Assessing the technical feasibility of a flexible, integrated Internet-of-things connected for asthma (C4A) system to support self-management

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Research and Applications

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Assessing the technical feasibility of a flexible, integrated Internet-of-things connected for asthma (C4A) system to support self-management: a mixed method study exploring patients and healthcare professionals perspectives

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ABSTRACT

Background: A connected system with smart devices could transform patient care and empower patients control of their asthma.
Objective: To explore how a connected-for-asthma system (C4A) with smart devices from multiple companies (smart-inhaler; smart-watch; smart-peak-flow meter, manual digital thermometer during the Coronavirus disease (COVID)-pandemic) could support asthma self-management.
Methods: In a proof-of-concept mixed-methods study (Winter 2021/2022), we collected data from devices linked via the C4A app enabling patients to self-monitor and share a monitoring summary (in PDF format) with their clinician. Ten patients (range of age/gender, asthma experience, Apple/Android user) via social media, used C4A for a month. We conducted pre/post-interviews with patients, and a single post-interview with an asthma nurse and 3 general practitioners. Thematic analysis, informed by the Unified Theory of Acceptance and Use of Technology was triangulated with descriptive analysis of usage data.
Results: The system was perceived as "easy" to use. During the study, 7517 data points were collected from 10 patients; monitoring reduced over the month. Patients used devices if they trusted their "accuracy," and adopted the system to monitor new medication or assess troublesome symptoms. One patient lost contact (because of COVID), 8 wanted to keep using C4A to manage their asthma, though were selective about the most useful devices. Clinicians wanted the report to provide an asthma score/status and reliever usage.
Conclusion: A connected system could enable flexible digital care by linking data from several devices to support self-management. To promote adoption/adherence, setup has to be simple, and patients need to trust that the devices accurately reflect their condition.

Key words: asthma, supported self-management, telehealth, mobile application, Internet-of-things

Lay Summary

During the COVID pandemic, patients had to rely on remote consultations to help them to live with their conditions. We aimed to explore how a connected digital system (C4A) linking with smart devices (inhaler/watch/peak flow meter) and a manual thermometer, with an option to share a report with their clinician, could support patients to look after their asthma. We recruited 10 patients to use C4A, observed their usage over a month, and undertook pre/post-interviews. We also interviewed an asthma nurse and 3 general practitioners for their views on the report format. Most patients chose to monitor their reliever inhaler rather than the preventer. 7517 data were logged, though recording reduced over the month. Patients felt "positive," found it "easy" to use the system and chose to use devices they thought were "accurate." Monitoring medication adjustments, having asthma (or COVID) symptoms motivated them to adopt/use the system. Clinicians wanted an overall asthma score/status and reliever usage on the report. A connected system could enable flexible digital approaches to care by providing on-going self-management data to support remote consultation. However, providing users with confidence in the "accuracy" of systems is needed to maintain patients' motivation to use the system.

INTRODUCTION

Healthcare organizations are increasingly recognizing the benefits of digitally supported self-management, accelerated by the Coronavirus disease 2019 (COVID-19) pandemic when patients were given sensors (eg, oximeters) to monitor their condition at home, generating data that could be transferred to clinicians for review in several regions of the UK.[1–5] Monitoring by primary care practices, local COVID services and/or social service teams detected early signs of deterioration and provided timely advice and support to prevent or shorten hospital stays and enable earlier discharge.[6,7] This model could be adapted for long-term conditions not only enabling monitoring but supporting self-management to optimize outcomes.[8–11]

As an exemplar, asthma is a highly variable long-term condition affecting more than 300 million people worldwide,[12] and resulting in 6.3 million primary care consultations in the United Kingdom each year.[13] There is overwhelming evidence to show that the traditional model of supported self-management (with action plans provided in routine face-to-face reviews) improves asthma control.[14,15] Peak flow measurement and reliever inhaler usage are ways to detect deteriorating asthma control and can trigger use of an action plan, agreed with the patient's clinician, which advises when and how to modify medications, and when and how to access medical advice'. The need for self-isolation during the pandemic promoted interest in remote asthma reviews and digital approaches to supporting self-management.[16,17]

Connected systems to support self-management

Definition

A connected self-management system is an architecture that uses diverse sensors linked to a platform (app) to collect and collate data relevant to a long-term condition to support patients' self-management decisions, with an option to share monitoring data with a clinician.

Connected systems to support self-management build on a basic architecture of diverse sensory devices that collect, collate, and share self-monitoring data between patients and (as/when appropriate) their healthcare advisors. They have the capability to interoperate with sensors from different brands, care services, and research databanks via Application Programming Interface (API) or Software Development Kit (SDK), enabling patients to choose what they wish to monitor and customize their own self-management strategies.[18] A central "app" can facilitate easy connectivity with chosen devices (ideally "plug-and-play"); allow manual entry of symptoms, display other "unconnected' public data, as well as summarize status. It can potentially incorporate artificial intelligence, interpreting data to provide timely feedback and advice reinforcing or replicating clinicians' support. Adopting a human behavior model in the development of the connected technology will optimize acceptability.[19]

Human behavior models for technology adoption and adherence

Behavior change models explore factors that influence behavior. They often starting by identifying a target behavior, and ask how technology can be designed to change the individual's target behavior (eg, COM-B[20] and BJ Fogg[21]). Others assess engagement with the technology and behavior change techniques as prerequisites to engaging with behavior change (eg, "Big E/Little e")[22,23] (see Table 1 for the definition). Attitude change models, explore how an individual thinks and feels about a technology and the factors that influence adoption and usage (eg, Technology Acceptance model [TAM]; Unified Theory of Acceptance and Use of Technology [UTAUT]).[24,25] Perceived usefulness and ease of use are commonly cited factors in these models.[26]

UTAUT is a model synthesized from 8 human behavior models (TAM, Social Cognitive Theory, Theory of Reasoned Action, Motivational Model, Theory of Planned Behavior [TPB], Combined TAM-TPB, Model of PC Utilization and Innovation and Diffusion Theory[24]) and provides theoretical underpinning of the individual adoption process within the social context. It is widely used to explore patients' adoption process for the technology with clinicians as the end user.[26] We therefore used the UTAUT in this study and define the 4 constructs in Table 1.

These behavior change models can support developers to understand the factors that influence patients and clinicians to adopt and continue using a technology to support asthma self-management. Using contemporary technology development approaches (such as *Agile and Lean*), and implementation frameworks (eg, Non-adoption, Abandonment, Scale-up, Spread, Sustainability[27]) can further help developers to build use cases for individual patients, contributing important insights on the individual adoption processes.[28,29]

Table 1. Definition of the 4 constructs of the Unified Theory of Acceptance and Use of Technology (UTAUT) and other behavior models and measurements for digital interventions that underpin our C4A platform development and future evaluation

Definition of the 4 constructs of the Unified Theory of Acceptance and Use of Technology (UTAUT) for our asthma study.	
Performance expectancy (perceived usefulness/ advantage outcomes)	The degree to which a patient believes the connected system would support them, and that they personally and/or the wider asthma community would benefit.
Effort expectancy (perceived ease of use)	The complexity of the connected system and the degree to which a patient believes that use of the system would be effortless.
Social influence (social factors)	The patient's perception that most people (either a person who is important to them or people around the patient) think they should use the technology; or the degree to which a patient believes using the technology can enhance their image within the social community.
Facilitating conditions (facilitating conditions/compatibility)	The degree to which a patient believes the technology is available or compatible with use in their context.
Definition of the behavior models and measurements for digital interventions.	
COM-B[20]	A "behaviour system" involving 3 essential conditions: capability, opportunity, and motivation to achieve a target behavior.
BJ Fogg[21]	A behavior change model showing that motivation, ability, and a prompt must converge at the same moment for a behavior to occur.
The behavioral intervention technology model[22]	A framework for explaining how a "concatenation" of component interventions can combine to form an implementable treatment that achieves change.
Little e/Big E[23]	A hybrid model that provides the structure inform measurements of digital behavior change intervention effectiveness. • "Little e" is engagement with the digital behavior change intervention (comprising engagement with the user interface and engagement with techniques for changing behavior). • "Big E" is engagement with the targeted health behavior (the intended outcome of a digital behavior change intervention).

In our past studies, we identified patients and clinicians' preferred features on a connected system to support asthma self-management, and used the findings to build a prototype connected system (Connected for Asthma, C4A).[18,31,48] In this proof-of-concept study, we aimed to explore in a real-life setting whether an early prototype of a connected system was feasible technically, and gain insight into participants views to inform the next phase of development in preparation for future evaluation.

METHODS

Study design

We conducted a mixed method explanatory study[30] between December 2020 and February 2021 (in the context of a COVID lockdown). We triangulated app usage data, e-mail enquiries and qualitative interviews with purposively selected patients to explore how/why they adopted the connected system, and to understand any difficulties they encountered in setting up or using the system.

C4A

C4A is an integrated system, which connects CE-marked smart devices (Findair One smart inhaler, Polar smartwatch, MIR smart peak flow meter, Smart Asthma peak flow meter smart inhalers) within an app to support remote asthma self-management. C4A was invented by the research team to pull data directly from the devices via Bluetooth Low Energy (BLE) (smart peak flow meter) or the device app via the proprietary API (smart inhaler and smartwatch) (see Figures 1 and 2). The system features were designed based on patients and clinicians preferred features (action plan, monitoring, education) identified in our previous study[31] along with weather and pollution information and links to Asthma and Lung UK's nurse Whatsapp and asthma information.[32] Manual logging of body temperature was enabled because of the COVID pandemic. Patients decided how often to use the system according to their own preferences, including if and when to complete the action plan either by copying the information from their existing paper-based action plan or in discussion with their GP/asthma nurses.

Regulatory approvals

Ethical approval was provided by the South-East Scotland Research Ethics Committee 02 (ref: 20/SS/0081), NHS R&D (ref: 2020/0170; AC20077). It was sponsored by the University of Edinburgh and NHS Lothian (Academic and Clinical Central Office for Research and Development) and funded by the MRC Confidence in Concept (ref: MRC/CIC7/71). All participants provided their fully informed consent.

Patient and clinician recruitment

Patient recruitment

We included patients who were resident in the United Kingdom, 16 years or older and who were actively treating their asthma,[33] with inhalers that were compatible with the FindAIR ONE inhaler sensor and who owned a smart phone (Android 6.0.1/iOS12.4.8 or above) or tablet (Android 9/iOS 12.4 or above). Patients were asked to confirm the type of inhaler they were using in the eligible check and send a picture of their inhalers to the researcher, in order to confirm there asthma was "active" such that they required treatment with inhalers.[33] The smart inhaler sensors are device-specific, but include most of the commonly available inhalers in the United Kingdom, including reliever medication, inhaled steroids and combination

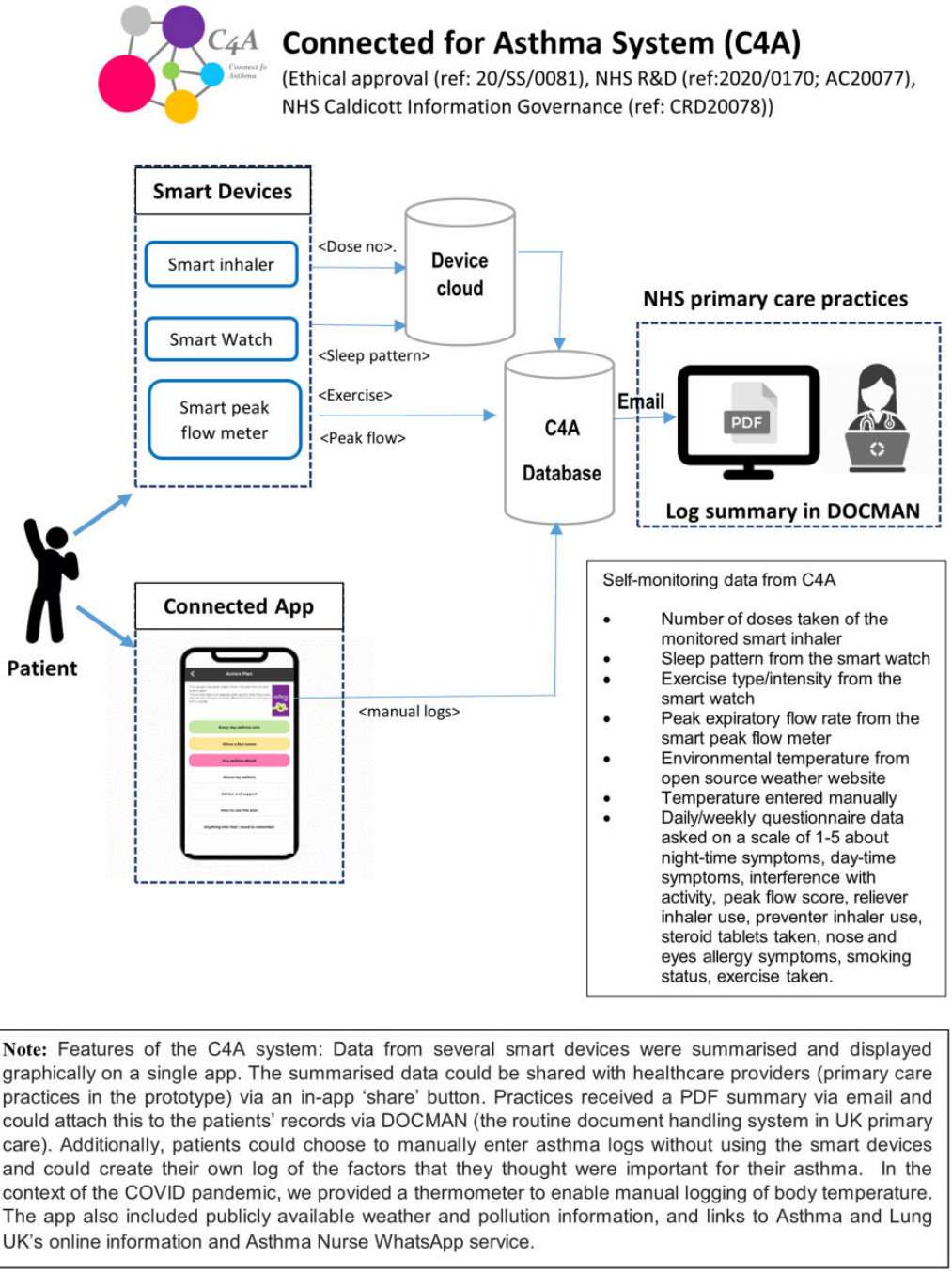


Figure 1. C4A system.

controller inhalers. Selected patients were given one smart inhaler sensor, togther with other smart deviecs (one smart peak flow meter and one smart watch) in a box, patients decided which inhaler (preventer, rescue or combined) they wanted to monitor. A full list of compatible devices is available on the FindAIR website (https://findair.eu/care) (see the device box to the selected patients in Figure 3).

We recruited patients from the following groups:

- Asthma social media groups: We posted advertisements on Facebook and Twitter of Asthma and Lung UK (UK and Scotland), Asthma UK Centre for Applied Research, Usher Institute, C4A, their followers such as Digital Health & Care Innovation Centre, Scotland and Asthma and Lung UK monthly newsletter (see Figure 4).
- C4A volunteer group: A group of 50 adult patient-participants in our previous studies[18,31,48] who have consented to being contacted about asthma technology research. We invited them via email.
- Primary care practices: Individual professionals who were involved in our previous studies[18,31,48] and have consented to be contacted about asthma technology research. They agreed to display our recruitment poster on externally facing windows or doors or on a wall where it could be seen during a remote consultation (see Figure 4).

Figure 2. Screenshots of C4A.

We included a recruitment URL in the social media posts and email invitations where potential participants could read the information leaflet, confirm their eligibility, provide basic demographic information, and give consent to be contacted (via contact details provided) to complete registration.

Purposive sampling of participants

We recruited 10 patients to use the C4A system for a month being sufficient to achieve our proof-of-concept aims within our limited resources. We purposively selected a maximum variation sample including a range of ages (16–25, 26–45, 16–65, 65 or over); ownership of an action plan (or not); duration of asthma (diagnosed <6 months, 6–12 months, 1–10 years, >10 years); hospital admission in the previous 12 months (or not); due to an annual asthma review within a month (or not); and Android/iOS users. These sampling factors were found to affect the asthma app usage based on our previous studies.[18,31,48]

Clinician recruitment

With the patient's consent, we approached their general practice (GP) or asthma nurse by e-mail with an attached information sheet to invite them to participate in the study. If their clinician agreed to participate, the patient was given an option on the app to share the PDF summary report with them. Clinicians from recruiting practices were also invited to participate and (if they were unable to recruit a patient) were sent a dummy PDF report to elicit their views on the format of C4A data sharing.

Note: The device's delivery logistics and remote system setup by patients

We packaged the smart devices in a parcel box and posted it to patients (see above images). The research team provided e-mailed a step-by-step setup guide to patients, with instructions on how to connect the devices to the C4A app, backed up by an e-mail helpline to deal with any problems. We promptly discussed and resolved any ad-hoc technical problems with the devices and/or the API/SDK connection. Technical problems encountered were logged, summarised and fed-back to the manufacturers to aid improvement of their devices and connectivity to C4A.

Patients to choose what devices they wanted to use to look after their asthma (see below) and connect them to C4A app. Patients can also use the devices alone and their full functions on the devices' proprietary app.

- Findair One smart inhaler: to count the numbers of doses that the patients used in the inhalers (other functionalities -https://findair.eu/)
- Polar smart watch: to measure the sleeping pattern and sleeping disturbance (minutes) of the patients (other functionalities - https://www.polar.com/uk-en/)
- MIR smart peak flow meter: to measure peak flow (other functionalities - https://www.mirsmartone.com/)
- Smart Asthma peak flow meter: to measure peak flow (other functionalities - https://smartasthma.com/how-to-use/)

Figure 3. Device box (Findair One smart inhaler, Polar smartwatch, MIR smart peak flow meter [left], Smart Asthma peak flow meter [right]).

Data collection

We collected 3 types of data:

1. *Quantitative data: Self-monitoring and system usage data. We collected date/time-stamped self-monitoring and usage data (see Figure 1), including how often they used the smart device/the connected app and if/when they had completed the digital action plan.*
2. *Qualitative data: Interview transcription.* We interviewed patients before and after the 1-month trial of C4A to explore

Figure 4. Poster at primary care practices (left) and asthma social media recruitment posts (right).

their preferences on logging their asthma (eg, what data they would like to log manually or automatically with smart devices), what triggered and motivated them to adopt and keep using the system, and the difficulties (if any) they encountered when connecting the smart device to the system to log data. Clinician interviews explored the feasible of using a connected system in primary care practice. See Supplementary File S1 for the topic guides.

Interviews were conducted remotely via video conference (to comply with COVID-19 social distancing requirements), digitally recorded, transcribed verbatim and entered into NVivo 20 for analysis.[34]

3. *Documentary data: Email enquiries*. Patients submitted ad-hoc technical questions during the study period via email. E-mail chains and related field notes were summarized in a word document for thematic analysis. Problems were subsequently explored during the interview.

Data analysis and synthesis

Quantitative analysis

Descriptive statistics were used to analyze patients' adoption and usage patterns, measured by the number of patents who logged their asthma status (eg, inhaler dose, peak flow, sleeping pattern) over 30 days. We used a bubble plot as that allowed us to illustrate 3 key variables of the adoption and usage pattern: the feature logged, number of patients, and the time-point. The findings were supplemented in the patient interviews by exploration of why they had chosen to log those data (or not).

Qualitative analysis

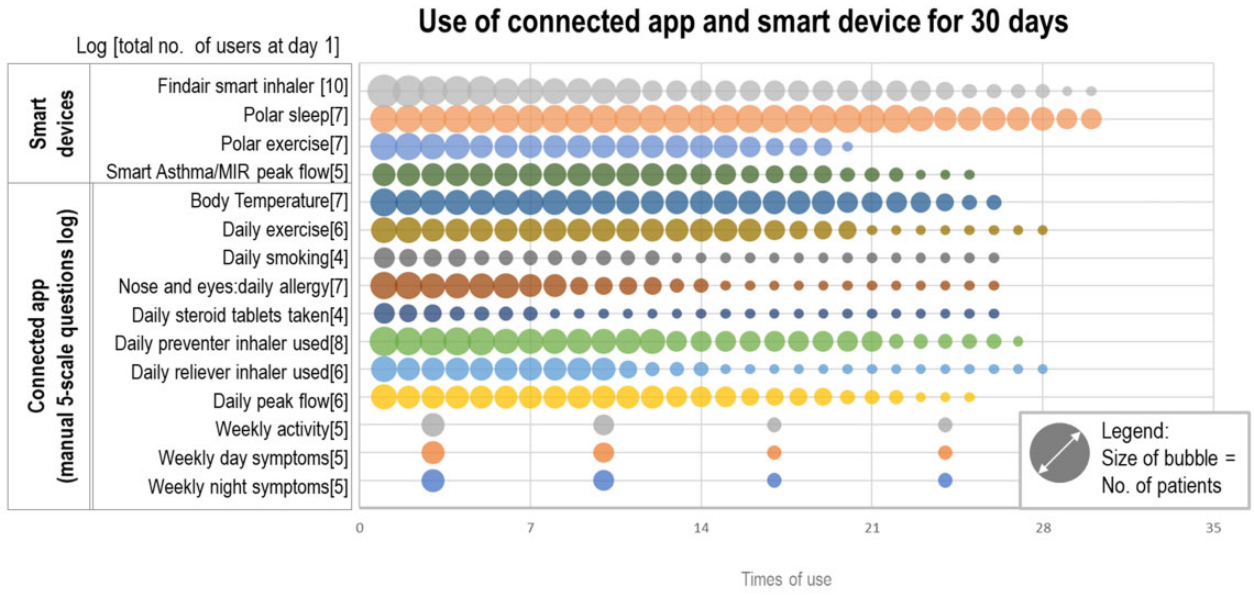
Framework analysis used the UTAUT model[20] coding the data in the domains of performance expectancy, effort expectancy, social influence, and facilitating conditions of C4A (see Table 1 for definitions of these categories). The researcher (CYH: an engineer with health service research experience) coded 2 interviews; a second investigator (HP: an academic GP) reviewed the coded transcriptions and provided a clinical perspective on the coding which was then standardized and applied (by CYH) to all the transcriptions.

Reflexivity and interpretation

The researcher had an engineering background, with experience in developing real-life technology systems and conducting clinical studies on apps and IoT (Internet-of-things). The findings, data synthesis and interpretation were discussed regularly within the multidisciplinary study team which included a patient representative, technology developer, healthcare professionals, and clinical researchers.

Table 2. Demographic information

Demographic information	Options	Participants ($n = 10$)
Age	16–25	2
	26–45	2
	46–64	4
	65 or over	2
Gender	Female	5
	Male	5
Years diagnosed with asthma	Less than 6 months	0
	6 months to 1 year	1
	1–10 years	3
	More than 10 years	6
Action plan ownership	Yes	5
	No	0
	No asthma action plan but I have been told what to do	5
Under the care of a hospital clinic for your asthma	No recent hospital admission for asthma	10
	I have been admitted because of my asthma in the last 12 months, but now my asthma care is provided by GP/asthma nurse	0
	I have been admitted because of my asthma in the last 12 months, and I am still attending the hospital (specialist) clinic	0
Scheduled asthma review over the next month	Yes	2
	No	8
Mobile OS users	Android (Android 8 or 10)	5
	iOS (iOS 13.7,14.3, 14.4)	5
How they heard about the study	Email invitation	6
	Poster	0
	Social media (Facebook)	1
	Social media (Twitter)	1
	Others: A participant shared details	2



Note: All patients were able to connect the smart devices with the connected app, though one patient did not use the system at all because of COVID-related family issues. Of the ten patients, all chose to monitor inhaler use with a smart sensor (four monitored the preventer, six monitored the reliever); eight also logged their preventer use manually in the daily questionnaire. Seven patients adopted the smart watch to monitor their sleep and exercise, only five manually logged their night symptoms and exercise on the app on a weekly basis. Body temperature and daily nose and eyes allergic symptoms were logged by seven of the patients. Seven patients completed the action plan, the other two did not use the plan because they felt their asthma was already well-controlled, one did not fill in the plan and lost contact after connecting the devices and attended the pre-study interview.

Figure 5. Participants' 30 days usage on the connected app and the smart devices.

RESULTS

Participants

Patients

Overall 27 patients expressed interest in the study. Social media invitations reached at least 3500 users with 4 responses; email invitations were sent to 50 patients in the C4A volunteer group of whom 21 (42%) expressed interest. Two patients heard about the study from a friend. None of the GP practices recruited any patients. We selected 10 participants to achieve a maximum variation sample. Participants' characteristics are detailed in Table 2. Of the 10 patients, most (4/10) were 46–64 years old and 6 had been diagnosed with asthma for more than 10 years. We achieved a balance for most characteristics with equal representation of sex, action plan ownership, and Android/iOS users. All participants were interested in technology; 4 had experience in data science and programming. None had a recent hospital admission for asthma. Although all were stable at recruitment, 4 patients experienced a change in their health status immediately before or during the study: 2 were more wheezy than usual, 1 had just changed their medication because of uncontrolled asthma, and 1 contracted COVID. Of these 4 patients, 3 contacted their GPs/asthma nurses for advice, and 1 decided not to bother their clinician during the busy COVID time.

Healthcare professionals

The 10 patient participants invited a healthcare professional from their primary care practice to take part in the study. Of these, 1 asthma nurse participated in an interview having received her patient's asthma report in the consultation. Another 5 primary care GPs/asthma nurses were invited, as an advisory group, to comment on a dummy PDF report (a de-identified monitoring summary) that the researcher sent from our connected system via email to DOCMAN (a correspondence manager linked with the electronic health record), and confirmed the feasibility of report sharing.

Adoption and system usage (quantitative data)

One patient had family problems and withdrew after submitting data for a few days. 7517 pieces of data were received from 9 patients during the 1-month trial. Figure 5 and Supplementary File S2 provide details of system usage. Most data logging reduced over the month of the study. By the 21st day, 7 patients were still monitoring their sleeping pattern with the smartwatch, but use of smart inhaler, smart peak flow and manual logging had reduced by more than 60%.

At the end of the study, 8 of the 9 patients wanted to keep using the connected app to manage their asthma, especially to with the smartwatch and smart inhaler. Only 5 believed they would keep using the smart peak flow meter. One patient did not want to continue using C4A because she felt she knew her asthma and did not trust the accuracy of the devices.

Framework (qualitative) analysis using the UTAUT model

All participants contributed the baseline interview; 9 provided an exit interview. We will describe our qualitative findings using the domains of the UTAUT model[20] to explore adoption and adherence under the headings of performance expectancy, effort expectancy, social influence, and facilitating conditions of the connected system.

Adoption: Performance expectancy

Most patients appreciated the objective log that supported self-analysis of what may be affecting their asthma over time. Other benefits were,

- Providing personalized medication advice according to the action plan that has been agreed with their clinician and reassuring them that they were taking the inhaler as prescribed by their clinician by looking at the numbers of doses that they have taken each day.
- Prompting them with timely advice that their condition was worsening.
- Reminding them to re-order medication before their inhalers had run-out by checking the dose counter, measured by the smart inhaler device.

> Honestly, it's crazy that technology doesn't exist…I think, I don't know, everyone/most people have a phone on them…The more data you have, the more insights you can have, the more you can make actions and controls around that. [P2, 26–45, Male]
>
> I think that technology and people having data is good for humans, like they should be more interested in your own health and not expect someone else to be interested…. [P9, 46–64 years old, Female]
>
> I'm really interested in technology, so I've got lots of techie items around the house, and I just thought that's quite an interesting way of combining the technology and the medical side, to sort of monitor how my asthma is. Because day-to-day, I'm just taking my inhalers and forgetting about it…. [P10, 16–25, Male]

Most patients chose to monitor their reliever inhaler with the smart sensor that we provided because they considered the device could let them know how often it had been used and what the potential triggers were to increased usage. A few patients chose to monitor their preventer because they recognized the importance of regular use and hoped the device would remind them to take it. One patient had a single combined inhaler (preventer and reliever in 1 inhaler) so the choice was not relevant.

Adoption: Effort expectancy

Some patients found it "really easy" and "very simple" to follow the guidance and set up the connection between the C4A app and the smart devices. The smart peak flow meter was "plug-&-play" and most patients were able to set this up to transfer peak flow measurements directly to the app. Some had difficulties in connecting with the smartwatch. This turned out to be due to the default anti-virus setting on their mobile phone that blocked the third-party app download and API bugs from the smartwatch. The anti-virus problems were resolved with email researcher support and the bugs corrected by the manufacturer. Setting up the medication information on the smart inhaler caused some queries about how to amend the dosage (the system defaulted to a dose that was not always what the patient used).

> So functionally I would say it [*the guidance*] was very helpful for connections and things like that and getting the app set up. That went all really smoothly. I managed to do that quite quickly. [P3, 26–45, Female]
>
> Had a little challenge about setting up the inhaler, I think I've got it now. I made a mistake at the beginning setting up the inhaler. [P4, 46–65, Male]

Adoption: Social influence

Patients described their clinicians as the biggest influence on what/how to monitor to make sense of their asthma. Some patients suggested it was sensible for the system to log asthma symptoms and medication use for a week because these were the logs and timeframe that clinicians typically asked about during review consultations. In contrast, they felt there was no need to monitor peak flow unless they felt unwell when peak flows were normally requested by their clinicians.

> I think the number of puffs you've had in a week (is the useful one), because that's the question that the asthma nurse will usually ask in the review, how often you're having it each week, so I think that's probably a useful one [P10, 16–25, Male]

Adoption: Facilitating conditions

The COVID pandemic both raised awareness of asthma and limited patients' access to normal practice support. Many were shielding or staying at home, and did not want to bother their clinician. This encouraged the use of connected devices to look after their own asthma, perceiving that self-management could reduce the NHS workload.

> What there is an impact (of the pandemic) on is how I'm more aware of it. [P4, 46–65, Male]
>
> I'm just very strict in following the rules… I would like the burden on the NHS to be lower, so I'd like more people to be self-managing generally in society, because we cannot go on with the burden on the NHS from everyone's health conditions… [P9, 45–64. Female]

Adherence

Adherence: Performance expectancy

The patients who wanted to keep using the system at the end of the study believed it had increased their ability to track their asthma allowing them to act promptly when the logs (eg, symptoms, sleeping pattern) "weren't great." Some patients wanted the system to be more personalized (or "relevant") such as providing intelligent "clinician-like" interaction (eg, questions such as "do you have extra mucus today?" or "did you wake up at five o'clock today?"). A patient who stopped logging did not feel there was added value to using smart devices compared to entering logs manually.

> … all the question was like, are your eyes itchy and all this. Now I had a wee bit of that but I had terrible mucus, terrible. [P9, 45–64, Female]
>
> … most of the features of these apps would've worked better without the devices. It wouldn't take much effort for me to manually log any inhaler usage and a manual reading of my peak flow. The only aspect made much easier by the device is obviously logging physical activity and health data with the Polar watch. [P6, 16–25, Female]

Adherence: Effort expectancy

Expectations on the ease of use, typically based on previous experience, informed opinions. Despite a number of snags, most of the technologically experienced participants felt that it was "simple enough" to use the connected app with the devices and described it as "straightforward" to use the smartwatch to log their sleeping and exercise pattern. The smart inhaler was considered "reasonably simple" to use.

> I think the app and the, you know, the interaction with the other apps is really positive because you need something quick in the morning. [P9, 46–64, Female]

They also used their past experience of using apps or smart devices, to define how they expected the system should work and considered unexpected operation as "inaccurate," and stopped using the devices. There were some concerns about the "accuracy" of smart devices. There were 3 "inaccurate" issues that were reported by the patients: First, the measurements from the smart digital peak flow meter were higher than the mechanical peak flow meter that patients had used previously which caused some anxiety and concern that the meter was not "accurate." The second was (apparently) missing inhaler data due to a lack of synchronization if the Bluetooth had disconnected from their mobile phone. Patients interpreted this as the device being "inaccurate." The third was a discrepancy between the sleep pattern sensed by the smartwatch and the patients' perception of their sleep. A few patients reported it was "inaccurate" as the sensor recorded that they were lying down, though they were not actually asleep.

> I think it (smart peak flow meter) overestimates my peak flow. . . . I was comparing it to the manual device from the NHS. And this is typically, it's not much, but it's typically about 50 or 60 higher than what I normally, compared to what I normally get. [P4, 46–65, Male]

> Well, things that it says, particularly on the sleep side, it's not accurate because if you lie down, it assumes you've gone to sleep but I will lie in bed and do the crossword for an hour before I turn the light out. [P7, 65 or over, Female]

Adherence: Social influence

The connected app allowed patients to record a single peak flow reading from the smart meter if they thought it was a good reading. Most patients, however, preferred to record the "best of three" measurements as this was the approach recommended by their clinicians and felt that they "should" or "probably" needed to follow this advice.

> When I've been to the asthma clinic, they have always stressed that I should do three readings and take the highest of those three, so I think three is what I'm used to. [P5, 65 or above, Male]

Adherence: Facilitating conditions

Individual patients' needs during the COVID period drove the use they made of the connected system. The patient who contracted COVID used the connected app to log body temperature and her asthma status. A patient who was feeling unwell shared data on the connected app with their asthma nurse for a remote consultation. A patient who was unsure if their excess mucus was due to a cold or their second COVID jab, changed their medication and used the connected app to monitor the effect on their asthma. Patients who had controlled asthma, continued logging as they wanted to contribute their data for research and help the asthma community.

DISCUSSION

Principal findings

Our technologically confident patients were mostly positive about using a connected system as a tool to self-manage their asthma. With one exception (a patient with COVID-related family problems) all the participants adopted the system, overcame any set-up difficulties and adhered to logging because of the perceived benefits to their asthma well-being, to facilitate data sharing and personalized clinical advice in remote consultations, and to contribute their data to asthma research. The choice of logging asthma symptoms, medication and "best of three" peak flows for a week was influenced by the perceived clinical requirements for information. A perception that smart devices were yielding "inaccurate" measurements was a disincentive to continued monitoring. Patients wanted objective data to support their self-management, for example to track the impact of medication changes, or COVID/vaccination on their asthma.

Strength and limitations

There are some limitations to our small study. First, this was a particularly well-motivated group of volunteers who, although they varied in competence generally felt confident around technology. They were typical of "early adopters," who are generally more willing to make an effort to understand and work with the technology despite early glitches.[35] They are also influential in persuading other, less confident, users to try out the technology as it moves toward mainstream.[36]

Due to limited resources in this proof-of-concept study, we could only support the app and provide smart devices for 10 patients. However, the participants submitted 7517 pieces of monitoring data and provided in-depth interviews alongside logged email enquiries enabling us to triangulate data from the different sources. Through discussion with the device manufacturers, the research team was able to understand the operation of the smart devices and to identify technological bugs and human factors underlying perceived "inaccurate" measurements. A specific example, which was discussed with the manufacturer, was the smart inhaler default setting that did not prompt the user to change to the prescribed dose. Although logging reduced over the month, retention was in line with that observed in noncommercial research[37,38] and was considerably better than the published commercial rate of 4% for healthcare apps.[39]

The pressures of managing the COVID-19 pandemic severely limited the involvement of clinicians in the study. We faced 2 problems. The clinicians who were interested in the connected system, were unable to recruit their patients as routine asthma review consultations had all but stopped. Conversely, our patient participants were aware of the pressures and felt unable to approach their clinicians to receive the report from our connected system. As a compromise, we invited interested clinicians to provide brief comments on the data-sharing format by sending them sets of dummy data. In line with the primary aim of this study to establish the proof-of-concept of using a connected system, we focused narrowly on the feasibility of sharing data with the primary care practices in our interviews with healthcare professionals. This limited our data collection to general practitioners and nurses and we did not collect details of their professional experience. We have explored the in-depth perceptions of clinicians in primary/secondary care, asthma nurses, and pharmacists on a connected system in a previous study.[31]

The COVID pandemic also prevented us recruiting patient participants via local community centers/libraries as planned to tackle the ethnicity or socioeconomic deprivation issues, because the venues were either closed or had no staff to support the recruitment.

With only 10 patient participants we were limited in the number of variables we could consider in our purposive sampling.[61] This meant we could not include social deprivation or ethnicity which would be important considerations in a larger study.[62–64] We opted for age, duration of asthma, risk of severe attacks, ownership of action, plans and confidence in using technology which our previous work suggested were important.[31,38]

Due to COVID restrictions, patient interviews were conducted online making it difficult for the researcher to observe how patients interacted with the app interfaces. However, the researcher asked systematically about each of the features on the app, explored any difficulties they encountered with the interface (including unclear wording or icons), and enquired about any features they felt were missing. Resource limitations meant we could not duplicate code all the interviews, but a second coder reviewed the first 2 transcripts from a clinical perspective and the CYP (who has an engineering background) completed analysis with an agreed coding framework.

Interpretation in relation to the published literature

Impact of the pandemic

The pandemic affected routine care for patients with long-term conditions.[40] Awareness of asthma increased with concerns about how COVID-19 would affect their asthma (and vice-versa) exacerbated by a reduction in routine clinical support and a move to remote care.[41] This encouraged proactive actions such as bulk ordering of prescription medications at the start of the pandemic,[42,43] and using on-line resources to learn about self-management.[46,47] Our participants saw the potential of the connected system to monitor the impact of COVID (or COVID immunization) on asthma and to be able to discuss this with their clinicians remotely. Similarly, remotely supported self-management has been used during COVID to support patients with other long-term conditions such as chronic pain,[44] diabetes,[46] COPD,[48] and epilepsy.[49] While our findings aligned with commonly described basic requirements to support adoption and continued use of any technology (easy to use interface, meeting users' needs and expectations),[65,66] we further explored a number of other factors that influences our participants' adoption and usage of a connected asthma system. Social technical factors such as the digital health policy in the local country, sufficient training/support for users to use the system, health information/information communication technology literacy, gender, age disparities, and digital divide also need to be considered for successful implementation.[67,68]

Perceptions of inaccuracy

We found that perceived "inaccuracy" of measurements from smart devices affected the trust in and discouraged the use of the connected system. This echoes with findings of other studies,[50] and adds to recognized challenges of implementing technical solutions (such as medical device legislation, data privacy, and data interoperability between the system and the patients' records[45,51]) alongside the imperative to ensure equitable access.[52] The perception of inaccuracy confers a sense of unease on the users and is not necessarily the fault of the technology itself (eg, a system bug or incorrect calculation due to a faulty algorithm), which are commonly discussed in other telehealth studies.[37,69]

Although most participants wanted to keep using the connected app, some were concerned about the "accuracy" of the CE-marked smart devices. The smart peak flow meter caused the most concern mainly because the measurements from the smart device were higher than from the familiar mechanical meter. This is a recognized discrepancy both when examined *in vitro*, and with the added variability of how individuals use the meter.[53] Guidelines recommend that individuals should use the same peak flow meter each time as the reading may vary by up to 20% between meters.[54]

Unsynchronized real-time data between the device and its cloud, and the loss of Bluetooth connection led participants to feel the smart inhalers were "inaccurate." This resonated with the experience of 21 patients using the AstraZeneca Turbu+ in a 3-week trial.[55] For smart devices with Bluetooth connection, a clear indication is required to reassure users that the data have been successfully transferred or to support re-connection if the link between the device and the cloud has failed.

Set-up challenges

Although some of our devices were "plug-&-play" with no setup required to connect with the app, others required installation of a device app on top of the connected app and using the proprietary API to pull data from the device. Our participants were technologically confident that they felt they can complete the device setup and connection by themselves, and in general found it easy to overcome initial problems and mostly complete the connection setup successfully. This is unlikely to be true of people with less experience in technology. Having a simple and open connected system is technically feasible. Platforms like If-This-Then-That (IFTTT) allow customable automation tasks with connections to multiple brands of devices such as smartwatches and smart speakers,[56] it provides an easy step by step, one stop interface, and sequential logic (if <trigger condition>, then <action on the devices>) to simplify the set up process The advanced universal plug-and-play (UPnP) protocol could be used to remove the complex setup process from patients.[57]

A "no effort" setup process, however, increases the risks of security issues, though strategies can be implemented in the system architecture to minimize these risks.[58] Aligned with the global agenda of the World Wide Web Consortium,[59] the UK NHS is moving toward an interoperable system that encourages healthcare innovation by third parties.[60] However, an ethical and profitable business ecosystem has to be developed if device manufacturers are to be encouraged to move away from restricting third-party connections via their proprietary device cloud/API to developing open devices with simple setup in order to widen device choice for patients.

CONCLUSIONS

In common with previous work, we found that a connected system could facilitate digital approaches to care by providing on-going self-monitoring data to support remote consultations; with the potential to support self-management by providing timely personalized advice within an agreed action plan on what to do if their condition shows signs of worsening. Adoption and adherence require an easy-to-use interface that meets the users' needs and expectations. In the novel context of our flexible, multidevice system, the set-up must be as easy as "plug and play" with no possibility of errors or default settings that could affect clinical care. Devices available to connect to such a system should not only be accurate (eg, certified by laboratory tests/CE marked registration), but the system should be designed to ensure the patient believes that the measurements "accurately" reflect their condition.

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AUTHOR CONTRIBUTIONS

CYH and HP designed the study. CYH undertook the data extraction and synthesized the data with HP. HP is the study guarantor. CYH with HP and BM wrote the initial draft and final version of the manuscript. MB and SM commented on implications from technology and clinical prospective. All authors approved the final version.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *JAMIA Open* online.

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CONFLICT OF INTEREST STATEMENT

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DATA AVAILABILITY

All data are incorporated into the article and the online supplementary material.

REFERENCES

1. COVID Virtual Wards. NHS,2022. https://www.england.nhs.uk/nhs-at-home/covid-virtual-wards/ Accessed April 03, 2022.
2. Oximetry @home. NHS, 2022, https://www.england.nhs.uk/nhs-at-home/covid-oximetry-at-home/ Accessed April 03, 2022.
3. Vindrola-Padros C, Sidhu MS, Georghiou T, *et al.* The implementation of remote home monitoring models during the COVID-19 pandemic in England. *EClinicalMedicine* 2021; 34: 100799.
4. McKinstry B, Alexander H, Maxwell G, Blaikie L, Patel S, Guthrie B.; Technology Enabled Care TeleCOVID Group. The use of telemonitoring in managing the COVID-19 pandemic: pilot implementation study. *JMIR Form Res* 2021; 5 (9): e20131.
5. Vindrola-Padros C, Singh KE, Fulop NJ, *et al.* Remote home monitoring (virtual wards) for confirmed or suspected COVID-19 patients: a rapid systematic review. *EClinicalMedicine* 2021; 37: 100965.
6. Virtual Wards: Relieving Pressure on the NHS While Caring for Patients at Home. NHS, 2022. https://www.nhsx.nhs.uk/key-tools-and-info/data-saves-lives/improving-individual-care-and-patient-safety/virtual-wards-relieving-pressure-on-the-nhs-while-caring-for-patients-at-home/ Accessed April 03, 2022.
7. Silven AV, Petrus AH, Bonten TN, *et al.* Telemonitoring for patients with COVID-19: recommendations for design and implementation. *J Med Internet Res* 2020; 22 (9): e20953.
8. Hanlon P, Daines L, Campbell C, *et al.* Telehealth interventions to support self-management of long-term conditions: a systematic meta-review of diabetes, heart failure, asthma, chronic obstructive pulmonary disease and cancer. *J Med Internet Res* 2017; 19 (5): e172.
9. Tucker KL, Sheppard JP, Bray EP, *et al.* Self-monitoring of blood pressure in hypertension: a systematic review and individual patient data meta-analysis. *PLoS Med* 2017; 14 (9): e1002389.
10. Kim Y, Park JE, Park DA, *et al.* Comparative effectiveness of telemonitoring versus usual care for type 2 diabetes: a systematic review and meta-analysis. *J Telemed Telecare* 2019; 25 (10): 587–601.
11. Liu K, Xie Z, Or CK. Effectiveness of mobile app-assisted self-care interventions for improving patient outcomes in type 2 diabetes and/or hypertension: systematic review and meta-analysis of randomized controlled trials. *JMIR Mhealth Uhealth* 2020; 8 (8): e15779.
12. What is the Prevalence of Asthma? National Institute for Health and Care Excellence. 2022. https://cks.nice.org.uk/topics/asthma/background-information/prevalence/ Accessed April 03, 2022.
13. Asthma Facts and Statistics. Asthma UK. 2022. https://statistics.blf.org.uk/ Accessed April 03, 2022.
14. Pinnock H, Parke HL, Panagioti M, *et al.*; PRISMS and RECURSIVE groups. Systematic meta-review of supported self-management for asthma: a healthcare service perspective. *BMC Medicine* 2017; 15 (1): 64.
15. Hodkinson A, Bower P, Grigoroglou C, *et al.* Self-management interventions to reduce healthcare use and improve QoL among patients with asthma: a SR and network meta-analysis. *BMJ* 2020; 370: m2521.
16. Pinnock H. Connecting professionals and patients: how technology can support asthma self-management. *Respir Drug Deliv Europe* 2017; 1: 43–52.
17. Remote Consultations. International Primary Care Respiratory Society. 2021. https://www.ipcrg.org/dth11 AccessedApril 03, 2022.
18. Hui CY, Mckinstry B, Fulton O, Buchner M, Pinnock H. What features do patients and clinicians 'want' in the future Internet-Of-Things (IoT) systems for asthma: a mixed method study. *Eur Respir J* 2020; 56: 1352.
19. Riley WT, Rivera DE, Atienza AA, Nilsen W, Allison SM, Mermelstein R. Health behavior models in the age of mobile interventions: are our theories up to the task? *Transl Behav Med* 2011; 1 (1): 53–71.
20. Michie S, Van Stralen MM, West R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. *Implement Sci* 2011; 6 (1): 1–2.
21. Fogg BJ. A behavior model for persuasive design. In: Proceedings of the 4th International Conference on Persuasive Technology; April 26, 2009: 1–7; California, USA.
22. Mohr DC, Schueller SM, Rashidi P, *et al.* The behavioral intervention technology model: an integrated conceptual and technological framework for ehealth and mhealth interventions. *J Med Internet Res* 2014; 16 (6): e146.
23. Cole-Lewis H, Ezeanochie N, Turgiss J. Understanding health behavior technology engagement: pathway to measuring digital behavior change interventions. *JMIR Form Res* 2019; 3 (4): e14052.
24. Davis FD. Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Q* 1989; 13 (3): 319–40.
25. Venkatesh V, Morris MG, Davis GB, Davis FD. User acceptance of information technology: toward a unified view. *MIS Q* 2003; 27 (3): 425–78.
26. Harst L, Lantzsch H, Scheibe M. Theories predicting end-user acceptance of telemedicine use: systematic review. *J Med Internet Res* 2019; 21 (5): e13117.
27. Greenhalgh T, Wherton J, A'Court C, *et al.* Beyond adoption: a new framework for theorizing and evaluating nonadoption, abandonment, and challenges to the scale-up, spread, and sustainability of health and care technologies. *J Med Internet Res* 2017; 19 (11): e367.

28. Agile Delivery. Gov.uk, 2022. https://www.gov.uk/service-manual/agile-delivery AccessedApril 03, 2022.
29. Lean Principles. NHS Improvement, 2017. https://www.england.nhs.uk/improvement-hub/wp-content/uploads/sites/44/2017/11/Going-Lean-in-the-NHS.pdf Accessed April 03, 2022.
30. Hanson WE, Creswell JW, Creswell JD, *et al.* Mixed methods research designs in counseling psychology. *J Couns Psychol* 2005; 52 (2): 224–35.
31. Hui CY, McKinstry B, Fulton O, Buchner M, Pinnock H. Patients' and clinicians' visions of a future internet-of-things system to support asthma self-management: mixed methods study. *J Med Internet Res* 2021; 23 (4): e22432.
32. Whatsapp Nurse Services. Asthma and Lung UK, 2022. https://www.asthma.org.uk/advice/resources/helpline/whatsapp-service/ Accessed April 03, 2022.
33. Quality and Outcomes Framework Guideline. NHS employers, 2019. https://www.england.nhs.uk/wp-content/uploads/2019/05/gms-contract-qof-guidance-april-2019.pdf Accessed April 03, 2022.
34. QSR International. NVivo 20. https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/support-services/nvivo-downloads Accessed April 03, 2022.
35. Rogers EM. *Diffusion of Innovations*. 5th ed. New York, NY: Free Press; 2003: 576.
36. Rogers EM, Singhal A, Quinlan MM. Diffusion of innovations. In: Stacks DW, Salwen MB, eds. *An Integrated Approach to Communication Theory and Research*. New York, NY: Routledge; 2014: 432–48.
37. Jaimini U, Thirunarayan K, Kalra M, Venkataraman R, Kadariya D, Sheth A. How is my child's asthma? *JMIR Pediatr Parent* 2018; 1 (2): e11988.
38. Hui CY, McKinstry B, Pinnock H, *et al.* Time to change the paradigm? A mixed method study of the preferred and potential features of an asthma self-management app. *Health Informatics J* 2020; 26 (2): 862–79.
39. Mobile App User Retention Rate Worldwide 2020. L. Ceci at Statista, 2021. https://www.statista.com/statistics/259329/ios-and-android-app-user-retention-rate/ Accessed April 03, 2022.
40. The Impact of the COVID-19 Pandemic on Noncommunicable Disease Resources and Services: Results of a Rapid Assessment. World Health Organization, 2020. https://www.who.int/publications/i/item/9789240010291 Accessed April 03, 2022.
41. The Remote Care Revolution During Covid-19. Health Foundation and Nuffield Trust, 2022. https://www.nuffieldtrust.org.uk/files/2020-12/QWAS/digital-and-remote-care-in-covid-19.html#1 Date last Accessed February 18 2022 (Accessed April 03, 2022).
42. Davies GA, Alsallakh MA, Sivakumaran S, *et al.*; EAVE II Collaborators. Impact of COVID-19 lockdown on emergency asthma admissions and deaths: national interrupted time series analyses for Scotland and Wales. *Thorax* 2021; 76 (9): 867–73.
43. Bloom CI, Wong E, Hickman K, *et al.* Influence of the first wave of COVID-19 on asthma inhaler prescriptions. *NPJ Prim Care Respir Med* 2021; 31 (1): 45.
44. Skene IP, Pfeffer PE. Improved asthma control during the COVID-19 pandemic: are there lessons to be learnt? *Thorax* 2021; 76 (9): 852–3.
45. McClatchey K, Jackson T, Chan Amy T, *et al.* COVID-19 information for people living with asthma: a rapid review of publicly available information guidance. *J Allergy Clin Immunol Pract* 2021; 9 (5): 2070–2.
46. Eccleston C, Blyth FM, Williams ACC, *et al.* Managing patients with chronic pain during the COVID-19 outbreak: considerations for the rapid introduction of remotely supported (eHealth) pain management services. *Pain* 2020; 161 (5): 889–93.
47. Kang J, Chen Y, Zhang C, *et al.* Effect of remote management on comprehensive management of diabetes mellitus during the COVID-19 epidemic. *Prim Care Diabetes* 2021; 15 (3): 417–23.
48. Wu F, Burt J, Hurst JR, *et al.* Specialty COPD care during COVID-19: patient and clinician perspectives on remote delivery. *BMJ Open Resp Res* 2021; 8 (1): e000817.
49. Power K, McCrea Z, Doherty C, *et al.* The development of an epilepsy electronic patient portal: facilitating both patient empowerment and remote clinician-patient interaction in a post-COVID-19 world. *Epilepsia* 2020; 61 (9): 1894–905.
50. Hui CY, McKinstry B, Pinnock H, *et al.* Patients' and clinicians' perceived trust in internet-of-things systems to support asthma self-management: qualitative interview study. *JMIR Mhealth Uhealth* 2021; 9 (7): e24127.
51. Gerke S, Shachar C, Cohen IG, *et al.* Regulatory, safety, and privacy concerns of home monitoring technologies during COVID-19. *Nat Med* 2020; 26 (8): 1176–82.
52. Latulippe K, Hamel C, Giroux D. Social health inequalities and eHealth: a literature review with qualitative synthesis of theoretical and empirical studies. *J Med Internet Res* 2017; 19 (4): e6731.
53. Nazir Z, Razaq S, Mir S, *et al.* Revisiting the accuracy of peak flow meters: a double-blind study using formal methods of agreement. *Respir Med* 2005; 99 (5): 592–5.
54. Global Report, Strategy for Asthma Management and Prevention. Global Initiative for Asthma (GINA),2021. https://ginasthma.org/gina-reports/ Accessed April 03, 2022.
55. Kuipers E, Poot CC, Teichert M, *et al.* 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 (5): e13551.
56. IFTTT. https://ifttt.com/explore Accessed April 03, 2022.
57. Goel SS, Goel A, Moltó G, *et al.* A review of Internet of Things: qualifying technologies and boundless horizon. *J Reliable Intell Environ* 2021; 7 (1): 23–33.
58. Pavlović N, Šarac M, Sharma DK, *et al.* An approach to adding simple interface as security gateway architecture for IoT device. *Multimed Tools Appl* 2022; 81 (26): 36931–46.
59. Open Standards principles. Policy paper. Cabinet Office. 2018. https://www.gov.uk/government/publications/open-standards-principles/open-standards-principles Accessed April 03, 2022.
60. Connected Digital System. NHS,2022. https://www.england.nhs.uk/digitaltechnology/connecteddigitalsystems/ Accessed April 03, 2022.
61. Daines L, Morrow S, Pinnock H, *et al.* Understanding how patients establish strategies for living with asthma: IMP2ART qualitative study. *Br J Gen Pract* 2020; 70 (694): e303–11.
62. Davies B, Kenia P, Gupta A, *et al.* Paediatric and adolescent asthma: a narrative review of telemedicine and emerging technologies for the post-COVID-19 era. *Clin Exp Allergy* 2021; 51 (3): 393–401.
63. Jacob C, Sezgin E, Ivory C, *et al.* Sociotechnical factors affecting patients' adoption of mobile health tools: systematic literature review and narrative synthesis. *JMIR Mhealth Uhealth* 2022; 10 (5): e36284.
64. Sittig DF, Singh H. A new socio-technical model for studying health information technology in complex adaptive healthcare systems. In: Patel VL, ed. *Cognitive Informatics for Biomedicine*. Cham: Springer; 2015: 59–80.
65. Or C, Tao D. Usability study of a computer-based self-management system for older adults with chronic diseases. *JMIR Res Protoc* 2012; 1 (2): e2184.
66. Or C, Dohan M, Tan J. Understanding critical barriers to implementing a clinical information system in a nursing home through the lens of a socio-technical perspective. *J Med Syst* 2014; 38 (9): 1–0.
67. World Health Organization. Digital Implementation Investment Guide (DIIG): Integrating Digital Interventions into Health Programmes. 2020. https://www.who.int/publications-detail-redirect/9789240010567 Accessed June 23, 2022.
68. Hui, CY, Abdullah, A, Pinnock, H, *et al.* Mapping national information and communication technology (ICT) infrastructure to the requirements of potential digital health interventions in low- and middle-income countries. *J Glob Health* 2022; 2:04094.
69. Sonney J, Ward T, Thompson HJ, *et al.* Improving Asthma Care Together (IMPACT) mobile health intervention for school-age children with asthma and their parents: a pilot randomised controlled trial study protocol. *BMJ Open* 2022; 12 (2): e059791.