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Feasibility of Mobile and Sensor Technology for Remote Monitoring in Cancer Care and Prevention

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Abstract

Objectives. *Remote monitoring (RM) of health-related outcomes may optimize cancer care and prevention outside of clinic settings. CYCORE is a software-based system for collection and analyses of sensor and mobile data. We evaluated CYCORE's feasibility in studies assessing: (1) physical functioning in colorectal cancer (CRC) patients; (2) swallowing exercise adherence in head and neck cancer (HNC) patients during radiation therapy; and (3) tobacco use in cancer survivors post-tobacco treatment (TTP).*

Methods. *Participants completed RM: for CRC, blood pressure, activity, GPS; for HNC, video of swallowing exercises; for TTP, expired carbon monoxide. Patient-reported outcomes were assessed daily.*

Results. *For CRC, HNC and TTP, respectively, 50, 37, and 50 participants achieved 96%, 84%, 96% completion rates. Also, 91-100% rated ease and self-efficacy as highly favorable, 72-100% gave equivalent ratings for overall satisfaction, 72-93% had low/no data privacy concerns.*

Conclusion. *RM was highly feasible and acceptable for patients across diverse use cases.*

Introduction

Accelerating the fight against cancer calls for enhanced information technology that will give clinicians access to patients' therapeutic response data in real-time, provide those patients with information critical to and tailored for self-care, and allow researchers to more easily identify emerging trends surrounding those processes.[1] This goal may be achieved with the implementation of systems that enable remote, and when warranted, real-time monitoring of patients' symptoms and other health-related outcomes in the context of cancer prevention, treatment and survivorship. Home- and sensor-based technology has provided a continuous assessment method for patients with heart conditions, diabetes, and asthma. [2-6] More recently, studies have shown that remote monitoring of symptoms during cancer treatment using a web-based questionnaire platform, coupled with intervention and support by care providers, was associated with better quality of life, fewer treatment interruptions, and improved survival in metastatic cancer patients. [7, 8]

The growing accessibility of mobile and sensor technology may offer scalable and cost-effective strategies to develop and test remote monitoring systems with the goal of optimizing cancer care outside of the clinic setting.[9, 10] The need for additional research has been cited, particularly to help define for which groups of patients and under which circumstances remote monitoring with mobile and sensor technology is most appropriate and acceptable and effective; this need may be particularly pronounced in oncology, where sequelae can be long-lasting.[11-16]

Envisioning the ability to use home-based mobile and sensor technology to address a wide array of challenging problems related to cancer prevention and treatment, and aiming to identify real-world problems faced by cancer clinicians and patients, we designed a software-based cyber-infrastructure to enable collection, storage, processing, visualization, analysis, and sharing of cancer patient and survivor data from multiple domains.[17, 18] The CYCORE (CYber-infrastructure for COmparative effectiveness REsearch) system was designed to combine data from user-friendly, patient-accessible platforms—including mobile sensors and smartphones—with web-based

data display interfaces from multiple sources, to help clinicians and researchers decipher important trends in research participants that are needed to facilitate assessment and clinical decision-making.

CYCORE was built as a service-oriented architecture (SOA) to provide loose coupling between its various system services, promoting independent development and reuse of software components. SOAs provide the means to offer, discover, and interact with CYCORE's capabilities, such as acquiring sensor data, storing and linking data from various sensors, processing data, or exporting data to other software packages used for outcomes assessment. The CYCORE cyber-infrastructure (CI) is the underlying computational and data infrastructure, which achieves coherent system integration out of a variety of distributed components and manages the lifecycle of all resources. Furthermore, CYCORE uses a Rich Services (RS) architectural blueprint, a type of SOA suitable to integrating crosscutting concerns. The RS architecture allows for infrastructure services, such as encryption, authentication, authorization, and auditing to be plugged into the architecture without modifying core system functionality. This feature ensures scalability, so CYCORE can grow without changes to the underlying CI as new needs are identified and new users engage with the system. We also continuously asses maintenance, usability, and reliability, and we integrate new device models as they become available to improve system quality.

The CYCORE user interface mandates role-based access and provides tailored views for each role. For example, the clinician interface provides a list of patients monitored by a given clinician and displays all sensor data and patient-reported outcomes in a format that simplifies decision-making. The researcher, on the other hand, may access the tools for study monitoring, patient enrollment, sensors assignment, and data analyses. CYCORE provides an integrated view of data from various sources and the ability to run analyses that correlates data and trigger alerts if required by clinicians.

Objective

Our research objective was to evaluate the feasibility and acceptability of using CYCORE for remote data collection, outside of the clinic setting, with cancer survivors in three studies that represented unique oncology settings and that assessed: (1) physical functioning in colorectal cancer (CRC) patients; (2) adherence to swallowing exercises in head and neck cancer (HNC) patients during radiation therapy; and (3) tobacco use in cancer survivors who completed an evidence-based tobacco treatment program (TTP).

Materials and Methods

This research was approved by the Institutional Review Board at the University of Texas MD Anderson Cancer Center (MDACC).

CYCORE system overview. The CYCORE system combined physical entities, such as sensors and mobile devices, with an underlying computational and data fabric. CYCORE had several data acquisition strategies to assimilate multiple sensor types. The CYCORE system consisted of a small plug-in computer-server with the role of sensor hub in the participant's home, and a backend CI that presented raw and analyzed data to researchers or clinicians. In the prototype used for this study, we developed and implemented our own sensor hub called the Home Health Hub, which was a physical device that aggregated sensor data collected by the patient and relayed these to the CI over an Internet connection. We also developed a smartphone application to enable patient self-recording of videos that automatically uploaded into CYCORE; these were used to monitor adherence. We integrated a customized electronic patient-reported outcome (PRO) system developed at MDACC to provide an app for patient questionnaires via an Android smartphone or tablet.

The system supported an interface with wide range of consumer-grade sensors that wirelessly transmit data to the home-based server. The sensors integrated into CYCORE for this study were blood pressure monitor and weight scale (A&D Medical), accelerometer (AwareTech Action Tracker), heart rate (Zephyr Technology Bio-Harness), GPS location, and CO monitor (PICO). The accelerometer, heart rate monitor, and GPS provided continuous data. For consumer-grade sensors, the manufacturer's procedures for determining the device calibration tolerance and for recalibration were implemented prior to each deployment. For validation, we employed sensors that exposed a digital interface to the measured values. Sensor data were aggregated, encrypted, and transmitted to a central CYCORE server, which notifies a server database of new data events. Using a web interface, research staff registered and assigned devices to patients, monitored data transmission, and handled technology issues that arose. CYCORE also supported the creation and use of clinician web interfaces for patient monitoring of data during the duration of the study.[18]

Study descriptions. We evaluated the feasibility and acceptability of the CYCORE system in three distinct studies with unique study populations, described below. Table 1 describes the types of sensor and mobile technology used in each study.

Table 1: Descriptions and purposes of sensors and devices used for remote monitoring of cancer survivors

CRC Patients: Physical Activity Measurement	
Device	**Purpose**
Miniature plug-in computer for receipt and transmission of sensor data	Collect, encrypt, and transmit data from the accelerometers, and the BP, HR, and GPS devices to CYCORE
Accelerometers (2), worn daily on waist	Monitor physical activity
Wireless blood pressure monitor, with cuff	Assess physiological changes related to physical activity
Heart rate monitor, worn daily using a chest strap	Assess physiological changes related to physical activity
Global positioning system (GPS), carried in pocket or purse	Monitor movement outside of the home
Smartphone with application for collection of patient-reported outcomes	Collect patient-reported outcome data related to physical activity adherence over multiple time points
HNC Patients: Adherence to Swallowing Exercises	
Device	**Purpose**
Smartphone with application for self-video capabilities and collection of patient reported outcomes	Capture adherence to swallowing exercises via video; collect treatment-related symptoms and self-report of swallowing exercises.
Cancer Survivors/TTP: Adherence to Smoking Cessation	
Device	**Purpose**
Small plug-in computer (Home Health Hub) for receipt and transmission of sensor data	Collect, encrypt, and transmit CO data to CYCORE
Carbon monoxide monitor, hand-held	Measure expired carbon monoxide three times daily
Smartphone with application for self-video capabilities and collection of patient reported outcomes	Assess adherence to CO monitoring; capture patient-reported outcomes data related to tobacco use

Physical activity to promote optimal quality of life in patients with advanced colorectal cancer (CRC). Home monitoring and receipt of reminders to remain physically active may help patients with advanced CRC maintain physical functioning and reduce symptoms and side effects during periods of acute treatment. Staying physically active and managing treatment side effects may, and in turn, help patients tolerate treatment with fewer interruptions, and potentially increase both the length and the quality of their survival. Since higher levels of physical activity are associated with reduced cancer incidence and recurrence, [19-21] we evaluated whether CYCORE would be feasible and acceptable for assessing activity and treatment side effects in CRC patients.

Adherence to swallowing exercises in head and neck cancer (HNC) patients receiving radiation treatment. HNC patients undergoing radiation treatment are recommended to follow a rigorous self-care regimen at home during their 6 to 7-week course of therapy. This regimen includes adherence to a standard-of-care [22-24] prescription of range-of-motion swallowing exercises intended to reduce long-term radiation treatment-induced swallowing complications, [25-27] including trismus, aspiration, mucositis, xerostomia, loss of taste, and fibrosis of the skin and soft tissue. [27-33] Because adherence to both the performance of swallowing exercises as well as appropriate technique is a critical goal for HNC patients during treatment, we assessed the feasibility and acceptability of capturing patients' self-recorded videos of their daily swallowing exercises. Such videos could be valuable tools for speech pathologists to review and counsel patients on proper technique and adherence to their prescribed swallowing exercises.

Remote collection of exhaled carbon monoxide measurements to assess smoking cessation. MDACC offers evidence-based smoking cessation treatment to cancer survivors and their family members through its Tobacco Treatment Program (TTP), as tobacco use is a contraindication for some cancer treatments and increases risks for complications from the disease as well as mortality. Treatment includes non-nicotine-based medications, nicotine replacement therapy, and behavioral counseling. A standard method of determining cessation status is

through in-clinic exhaled carbon monoxide (CO) monitor measurements, which are only clinically relevant if collected within a day or so of the last smoking bout, limiting the test's usefulness in validating less frequent smoking behavior. We assessed the feasibility and acceptability of remotely collecting exhaled CO measurements 3 times daily from cancer survivors who had completed the TTP, and to video-record those measurements as an indicator of adherence.

Participant eligibility and recruitment. Eligible participants for all studies were 18 years of age or older, English proficient, and had a prior cancer diagnosis. The CRC study included CRC cancer survivors who had completed surgery at least 8 weeks prior to study entry, and who may or may not have been receiving chemotherapy. Those recruited for the HNC study were currently undergoing radiation treatment but were excluded if they had a current swallowing disorder unrelated to their cancer diagnosis. TTP recruits had a history of any cancer other than non-melanoma skin cancer and were current or former smokers but were excluded if they had a known active substance use disorder or had undergone major surgery during the previous eight weeks. For the CRC and HNC studies, eligible patients were identified from medical records and were recruited in clinic. For the TTP study, candidates were identified from program completion records and were recruited via a mailed letter from the TTP director.

Study procedures. Participants were provided with study-specific devices and were instructed to use them at home for two non-consecutive 5-day periods, separated by 2 weeks of non-usage. Following informed consent, participants were trained on the use of their devices.

CRC study participants were asked to record two blood pressure (BP) readings, one sitting and one standing, upon arising in the morning and prior to bedtime in the evening. Using a smartphone provided by the study, they completed morning or evening assessments using a mobile app that included standard measures regarding exercise frequency, type, self-efficacy, social support and physical functioning, plus daily random assessments regarding severity of symptoms (fatigue, pain, trouble concentrating, and mood). CRC participants wore a heart rate (HR) monitor and accelerometer during waking hours and used a global positioning system (GPS) device. HNC study participants used a study-provided smartphone to video-record all swallowing exercise sessions prescribed by their speech pathologist and, once-a-day, to self-initiate an assessment of symptoms and adherence to swallowing exercises. TTP study participants exhaled into a hand-held carbon monoxide (CO) monitor three times a day and used a smartphone to video-record those breath tests. Prior to each use of the CO monitor, participants also used the phone to self-initiate questionnaires about the number of cigarettes smoked and exposure to second-hand smoke. Additionally, at three randomly-assigned time points, TTP participants responded to phone-prompted questions about fatigue, pain, trouble concentrating, and mood.

Participants' perceptions of usability, acceptability, and satisfaction were assessed at seven time points across each study via in-person or phone interviews with research staff. After the baseline training, staff administered a four-item measure regarding ease of use and self-efficacy for using each device. On days 2 and 4 of each 5-day device-use period, participants answered a 6-item measure regarding device problems, medical concerns related to the devices, ease of use, ability to use each device (including reasons for not using a device or why using it was difficult), and what was disliked about each device or that reduced the desire to use that device. [32, 33] This measure was re-administered on day 6 following each 5-day device-use period and included additional questions that assessed belief about the usefulness of automatic data provision to their doctor, concern about data privacy, helpfulness of the initial training session and printed instructions, importance of viewing the data collected, confidence in ability to use at home, and overall satisfaction with device use. Open-ended queries, in all but the post-training survey, solicited additional comments about device use.

Analysis. We defined indicators of adherence to daily use of devices for each study as the percent of participants who completed the following during 7 of the 10 device-use days: any BP reading (CRC study), any video showing performance of swallowing exercises (HNC study), and any video showing a CO measurement (TTP study). Videos smaller than 1000 KB were not included in those counts as they were deemed to be unusable. The primary outcome was study completion, defined by completion of the final study (week 4, day 6) survey. Other outcomes of interest were usability and acceptability ratings, and adherence to the requirements for daily use of devices. Open-ended responses to survey items completed by patients were analyzed using a constant comparative approach based on grounded theory. [34]

Results

Sample size, demographic characteristics and completion rates, which established feasibility, for each study are shown in Table 2. In reviewing study-specific adherence, we found that 47/48 (98%) of CRC participants who completed the CRC study, transmitted BP data on at least 7 of 10 device use days. Of HNC study participants, 30/31 (97%) self-recorded any videos that captured performance of swallowing exercises (mean, 32.7; range, 1-118 of

1000 KB or greater in size) over the 10-day device-use period; while 16/31 (52%) captured videos on at least 7 of those 10 days. Of TTP participants, 48/48 (100%) self-recorded any video of CO monitor usage (mean, 27.7; range, 2-72 of 1000 KB or greater in size); while 43/48 (90%) captured videos on at least 7 of 10 days.

We found a high completion rate for the device usability and acceptability surveys for all three studies (includes missed surveys due to withdrawal): CRC, 316 of 350 possible surveys (92%); HNC, 213 of 259 (82%); and TTP, 328 of 350 (94%). Participants' mean responses to the final (week 4, day 6) survey about device usability and acceptability are shown in Figure 1. Scores were generally high on ease of use of devices, self-efficacy, and overall satisfaction, and generally low regarding data privacy concerns.

We found commonalities in participant responses—when provided—to the open-ended questions about what they liked most about using the devices at home. CRC study participants most liked being able to see or monitor the BP results (13/45, 29%); being able to use the devices at home (or not having to travel [in general, or to see the doctor]) (9/45, 20%); and that device use was easy or simple (12/45, 27%) and convenient (5/45, 11%). Some example responses from open-ended questions follow: "Using the blood pressure cuff keeps you kind of in tune with what's happening, blood pressure-wise." "Someone received the data at the moment versus me having to explain how I felt at the moment. It picked up certain things that I may have forgotten about." "I think that whenever you're monitoring that information and you need it, it's much easier to do it at the house than go to the doctor's office."

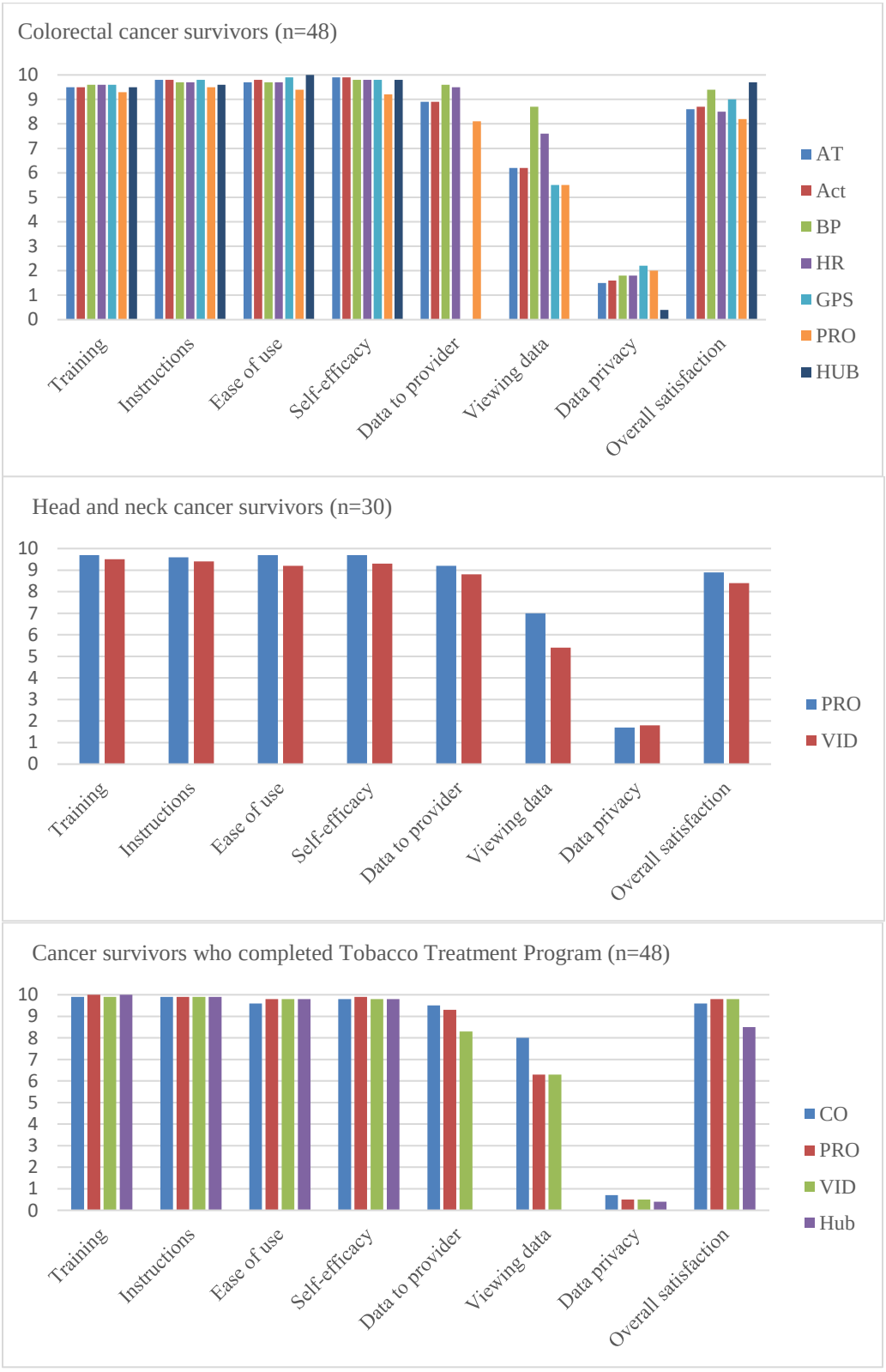
HNC study responders most liked that device use provided motivation or a reminder to do the swallowing exercises (8/29, 28%); and that using the devices was easy (7/29, 24%) and convenient (7/29, 24%). Answers to the open-ended questions included the following: "It motivated me to do exercises I might have skipped otherwise." "This is something in the future that the patients can use to keep in touch with their doctors, and their doctors can monitor them at home while they're going through treatment." "I did it at my leisure, first thing when I woke up. I was at a hotel."

TTP responders most liked being able to use the devices at home (or not having to travel [in general, or to see the doctor]) (15/39, 38%); being able to see or monitor the CO results (9/39, 23%); and that it was easy (8/39, 21%) and convenient (6/39, 15%). Some sample statements follow: "If I had to go into an office, it would be tough to get this in three times a day." "I like the idea that I could see the readings, and I could tell how much how much carbon monoxide was in my body." "If I could have kept the devices longer, it probably would have worked to wean me off of smoking."

Table 2. Demographic characteristics and study completion rates for colorectal cancer survivors (CRC), head and neck cancer survivors (HNC) and cancer survivors who completed the Tobacco Treatment Program (TTP)

		CRC	**HNC**	**TTP**
Age (years), M (range)		55 (25-79)	56 (23-78)	54 (29-72)
Study completion % (n)		96 (48)	84 (31)	96 (48)
Sex % (n)	Female	50 (25)	27 (10)	72 (36)
Race/ethnicity % (n)	White	70 (35)	91 (34)	70 (35)
	Black	14 (7)	3 (1)	16 (8)
	Hispanic	8 (4)	3 (1)	14 (7)
	Asian/other	8 (4)	3 (1)	
Education % (n)	< High school graduate	6 (3)	5 (2)	8 (4)
	High school graduate	12 (6)	11 (4)	30 (15)
	Trade/vocational/some college	28 (14)	22 (8)	30 (15)
	College graduate	40 (20)	32 (12)	22 (11)
	Post-college	12 (6)	14 (5)	6 (3)
Marital status % (n)	Married	68 (34)	97 (36)	46 (23)

Figure 1. Participants' responses to post-study evaluation questionnaire[1] regarding usability and acceptability of study devices (range, 0= not at all, 10=extremely)



Legend: AT: ActionTracker, commercial accelerometer; **Act**: Actigraph accelerometer; **BP**: blood pressure monitor; **HR**: heart rate monitor; **CO**: carbon monoxide monitor; **PRO**: patient-reported outcomes mobile application; **VID**: video mobile application; **Hub**: Home Health Hub

[1]Post-study evaluation questions included: 1) helpfulness of baseline training session (training); 2) clarity of printed instructions used at home (instructions); 3) ease of device use at home (ease of use); 4) Confidence in ability to use device at home (self-efficacy); 5) usefulness of automatic data provision to doctor (data to provider; N/A for GPS, Hub); 6) importance of seeing device reading at home (viewing data, N/A for Hub); 7) concern about data privacy (data privacy); 8) overall satisfaction with device (overall satisfaction).

Discussion

Based on the high study completion rates and participants' responses to evaluative questionnaires, our findings showed that remote, home-based monitoring for important cancer-related health outcomes was feasible and acceptable in all three groups of patients in our study sample. We found that patients, some of whom were quite ill and were burdened by frequent clinic and hospital visits, willingly used a variety of mobile sensors at home to measure biometric and self-reported outcomes related to physical activity (CRC patients and survivors); swallowing exercise adherence during RT (HNC patients); and smoking cessation adherence (cancer survivors who were former or current smokers). Participants from all three studies were receptive to using the devices and found that doing so was simple, easy, and convenient.

Compared to participants in the CRC and TTP studies, those in the HNC group had the lowest rates of study- and survey completion, and device use. Based on responses to their user questionnaires, a subset of HNC participants indicated that recording the videos took too much time (4/29, 14% of responders), that the recordings were harder to do as treatment progressed and, subsequently, as patients' treatment burden typically increases, causing them to feel worse (6/29, 21%), and that feedback about content of the videos was nonexistent during the course of the study (3/29, 10%). As these studies were conducted to determine feasibility and acceptability, we did not provide feedback to HNC participants regarding their adherence or quality of performance of swallowing exercises. Future efforts to incorporate rapid, specific feedback to patients that is aimed at helping them improve an important self-care regimen, such as the one recommended for HNC patients, may increase the perceived value, satisfaction and adherence to remote monitoring protocols.[35][36][37])

TTP participants' responses also supported the value of incorporating clinician review of data and feedback to patients: after the final week of device use, TTP participants indicated that it would be useful for their physicians to be able to monitor the CO and the self-reported data: "It made me more accountable. I smoked less than I usually would because it reported my smoking habits."

As noted above, the HNC group's overall satisfaction with using the phone to record videos lessened end of the study; however, their week 4 mean score still indicated that the group experienced high satisfaction with using the phone for that purpose. This is quite impressive, considering that by week 4 of our study, this group was entering week 4 or 5 of RT, a time during which symptom burden is particularly onerous.

While studies like ours can demonstrate the potential feasibility, as well as efficacy, of integrating sensors, mobile devices, and wireless networks with the goal of improving cancer care and patients' quality of life, concerns about security and privacy related to the use of this technology have been raised. Patients in our study reported relatively low levels of concern about data privacy, which may be an important factor in securing broader acceptability for remote monitoring models such as CYCORE. Patients' privacy concerns may be minimized if they perceive a value in the use of technology, particularly in partnership with a trusted source, their health care providers. Nonetheless, systems such as CYCORE will likely achieve their potential benefits if the security and integrity of data can be assured.

Our study sample was limited in regard to diversity in race/ethnicity and educational attainment. While our sample reflects the overall patient population at our institution, our findings may not be generalizable to populations experiencing technology disparities. The COVID-19 epidemic illuminated longstanding systemic disparities in technology access and digital literacy.[40] These disparities hindered the ability to access health care during the pandemic through telemedicine, and also impeded early access to COVID-19 vaccines which depended on the ability to navigate mobile apps and internet portals. Persons at risk for experiencing these technological disparities are commonly in rural areas, lower-income neighborhoods and minority communities and often medically underserved and at increased risk for cancer as well as higher morbidity and mortality from the disease; potentially, those who may benefit from remote monitoring to help manage their illness. Future research on remote patient monitoring must focus on understanding how technology access and literacy affects usability and feasibility when implementing such interventions.[41]

Evaluation of CYCORE continues through expansion of its technical capabilities, increasing the number of participants studied, and through additional studies within the cancer care community. Ongoing and completed studies are focused on efficacy of remote monitoring during acute periods of cancer treatment, as well as research to further establish feasibility and define methodology for use in challenging patient populations.[39] These studies are expanding the types of sensor and mobile data collection methods within CYCORE, including widely used commercially available devices such as Fitbits, further demonstrating that the system is agnostic to the type of device used and the health-related application. The goal is to continue to develop a community of users who would benefit from CYCORE's capabilities for remote monitoring of patient behavior, all in support of optimizing cancer care [38] by objectively assessing treatment adherence, symptoms, side effects, and toxicities. This should lead to greater patient understanding of and, thus, engagement in their own care, and improvements in data collection for clinical trials including capturing data not typically collected that is highly relevant to cancer recovery and survivorship.

Conclusion

Our study contributes to a growing body of research on remote patient monitoring in oncology, particularly studies that combine electronic patient-reported outcomes with collection of biometric outcomes using non-invasive digital devices.[42] A system like CYCORE that gathers and integrates patient-generated health information in cancer prevention and treatment research is highly feasible and acceptable to patients, clinician and researchers. It supports the collection of new forms of data on behaviors and symptoms that are needed to fully determine the course of cancer treatment and health outcomes. These successful examples of remote monitoring through sensors in the homes of different group of cancer patients show promise for broadening the scope and quality of data in cancer prevention, treatment and control. They also demonstrate how patients can be enabled to participate actively in their prevention and treatment regimens, an essential component of successful health outcomes.

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