime, low inhalation flow, and dose dumping. This data can be used to determine when less medication is delivered due to inhaler technique errors, and thus, the INCA device can be used to assess differences between "attempted" adherence, or adherence based on time of medication use and "actual" adherence, or adherence based on proper use of the inhaler.[34] In one report based on 184 persons with COPD, the mean rate of controller medication attempted adherence was 58.7%, while actual adherence was only 23% and only 7% of participants had actual adherence above 80%, underscoring the importance of providing patients with tools to learn proper inhaler technique.[35] The INCA device is currently being evaluated for its ability to improve uncontrolled asthma in the Inhaler Compliance Assessment Device in Symptomatic Uncontrolled Asthma (INCA Sun) study[36].

Teva's ProAir Digihaler is the first digital inhaler with built-in sensors to be approved by the FDA.[37,38] An accompanying smartphone app is set to be released for both Google and iOS systems, and the national launch of the app and inhaler is set for 2020. A pilot study of 360 participants showed that a predictive model created with data recorded by the Digihaler predicted asthma exacerbations with an area under the receiver operating characteristic curve (AUC) of 0.75.[39] The most predictive factor in the model was the average number of albuterol inhalations per day during a period of five days before an exacerbation. In addition to monitoring time of use, the inhaler sensors are able to detect whether the inhaler was used correctly via measures of peak inspiratory flow, inhalation duration, and other metrics. Further studies have not evaluated the efficacy of Digihalers, however, its pilot data and FDA approval support the movement towards more sensor-based data collection to improve inhaler use and asthma self-management.

Potential Benefits of Using Mobile Health and Inhaler-Based Monitoring Devices for Asthma Management

The ability to longitudinally collect symptom, trigger, and inhaler usage data from individuals with asthma permits the detection of significant changes over time to help patients and their caregivers determine whether symptoms are worsening. Data from external information sources, including weather, allergen and air quality reports can be integrated with user-specific data to enhance predictions on when patients may experience symptoms and/or need to avoid triggers. For this data from external sources to be effective in asthma management, summaries of the relationships among symptoms, triggers, and inhaler usage must be presented appropriately to patients and their caregivers to reinforce positive behaviors (e.g., medication adherence) and provide alerts when symptoms are expected to worsen (e.g., downward pulmonary function trend, increased triggers). Similarly, appropriately summarized data from apps and inhaler-based monitors can be integrated into data streams facing healthcare providers to help them determine whether medication plans should be altered or if further education on adherence or inhaler usage is needed.

Due to the importance of proper inhaler technique and medication adherence in asthma management, education on app and inhaler-based device usage is essential, whether included in app materials or provided via in-person education prior to long-term use. Monitoring use of controller medications for asthma (e.g., inhaled corticosteroids) is most valuable to assess medication adherence, while tracking use of rescue medications (i.e., β_2-agonists) is valuable to both assess medication adherence and determine when symptoms are worsening. Beyond monitoring individuals, integrating data on rescue medication usage more broadly can point to geographic regions or events that trigger symptoms in large numbers of people, and thus, advise susceptible individuals on regions or events that should be avoided as well as suggest potential community-level interventions to improve health.[40]

As the above studies show, the effective combination of educational material and actionable feedback into apps, including those paired with inhaler-based monitoring devices, could support population care of individuals with asthma and enhance personalized interventions informed by patient-specific data. Thus, when apps and inhaler-based monitoring devices for disease self-management are designed as telehealth interventions to enable shared decision-making and proactive care by both patients and healthcare providers—core elements of the chronic care model [41,42]—they have the potential to improve health care performance. Use of the apps with effective feedback shifts chronic disease management from a reactive position, in which patients seek care after a problem has occurred, to a proactive stance in which at-risk patients are identified early and supported to avoid exacerbations. Clinical decision support systems can be built to aid healthcare providers in identifying individuals who are not adhering to recommended treatment, are at risk for exacerbations, and/or have uncontrolled disease. Alternatively, individuals with asthma can use information gathered from such apps to seek care and share data with providers at the point of care. The end result of either system would be improved health care performance.

Barriers to the Adoption of Mobile Health and Inhaler-Based Monitoring Devices

Some progress has been made in the evaluation of apps and inhaler devices to establish their utility, but barriers remain for asthma apps to be widely adopted by patients or recommended by providers. First, few efficacy and effectiveness studies have been conducted or demonstrated effectiveness of mobile health and inhaler-based monitoring devices for asthma. No accepted measure of app quality exists, and apps are not regulated or approved by the FDA unless they involve connection to a regulated medical device for the purposes of controlling its operation, function, or energy source, and displaying, transferring, storing, or converting patient-specific medical device data, which few do. Because there is no standard measure or approach to determine whether apps are of high quality, comparison of various apps is challenging. Some independent organizations have noted this knowledge gap and efforts to create frameworks for assessing healthcare apps are underway.

Another potential barrier to adoption of mobile health devices is cost. Inhaler-based monitoring devices are expensive for some patients to pay out-of-pocket, especially since the data to support their use is based on relatively small studies. If health insurers were to cover the cost of inhaler-based monitoring devices, demonstrations of widespread effectiveness would be needed. Increasing affordability of such devices may increase the rate of adoption.

For data from apps and inhaler-based monitoring devices to be most useful to healthcare providers, they must be integrated seamlessly into existing electronic health record (EHR) systems or other provider-facing dashboards. Accomplishing this important task requires local information technology support and can be slowed by local processes and regulations.

While the technology and standards to integrate app data into EHRs exist,[43,44] healthcare providers already face more data streams and alerts than they can effectively pay attention to, and thus, designing and testing the integration of app data looms as another potentially laborious process that may bring negative results.[45] Further, some providers may have concerns regarding liability they incur when recommending apps/devices to patients, monitoring data collected by the apps, and responding to potential alerts. Including input from healthcare providers is thus critical when a goal of apps/devices is their eventual integration into clinical practice.

Usability of apps and devices, as well as human factors issues, are critical considerations for initial and sustained user engagement, yet they are not sufficiently considered in studies published thus far.[46,47] To overcome barriers related to engagement, usability evaluation sessions should be conducted in the early stages of design, in pilot tests, and subsequently, during formal evaluation studies, as doing so reduces costs and increases the likelihood of technology adoption in the long run. Strategies for increased engagement include gamification (present in several educational tools), personalized recommendations (e.g., Propeller Health app) and incorporating persuasive design/behavior change principles, which is a prominent predictor of adherence to apps.[48] A successful model of the application of user-centered design principles to create an asthma mHealth app is that by Rudin and colleagues: their team conducted 19 design sessions with nine adult patients and seven clinicians to identify core components of a symptom monitoring tool prior to actually building one.[49]

In addition to sustaining user interest, apps must also ensure data privacy and security before some individuals will be comfortable using them and healthcare providers will feel comfortable recommending them. Apps that involve tracking individual locations and for which individuals enter personal data are the most vulnerable for loss of privacy or possible unwanted disclosure of personal health information. One study that systematically assessed availability of privacy statements for the most commonly used apps found that only 30% had privacy statements that addressed whether entered information could be shared with third parties.[50]

Finally, greater reliance on apps and inhaler-based monitoring devices for asthma management necessitates an understanding of the acceptability and utility of these tools among *all* patients, including those who are disproportionately affected by diseases. In the case of asthma, tools must be designed to address the concerns and barriers faced by racial/ethnic minority groups, women, children, and those of low socioeconomic status, all of whom are disproportionately affected by asthma.[51,52] Evidence exists showing that digital interventions targeting asthma populations at greatest risk are helpful,[13] but digital health tools must continue to be designed and tested in these populations while considering their cost. The design of apps/technology for asthma management across the lifespan will continue to differ, as children (and their parents) require different strategies than adults, but it is possible that single apps may offer different displays to engage users of different ages. With the effective design, adoption, and use of asthma apps and inhaler devices, asthma morbidity may be reduced in high-risk groups.

Conclusion

Mobile health and inhaler-based devices have great potential to revolutionize care for asthma by becoming mainstream tools to assist patients in self-monitoring and decision-making, especially patients with persistent asthma and those who have difficulty keeping symptoms under control. Although the number of asthma apps and inhaler-based monitoring devices is rapidly increasing, most are currently limited by the lack of demonstrated efficacy and effectiveness. Initial use of such tools has found that sustaining user engagement is challenging and some people have concerns with data privacy. Potential high costs are also a salient limitation for the widespread use of inhaler-based monitoring devices. Addressing these barriers as the asthma mobile health landscape expands is critical. Future efforts that evaluate individual apps, as well as compare usability and effectiveness of various apps in single studies, are necessary to provide evidence regarding their suitability for clinical use.

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Abbreviations

ACT	Asthma Control Test
DPI	dry powdered inhaler
ED	emergency department
HA	human augmentics
MDI	metered dose inhaler
pMDI	pressurized metered dose inhaler
SABA	short-acting beta agonist
SPV	social persuasive visualization

References

1. Nurmagambetov T, Kuwahara R, Garbe P. The Economic Burden of Asthma in the United States, 2008-2013. Ann Am Thorac Soc. 2018;15:348–56. [PubMed: 29323930]
2. Fanta CH. Asthma. N Engl J Med. 2009;360:1002–14. [PubMed: 19264689]
3. Desai M, Oppenheimer JJ. Medication adherence in the asthmatic child and adolescent. Curr Allergy Asthma Rep. 2011;11:454–64. [PubMed: 21968618]
4. Engelkes M, Janssens HM, de Jongste JC, Sturkenboom MCJM, Verhamme KMC. Medication adherence and the risk of severe asthma exacerbations: a systematic review. Eur Respir J. 2015;45:396–407. [PubMed: 25323234]
5. Gillette C, Rockich-Winston N, Kuhn JA, Flesher S, Shepherd M. Inhaler Technique in Children With Asthma: A Systematic Review. Acad Pediatr. 2016;16:605–15. [PubMed: 27130811]
6. Pepper AN, Cooke A, Livingston L, Lockey RF. Asthma and chronic obstructive pulmonary disease inhalers: Techniques for proper use. Allergy Asthma Proc. 2016;37:279–90. [PubMed: 27401315]

7. Kocks JWH, Chrystyn H, van der Palen J, Thomas M, Yates L, Landis SH, et al. Systematic review of association between critical errors in inhalation and health outcomes in asthma and COPD. NPJ Prim Care Respir Med. 2018;28:43. [PubMed: 30446655]
8. Klijn SL, Hiligsmann M, Evers SMAA, Román-Rodríguez M, van der Molen T, van Boven JFM. Effectiveness and success factors of educational inhaler technique interventions in asthma & COPD patients: a systematic review. NPJ Prim Care Respir Med. 2017;27:24. [PubMed: 28408742]
9. Soones TN, Lin JL, Wolf MS, O'Conor R, Martynenko M, Wisnivesky JP, et al. Pathways linking health literacy, health beliefs, and cognition to medication adherence in older adults with asthma. J Allergy Clin Immunol. 2017;139:804–9. [PubMed: 27555454]
10. Koumpagioti D, Boutopoulou B, Priftis KN, Douros K. Effectiveness of an educational program for children and their families on asthma control treatment adherence. J Asthma Off J Assoc Care Asthma. 2019; 1–7.
11. Plaza V, Peiro M, Torrejon M, Fletcher M, Lopez-Vina A, Ignacio JM, et al. A repeated short educational intervention improves asthma control and quality of life. Eur Respir J. 2015;46:1298–307. [PubMed: 26405291]
12. Capstick TG, Clifton IJ. Inhaler technique and training in people with chronic obstructive pulmonary disease and asthma. Expert Rev Respir Med. 2012;6:91–101; quiz 102–3. [PubMed: 22283582]
13. Perez L, Morales KH, Klusaritz H, Han X, Huang J, Rogers M, et al. A health care navigation tool assesses asthma self-management and health literacy. J Allergy Clin Immunol. 2016; 138:1593–1599.e3. [PubMed: 27744030]
14. Mokoka MC, McDonnell MJ, MacHale E, Cushen B, Boland F, Cormican S, et al. Inadequate assessment of adherence to maintenance medication leads to loss of power and increased costs in trials of severe asthma therapy. Results from a systematic literature review and modelling study. Eur Respir J. 2019;
15. Klok T, Kaptein AA, Brand PLP. Non-adherence in children with asthma reviewed: The need for improvement of asthma care and medical education. Pediatr Allergy Immunol. 2015;9.
16. Morton RW, Everard ML, Elphick HE. Adherence in childhood asthma: the elephant in the room.: 5.
17. Himes BE, Weitzman ER. Innovations in health information technologies for chronic pulmonary diseases. Respir Res. 2016;17:38. [PubMed: 27048618]
18. Fedele DA, Cushing CC, Fritz A, Amaro CM, Ortega A. Mobile Health Interventions for Improving Health Outcomes in Youth: A Meta-analysis. JAMA Pediatr. 2017;171:461–9. [PubMed: 28319239]
19. Dimitrov DV. Medical Internet of Things and Big Data in Healthcare. Healthc Inform Res. 2016;22:156–63. [PubMed: 27525156]
20. Mobile Fact Sheet [Internet]. Washington, D.C: Pew Research Center; 2018 2 Available from: https://www.pewinternet.org/fact-sheet/mobile/
21. Labrique A, Vasudevan L, Mehl G, Rosskam E, Hyder AA. Digital Health and Health Systems of the Future. Glob Health Sci Pract. 2018;6:S1–4. [PubMed: 30305334]
22. Wu AC, Carpenter JF, Himes BE. Mobile health applications for asthma. J Allergy Clin Immunol Pr. 2015;3:446–8 e1-16.
23. Blaiss MS. Asthma mobile applications: Are they ready for prime time? Ann Allergy Asthma Immunol Off Publ Am Coll Allergy Asthma Immunol. 2018;120:347–8.
24. Kagen S, Garland A. Asthma and Allergy Mobile Apps in 2018. Curr Allergy Asthma Rep. 2019;19:6. [PubMed: 30712150]
25. Chan Y-FY, 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. [PubMed: 28288104]
26. 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. [PubMed: 25856270]

27. Williams AM, Phaneuf DJ, Barrett MA, Su JG. Short-term impact of PM2.5 on contemporaneous asthma medication use: Behavior and the value of pollution reductions. Proc Natl Acad Sci U S A. 2019;116:5246–53. [PubMed: 30478054]
28. 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. [PubMed: 23460785]
29. 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 Pr [Internet]. 2016; Available from: http://www.ncbi.nlm.nih.gov/pubmed/26778246
30. 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. [PubMed: 30524644]
31. 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 Off Publ Am Coll Allergy Asthma Immunol. 2017;119:415–421.e1.
32. Foster JM, Smith L, Usherwood T, Sawyer SM, Rand CS, Reddel HK. The reliability and patient acceptability of the SmartTrack device: a new electronic monitor and reminder device for metered dose inhalers. J Asthma Off J Assoc Care Asthma. 2012;49:657–62.
33. Chan AHY, 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. [PubMed: 25617215]
34. Sulaiman I, Seheult J, Sadasivuni N, MacHale E, Killane I, Giannoutsos S, et al. The Impact of Common Inhaler Errors on Drug Delivery: Investigating Critical Errors with a Dry Powder Inhaler. J Aerosol Med Pulm Drug Deliv. 2017;30:247–55. [PubMed: 28277810]
35. Moran C, Doyle F, Sulaiman I, Bennett K, Greene G, Molloy GJ, et al. The INCATM (Inhaler Compliance AssessmentTM): A comparison with established measures of adherence. Psychol Health. 2017;32:1266–87. [PubMed: 28276739]
36. 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. [PubMed: 27587321]
37. Teva Announces FDA Approval of ProAir® Digihaler™ | Asthma and Allergy Foundation of America [Internet]. [cited 2019 Aug 16]. Available from: https://community.aafa.org/blog/teva-announces-fda-approval-of-proair-digihaler
38. Teva's ProAir Digihaler FDA Approved to Monitor Asthma and COPD Treatment | Medgadget [Internet]. [cited 2019 Aug 16]. Available from: https://www.medgadget.com/2018/12/tevas-proair-digihaler-fda-approved-to-monitor-asthma-and-copd-treatment.html
39. Safioti G, Granovsky L, Li T, Reich M, Cohen S, Hadar Y, et al. A Predictive Model for Clinical Asthma Exacerbations Using Albuterol eMDPI (ProAir Digihaler): A 12-Week, Open-Label Study. :2.
40. Su JG, Barrett MA, Henderson K, Humblet O, Smith T, Sublett JW, et al. Feasibility of Deploying Inhaler Sensors to Identify the Impacts of Environmental Triggers and Built Environment Factors on Asthma Short-Acting Bronchodilator Use. Environ Health Perspect. 2017;125:254–61. [PubMed: 27340894]
41. Bodenheimer T, Wagner EH, Grumbach K. Improving primary care for patients with chronic illness. JAMA. 2002;288:1775–9. [PubMed: 12365965]
42. Bodenheimer T, Wagner EH, Grumbach K. Improving primary care for patients with chronic illness: the chronic care model, Part 2. JAMA. 2002;288:1909–14. [PubMed: 12377092]
43. Mandl KD, Mandel JC, Murphy SN, Bernstam EV, Ramoni RL, Kreda DA, et al. The SMART Platform: early experience enabling substitutable applications for electronic health records. J Am Med Inform Assoc JAMIA. 2012;19:597–603. [PubMed: 22427539]
44. Day FC, Pourhomayoun M, Keeves D, Lees AF, Sarrafzadeh M, Bell D, et al. Feasibility study of an EHR-integrated mobile shared decision making application. Int J Med Inf. 2019;124:24–30.

45. Backman R, Bayliss S, Moore D, Litchfield I. Clinical reminder alert fatigue in healthcare: a systematic literature review protocol using qualitative evidence. Syst Rev. 2017;6:255. [PubMed: 29237488]

46. Wildenbos GA, Peute LW, Jaspers MWM. Influence of Human Factor Issues on Patient-Centered mHealth Apps' Impact; Where Do We Stand? Stud Health Technol Inform. 2016;228:190–4. [PubMed: 27577369]

47. Maramba I, Chatterjee A, Newman C. Methods of usability testing in the development of eHealth applications: A scoping review. Int J Med Inf. 2019;126:95–104.

48. Baumel A, Yom-Tov E. Predicting user adherence to behavioral eHealth interventions in the real world: examining which aspects of intervention design matter most. Transl Behav Med. 2018;8:793–8. [PubMed: 29471424]

49. Rudin RS, Fanta CH, Predmore Z, Kron K, Edelen MO, Landman AB, et al. Core Components for a Clinically Integrated mHealth App for Asthma Symptom Monitoring. Appl Clin Inform. 2017;8:1031–43. [PubMed: 29241243]

50. Sunyaev A, Dehling T, Taylor PL, Mandl KD. Availability and quality of mobile health app privacy policies. J Am Med Inform Assoc JAMIA. 2015;22:e28–33. [PubMed: 25147247]

51. Forno E, Celedón JC. Health disparities in asthma. Am J Respir Crit Care Med. 2012;185:1033–5. [PubMed: 22589306]

52. Greenblatt R, Mansour O, Zhao E, Ross M, Himes BE. Gender-specific determinants of asthma among U.S. adults. Asthma Res Pract. 2017;3:2. [PubMed: 28138394]

53. Burbank AJ, Lewis SD, Hewes M, Schellhase DE, Rettiganti M, Hall-Barrow J, et al. Mobile-based asthma action plans for adolescents. J Asthma Off J Assoc Care Asthma. 2015;52:583–6.

54. Ryan D, Price D, Musgrave SD, Malhotra S, Lee AJ, Ayansina D, et al. Clinical and cost effectiveness of mobile phone supported self monitoring of asthma: multicentre randomised controlled trial. BMJ. 2012;344:e1756. [PubMed: 22446569]

55. Ahmed S, Ernst P, Bartlett SJ, Valois M-F, 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. [PubMed: 27908846]

56. 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. [PubMed: 23936890]

57. 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 [Internet]. 2019 [cited 2019 Mar 13];7 Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6369424/

58. Lau AYS, Arguel A, Dennis S, Liaw S-T, 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. [PubMed: 26678294]

59. 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 Off Publ Am Coll Allergy Asthma. Immunol. 2018;120:395–400.e1.

60. Managing Asthma with Your Smartphone | Division of Allergy & Immunology | Albert Einstein College of Medicine [Internet]. [cited 2019 May 17]. Available from: https://www.einstein.yu.edu/Managing-Asthma-With-Smartphone.aspx

61. Adapting and Expanding the Asthma-Educator App - Full Text View - ClinicalTrials.gov [Internet]. [cited 2019 May 17]. Available from: https://clinicaltrials.gov/ct2/show/NCT03930381

62. Taylor TE, Zigel Y, Egan C, Hughes F, Costello RW, Reilly RB. Objective Assessment of Patient Inhaler User Technique Using an Audio-Based Classification Approach. Sci Rep. 2018;8:2164. [PubMed: 29391489]

63. Charles T, Quinn D, Weatherall M, Aldington S, Beasley R, Holt S. An audiovisual reminder function improves adherence with inhaled corticosteroid therapy in asthma. J Allergy Clin Immunol. 2007;119:811–6. [PubMed: 17320942]

64. Melvin E, Cushing A, Tam A, Kitada R, Manice M. Assessing the use of BreatheSmart® mobile technology in adult patients with asthma: a remote observational study. BMJ Open Respir Res. 2017;4:e000204.

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. [PubMed: 28193465]

Table 1.

Standalone Apps for Asthma Management. A selection of mobile applications that have been evaluated for their ability to improve asthma control.

App Name	Major Function	Secondary Functions	Study Population Characteristics	Evidence/Impact
Health App	Tracks symptoms and peak flow	-Receives customized advice -Medication reminders -General asthma information reminders	20 patients aged 12-17 year with persistent asthma recruited from pediatric specialty clinics at Arkansas Childrens Hospital	ACT score improved from 16 to 18 and asthma attack prevention domain improved from 34 to 36 [53]
t+ Asthma App	Tracks symptoms, drug use, and peak flow	-Sends information from patient to provider	288 patients aged 12+ years with poorly controlled asthma recruited from UK primary care practices	No significant change in asthma control, exacerbations, steroid courses, or unplanned clinic visits[54]
My Asthma Portal App (MAP) (web based application)	Tracks symptoms,physical activity, and medication	-Real-time feedback and monitoring from a nurse	100 patients aged 18-69 years with poor asthma control recruited from pulmonary clinics in two tertiary care hospitals located in Montreal,Canada	Increased quality of life but no better control over asthma [55]
POPET App (Physician On-call Engagement Trial)	Tracks health and medication compliance	-Sends information from patient to provider	136 patients aged 25-41 years with a diagnosis of mild to severe persistent asthma recruited from Pulmonary Diseases Departments across Turkey	ACT score improved [26]
SPA (Smartphone Application)	Tracks symptoms	-Receives environmental alerts and treatment advice	22 patients aged 18+ years with a physician diagnosis of asthma who reported symptoms worsening with exposure to air pollution recruited from the Primary Care Asthma Program in Windsor, Ontario.	Quality of life improved [56]
Breathe App (Available on iOS)	Tracks symptoms	-Gives customized advice based on asthma action plan -General asthma information -Send warning and risk reminders	344 patients with asthma and mean age 45.3 years recruited from six primary care and two specialty asthma clinics in Ontario, Canada.	Increased adherence to control plan and quality of life[57]
PCHMS App (Personally Controlled Health Management System)	Gives information on asthma and management tools	-Access to medical records	330 patients aged 18+ years with asthma recruited via advertisement through Asthma Foundation Australia and the National Asthma Council Australia.	No decreased hospitalization or increased adherence to asthma action plan [58]
AsthmaCare App*	Medication and treatment plan reminders	-Trigger reminders	239 patients aged 6 months to 21 years with persistent asthma were recruited when presenting with an asthma exacerbation to the Emergency Department from Nationwide Children's Hospital in Columbus, Ohio.	No decrease in hospital visits however increased asthma control 6 months later[59]
ASTHMAXcel App (Available on iOS)	Videos teach about how and when to use inhalers and spacers	-Teaches how to reduce triggers at home	130 participants aged 15-21 years with persistent asthma recruited at Montefiore Medical Center, Bronx, NY	Decreased hospitalizations, increased control and quality of life[60,61]

Table 2.

Inhaler-Based Monitoring Devices Available for Asthma Management. A selection of inhaler-monitoring devices, along with mobile applications, that may improve asthma control.

Device Name	Device Function	Corresponding App	Data/Results Reported	Study Population Characteristics	Evaluation
Inhaler Complianc e Assessmen t (INCA)	Time-stamped audio recording of inhaler use.	Onboard data storage / no app	Raw audio files must be transferred to a computer for analysis.	184 participants with mean age 70.9 +/− 9.65 years and asthma recruited at an academic teaching hospital in Dublin, Ireland	-Can measure impact of technique errors (failure to prime inhaler, low inhalation flow, dose dumping) on reduced medication delivery [34] -Can distinguish between intentional and unintentional adherence [35]
Flo-Tone	Inhaling speed and volume can be measured by sound and length of inhalation. Measures if user coordinates actuation with inhalation.	No data storage	Inhalation causes a whistle to sound as a signal to dispense medication. Keeping the whistle sounding is indicative of good technique. The function of the device is to give feedback on and improve inhaler usage technique.	62 patients aged 17-82 years with asthma (n=30) COPD (n=27) and asthma+COPD (n=5) were recruited from both in-patient wards and outpatient respiratory clinics at Beaumont Hospital, Dublin, Ireland	-Analysis of the audio-based method of data collection showed a frame-by-frame accuracy of 88.2% in classifying actuation, inhalation and exhalation. The analysis showed that 89% of patients made at least one technique error, even after training by an expert clinical reviewer [62]
SmartTrack	Records date, time, and number of actuations used, missed doses, and when inhaler is inserted and removed.	Hailie	App displays data to help track medication usage; provides alerts when medications are missed.	2,045 patients aged 6-15 years were recruited when admitted to the Auckland regional emergency department with a possible asthma diagnosis	-Use of device resulted in 84% median percentage of adherence in an intervention group versus 30% in control group [33]
SmartInhal er	-Records date and time of inhaler use. -Emits an audible reminder at preset times. -The device has a light, which is green before MDI use, changing to red once used.	Onboard data storage	Sensor data can be sent to a computer with a communication link, USB, or cellular upload for analysis.	110 patients aged 12-65 years with a diagnosis of asthma were recruited from research volunteer databases, newspaper advertisements, and informal contacts in Wellington, New Zealand.	-Those using device as intervention adhered to medication use 18% percentage points more than the control group; more participants in the intervention group used >50%, >80%, and >90% of their medication, with proportion ratios of use (compared to the control group) being 1.33, 2.27, and 3.25, respectively [63]
Propeller Health	-Records date and time of inhaler use -Records geographic location of use via the paired smartphone app	Propeller Health	-Records symptoms, medication usage, and environmental factors -Tracks inhaler usage data automatically so triggers and symptoms can be followed and recorded-customizable schedule available to set medication reminders -Uses the ACT or CAT to assess control of asthma or COPD, respectively -Integrates data to be able to see inhaler use along with possible triggers -App can send information from patient to the provider.	Barrett et al 2017: 120 participants aged 5- 67 years with a physician diagnosis of asthma were recruited from community asthma activities, clinics, and retail pharmacies. Merchant et al 2018: 224 patients aged 3-88 years old with a diagnosis of asthma were recruited during routine asthma care in specialty and primary care clinics. Merchant et al 2016: 495 participants with a mean age of 36 years with a diagnosis of asthma were recruited from Woodland Healthcare and Mercy Medical Group in Yolo and Scramento, California.	-Daily average SABA uses per person decreased by 0.41 for the intervention arm and by 0.31 for control arm between the first week and the remainder of the study period [29] -Asthma-related ED visits and combined ED and hospitalization events decreased before and after use of Propeller Health system [30] - SABA use was shown to drop by 39%, and symptom-free days were shown to increase by 12% in first month of intervention; each intervention month showed an increase in percent of patients with well-controlled asthma [31]

Device Name	Device Function	Corresponding App	Data/Results Reported	Study Population Characteristics	Evaluation
HeroTrack er	Records date and time of inhaler use	Breathesmart	-Reminds users to take medication per prescribed plan -Tracks inhaler use over time -Permits symptom recording	100 study subjects aged 18+ years with a self-identified diagnosis asthma were recruited within the USA through social media websites and ad placements online.	-This device is currently being tested in a clinical trial [64]
Human Augmentic s (HA)	Records date and time of inhaler use	Social Persuasive Visualization (SPV) app – not publicly available	-Reminds users to take medication per prescribed plan -Tracks inhaler use over time -App developed specifically for use by minority adolescents using captology and the Elaboration Likelihood Model to persuade users to regularly adhere to medication	12 patients aged 11-16 years withpersistent asthma were recruited from Rush Pediatric Primary Care Center in Chicago, IL	-Pilot study showed an 83% acceptance rate and improved adherence. 8% and 58% of patients achieved clinically significant adherence targets at baseline and last week of the study period,respectively [65]
ProAir Digihaler	-Records date and time of inhaler use -Records peak inspiratory flow, volume inhaled, time to peak flow, and inhalation duration	ProAir Digihaler app	-Can share daily, weekly, and monthly reports of inhaler use with caregivers and healthcare professionals -Has a built-in electronic module which stores data on inhaler events	360 patients aged 18+ years with exacerbation prone-asthma	-Pilot study showed that data recorded by the Digihaler could predict asthma exacerbations with an area under the receiver operating characteristic curve (AUC) of 0.75 [39]