Seminars in
RADIATION ONCOLOGY

Big Data From Small Devices: The Future of Smartphones in Oncology

Juhi M. Purswani, MD,[*] Adam P. Dicker, MD, PHD,[†] Colin E. Champ, MD,[‡] Matt Cantor, MBA,[‖] and Nitin Ohri, MD, MS[¶]

Technological advancements in the capabilities of modern smartphones offer tremendous potential to generate big data from small devices that could influence oncologists' decision-making. Here we describe the value of patient-generated health data (PGHD) that can be captured using mobile devices. We comment on the current use of smartphones in oncology clinical research and describe how smartphones will bring big data into the oncology clinic by enabling continuous patient monitoring, information sharing, and personalized clinical decision making in cancer care. Lastly, we describe practical considerations about how we can access and store PGHD in the future, describing how to harness the clinical value of PGHD and comment on the emerging applications for digital biomarkers captured by smartphones.

Semin Radiat Oncol 29:338–347

Introduction

The number of global smartphone users worldwide in 2019 is expected to exceed 2.5 billion.[1] Modern smartphones are sensor-rich and computationally powerful companions that capture information about daily activities, movement patterns, and social behaviors. Smartphone-sensing systems run consumer-generated applications ('apps') that allow for collection, storage, and streaming of large volume data from patients. Over 165,000 mobile device health apps—many of which are focused on fitness, stress, or diet/nutrition—are available via the Apple App Store and Google Play.

Digital biomarkers include consumer-generated physiologic and behavioral measures collected through digital tools, such as calories, steps taken, sleep efficiency, heart rate variability, and body temperature. Large studies have demonstrated the validity of wearable sensors, such as smartwatches, accelerometers, and smartphones, to capture digital biomarkers from diverse patient populations for the purpose of enhancing health outcomes.[2-4] Smartphone-generated data streams could be particularly useful in providing continuous, dynamic, and objective assessments of cancer patients' health status between clinician visits.

The Value of Patient-Generated Health Data in Oncology

Patient-generated health data (PGHD) has been defined as "health-related data—including health history, symptoms, biometric data, treatment history, lifestyle choices, and other information created, recorded, gathered, or inferred by or from patients or their designees (ie, care partners or those who assist them) to help address a health concern."[5] The key features of PGHD are that patients, not providers, collect and record their data.

Traditionally, PGHD have been collected through patient-reported outcomes (PROs), which provide direct information about symptom burden, self-care tasks, and patients' ability to adhere to treatments and lifestyle

*New York University School of Medicine, New York, NY.
†Department of Radiation Oncology, Sydney Kimmel Medical College and Cancer Center at Thomas Jefferson University, Philadelphia, PA.
‡Department of Radiation Oncology, Duke University Medical Center, Durham, NC.
‖Koneksa Health Inc., New York, NY.
¶Department of Radiation Oncology, Montefiore Medical Center, Albert Einstein College of Medicine, Bronx, NY.

Financial and Conflicts of Interests Disclosure: Dr. Dicker is supported by a Challenge grant from the Prostate Cancer Foundation. Research reported in this publication utilized the resources at Sidney Kimmel Cancer Center at Jefferson Health and was supported by the National Cancer Institute of the National Institutes of Health under Award Number P30CA056036. Dr. Ohri receives consulting fees from Merck and AstraZeneca and research support from Merck. Neither Merck nor AstraZeneca provided input into manuscript preparation or any aspects of this work. There are no relevant affiliations, financial disclosures, conflicts of interest, and/or acknowledgements for all the other authors.

Address reprint requests to Nitin Ohri, MD, MS, Department of Radiation Oncology, Albert Einstein College of Medicine, New York, NY 10032. E-mail: nohri@montefiore.org

https://doi.org/10.1016/j.semradonc.2019.05.008
1053-4296/

recommendations. Self-administered instruments can be burdensome to both patients and research staff. Other limitations include poor patient recall, inaccurate reporting, and missing or inconsistent data. These shortcomings can be surmounted by other forms of PGHD that can be collected passively, continuously, and objectively by personal devices.

Measuring Physical Activity in Oncology

Physical activity level, assessed before, during, and after cancer treatment, is known to be a meaningful predictor of long-term clinical outcomes.[6] Changes in pain, anxiety, fatigue, or sleep patterns may manifest as changes in physical activity (or vice versa),[7] and all of these parameters may influence quality of life, tolerance to and efficacy of treatment, and subsequent clinical outcomes. Capturing physical activity is facilitated by recent technological advances that can provide a window into patients' experiences between clinic visits.

The value of activity data generated by wearable devices has been explored in numerous cancer care settings. Observational studies have demonstrated that step counts tend to decline during a course of radiotherapy[8] or following surgery and that increases in daily step counts correspond to decreases in pain,[9] improved quality of life,[10,11] and favorable performance status.[12] It has also been demonstrated that declining step counts measured by a pedometer in cancer patients during chemo- and radiotherapy is associated with increased risk of hospitalization during treatment.[13] It is possible that activity data from wearable devices can supplant existing scales of cancer patients' functional capacity.[14]

Modern smartphones are equipped with accelerometers that record accelerations in one or more planes. These data elements are processed into more meaningful variables, such as step counts; time spent in sedentary, light, moderate, or vigorous physical activity; and flights of stairs climbed. These data are readily available to smartphone users and could easily be shared with health care providers.

Other Forms of PGHD

Smartphones increasingly include numerous diverse embedded sensors for data capture and can interface with "wearables" and other devices to collect a variety of digital biomarkers. Pattern recognition algorithms can aggregate these and other measures to generate estimates of users' status such as stress level or mood. Smartphone-based sensors include cameras, accelerometers, gyroscopes,[15] magnetometers, proximity sensors, light or UV sensors,[16] barometers, thermometers, air humidity sensors, and pedometers. Additional biometric data can be captured using multifunctional sensor platforms. These include pulse, heart rate variability, respiratory rate, blood pressure, body temperature, weight, environmental exposures, sleep behavior, communication patterns, and events related to mobility, such as gait changes and falls.

Add-on sensors use external devices, such as smartphone cases to detect environmental exposures[17] or wearable pedometers to measure physical activity. Monitoring vital signs through smartphones has classically relied on standard point-of-care tools (blood pressure cuff, pulse-oximeter, etc) that require manual entry of health data into apps by either patients or health care staff. Small studies in healthy subjects have demonstrated that smart phones can accurately measure respiratory rate[18] and heart rate[19] without the need for peripheral devices. While validation of these findings is needed in cancer patients, peripheral devices can already be linked with smartphones using Near Field Communication Technology to provide real-time data to clinicians.[20-23]

Smartphones in Cancer Research

Several reports indicate that cancer patients demonstrate a high level of acceptance of smartphone-based trials and interventions.[24,25] A systematic search of published clinical studies (Fig. 1) in cancer patients that incorporated the use of a smartphone app found 18 such studies where the app was designed for patient use, 14 of which relied upon data entry by patients (summarized in Table 1). In these studies, smartphone apps were largely evaluated as tools to enhance physical function and physical activity[26-29]; enhance quality of life[29-31]; reduce treatment related symptoms,[32] including pain[33] and treatment complications[34]; deliver health information[32]; and offer clinical follow-up.[26]

Some studies describing smartphone collection of PROs related to sleep, anxiety, mood and relationship communication,[35,36] and toxicity monitoring[37] have utilized the smartphone app itself as a platform for patient self-reporting, discarding the need for ancillary patient surveys and tools. Though many of these studies are collecting valuable PGHD, the process of acquiring data requires active patient engagement and are limited by the flaws of self-report methods, and more importantly, limited in the ability to generate big data over long periods of time.

Objective parameters of patients' daily function, such as physical activity, has been shown to correlate with QoL.[38] Smartphone metadata may even have the capacity to independently assess certain aspects of patients' QoL.[39] We have only identified 4 published studies leveraging smartphones as stand-alone devices to collect objective PGHD[40-43] (Table 2). Other studies utilized apps paired with pedometers to measure step counts as part of an exercise intervention, where physical activity measurements were also captured by patient self-report[30,44] or with traditional biometric measurements of cardiorespiratory endurance, lower extremity strength, and gait speed.[27,32]

Passively recorded data will expand the roles smartphones can play in enhancing cancer patients' evaluation and care at the time of diagnosis, during treatment, and in the post-treatment survivorship setting. Push notifications can create a feedback loop between data recorded passively and active patient engagement. Smartphones could therefore play a central role in a class of trials where mobile devices implement an activity intervention, record uptake of the

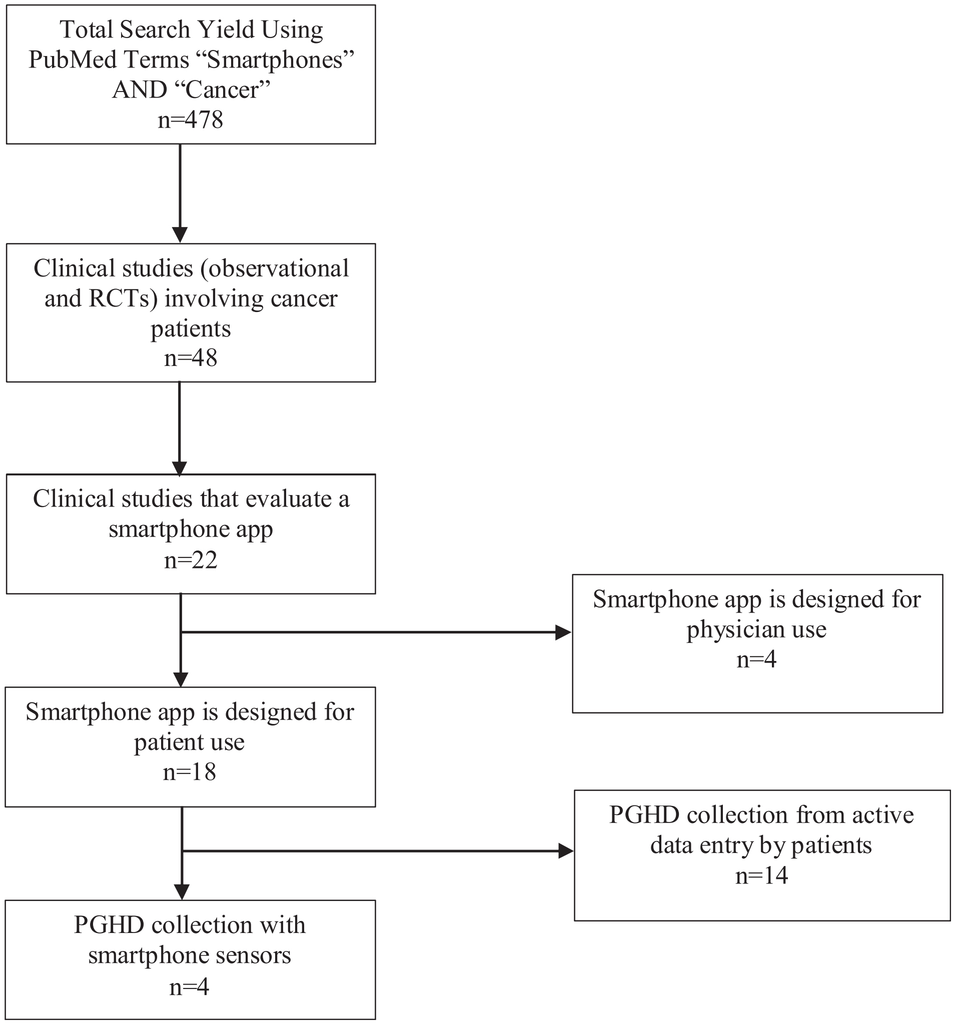

Figure 1 Published clinical studies using smartphones in cancer patients.

intervention, and measure effects of the intervention on patients' behavior and health.

Evaluating the Cancer Patient

Practice-shaping clinical trials in oncology often limit enrollment to patients with excellent performance status and limited medical comorbidities. In the real world, clinicians consider a large range of factors to try to determine if a patient is likely to tolerate aggressive cancer therapy. PGHD from smartphones could help identify such patients. Incorporating PGHD in clinical trials might even reveal factors that predict benefit from treatment. PGHD could then conceivably serve as a biomarker upon which clinical decisions are based.

A systematic review concluded that in healthy volunteers the accuracy of smartphones in measuring physical activity was rated “average-to-excellent”[45] and smartphone-measured step counts have demonstrated excellent validity and reliability when tested against a stand-alone accelerometer among patients undergoing active cancer treatment.[40] Daily step count, which is perhaps the simplest form of activity-related PGHD obtainable using wearable devices, has already been shown to be a powerful predictor of symptom burden,[9,38] hospital admissions,[13,46] and death[46] in several trials.

Monitoring Patients During Cancer Therapy

The potential for enhanced patient monitoring to improve clinical outcomes among cancer patients undergoing chemotherapy has been demonstrated using symptom self-reporting tools.[47] PROs and other forms of PGHD acquired using mobile devices can provide further gains in understanding our patients' experiences, predicting adverse events, and improving long-term clinical outcomes.

Among cancer patients, a smartphone-based symptom reporting tool used during chemotherapy has been shown to yield high rates of patient engagement and satisfaction[48] and is being tested in an 1100-patient randomized trial.[49] In a pilot study of adult patients with active cancer receiving chemotherapy, daily steps were monitored by a smartphone accelerometer. Chemotherapy-related toxicities were reported using the smartphone app on days in which a greater than 15% decline in the number of steps were

Table 1 Clinical Studies in Cancer Patients Using Smartphone Apps and Patient Self-report Methods to Collect PGHD

Patients	Smartphone Application and Supported Operating System (OS)	Purpose of Smartphone App	Patient Generated Health Data (PGHD)	Source of PGHD	Key Findings
108 patients diagnosed with head and neck cancer randomized to smartphone app vs. standard telephone follow-up[26]	App: WeChat OS: not specified	Clinical follow-up	• User satisfaction	Self-report on surveys	• Time consumption for each patient (23.36 ± 6.16 min) was significantly shorter compared to telephone follow-up (42.89 ± 7.15 min) ($P < 0.001$) • The overall satisfaction rate with smartphone follow-up was 94.34% compared with 80.43% in telephone follow-up group (95% CI: 0.057-0.067; $P = 0.034$)
132 patients with nasopharyngeal carcinoma who underwent concurrent chemoradiotherapy randomized to smartphone app vs. standard of care[34]	App: not specified OS: not specified	Reduce treatment complications and improve quality of life in the post-treatment period	• Adverse effects of radio- and chemotherapy • Quality of life	Self-report on surveys	• Incidence of adverse effects was significantly lower than in the control group and QoL was significantly higher than in the control group ($P < 0.05$)
88 breast cancer survivors who carried out a 12-week exercise program via smartphone app with pedometer[44]	App: Smart After Care OS: not specified	Promote physical activity	• User satisfaction	Self-report on surveys	• Mean score of overall satisfaction rated on the 5-point Likert scale was 4.22 ± 0.73
40 adolescents with cancer who used a smartphone app for 28 days[33]	App: Pain Squad+ OS: Apple iOS 6	Real-time pain management	• Pain	Self-report on surveys	• Statistically significant improvements in pain intensity, pain interference, and quality of life with app use (effect sizes range: 0.23-0.67)
32 adult patients diagnosed with cancer randomized to 12-week intervention with smartphone app vs. standard of care[28]	App: Runkeeper OS: Android or Apple iOS	Enhance physical activity	• Physical activity	Self-report on surveys	• 51% increase in physical activity (medium estimated effect size $r = 0.40$) and 46% increase in total minutes of physical activity ($r = 0.37$) in patients using smartphone app
284 colon cancer survivors randomized to receive a smartphone with app vs. standard of care[29]	App: SurvivorCHESS OS: not specified	Enhance physical activity, quality of life and distress	• Duration of physical activity • QoL and distress items	Self-report on surveys	• Nonsignificant increase in moderate to vigorous physical activity at 6 months from baseline (19.4 min to 50 min vs 15.5 min to 40.3 min, $P = 0.083$)
102 colorectal cancer patients undergoing chemotherapy who underwent 12 weeks of smartphone aftercare[32]	App: mobile health app paired with wearable device OS: not specified	Improve physical capacity, treatment related symptoms, and health information delivery	• Strength • Cardiorespiratory endurance • Fatigue, nausea, vomiting	Self-report on surveys	• Lower extremity strength and cardiorespiratory endurance were significantly improved after intervention ($P < 0.001$) • Fatigue ($P < 0.007$), nausea, and vomiting ($P < 0.04$) were reduced

(continued on next page)

Table 1 (Continued)

Patients	Smartphone Application and Supported Operating System (OS)	Purpose of Smartphone App	Patient Generated Health Data (PGHD)	Source of PGHD	Key Findings
356 breast cancer patients performing a 12-week regimen of aerobic and resistance exercise randomized to receive a pedometer with smartphone app vs. standard of care[30]	App: smart after care paired with pedometer OS: not specified	Enhance physical function, activity, and QoL	• Step count	Self-report on surveys	• Physical function, activity, and QoL scores were not significantly improved using smartphone app compared to conventional program
112 women diagnosed with breast cancer ≤5 years randomized to smartphone app mindfulness training vs. standard of care[31]	App: HeadSpace OS: Android or Apple iOS	Enhance QoL through mindfulness training	• QoL	Self-report on REDcap	• Higher QoL reported among patients who used app from baseline to follow-up ($P < 0.01$)
30 breast cancer patients receiving chemotherapy using a smartphone app for 90 days during treatment[35]	App: Pit-a-Pat OS: Android or Apple iOS	Collection of patient reported outcomes	• Sleep patterns • Anxiety severity • Mood status	Self-report on app	• There was a 45% overall compliance rate for self-reporting sleep-disturbance data on the app • Patient reporting rate was higher when self-report on the app occurred on the day immediately after enrollment compared to when there was a ≥2 day lag time (51.6% vs 29.6%, $P = 0.03$)
107 patients with stage II-IV breast or colorectal cancer and their spouses using a smartphone app for 14 days[36]	App: not specified OS: Android or Apple	Collection of patient reported outcomes	• Relationship satisfaction • Communication	Self-report on app	• Expressing one's feelings was unassociated with relationship satisfaction in couples with cancer while holding back from doing so was associated with relationship satisfaction in both patients and their spouses
101 patients undergoing routine chemotherapy who used a smartphone app during treatment at least once[37]	App: PRO-SMART OS: Android or Apple iOS	Toxicity monitoring	• Symptomatic AEs associated with chemotherapy	Self-report on app	• There was a significantly increased number of symptomatic AEs recorded in health record after introduction of app compared to usual practice (before PRO-SMART)(mean ± standard deviation increased from 0.92 ± 0.80 to 2.26 ± 1.80, $P < 0.001$) • There was a significantly increased grading of AEs with use of the app compared to usual practice (from 0.81 ± 0.69 to 1.00 ± 0.62, $P = 0.029$).

(continued on next page)

Table 1 (Continued)

Patients	Smartphone Application and Supported Operating System (OS)	Purpose of Smartphone App	Patient Generated Health Data (PGHD)	Source of PGHD	Key Findings
112 patients with lung, breast, or colorectal cancer randomized to use a smartphone app vs. standard of care[48]	App: not specified OS: not specified	Toxicity monitoring	• Life-threatening symptoms	Self-report on app	• Patients reported improvements in communication with health professionals, and in the management and monitoring of their symptoms
100 prostate cancer patients who underwent surgery participating in a pedometer vs. smartphone based exercise program[27]	App: smart after-care paired with pedometer OS: not specified	Enhance physical activity	• Physical status and function	Traditional biometric measurements	• There were increases in physical function in patients using smartphone and pedometers • There were no significant differences in uptake/adherence in the smartphone vs pedometer group

Abbreviations: AE, adverse event; OS, operating system; QoL, quality of life.

recorded (30%, n = 6). For 60% of patients, toxicities were managed over the phone and for 27.5% of patients were sent for urgent medical intervention.[41]

Other opportunities to monitor patients during cancer therapy using digital biomarkers include recording heart rate variability [50] and tracking sleep patterns,[51] both with patterns that have been linked to risk of death. The boundaries of digital PGHD may be expanded to include data that are not directly health-related but may nevertheless influence health outcomes. Examples include location, social, or financial information, all shown to influence treatment adherence in patients treated with definitive radiotherapy.[52,53]

Post-treatment Survivorship Period

Capturing long-term QoL data in the survivorship setting represents a major challenge in oncology. Longitudinal symptom profiling using digital biomarkers could be ideal for the post-treatment setting, a time where face-to-face clinician encounters become infrequent.[42,54] Many potential sequelae of cancer therapy that would be difficult to assess during standard encounters, such as sleep aberrations, decreased mobility, and cognitive decline, could longitudinally be tracked using mobile devices.

To date, there is a lack of published studies that used objective smartphone sensing to capture metrics directly related to QoL in the post-treatment survivorship period. In a study of healthy subjects, an app designed for continuous multiparametric acquisition of movement, location, phone calls, conversations, and data use from patient smartphones was employed to monitor the physical, social, psychological, and environmental aspects of patient health.[55] While feasibility in this population was demonstrated, further studies in cancer patients are needed to accurately correlate QoL items with objective smartphone data. The ability to continuously monitor QoL parameters using PGHD will provide important insight into the long-term morbidity of disease and treatment.

Practical Considerations

Data Collection: Choosing Digital Endpoints

There are several important considerations when using a digital approach to gather PGHD (Fig. 2). Selection of a digital biomarker and an appropriate smartphone sensor platform would ideally be based on high-level clinical data. Physical activity metrics captured using smartphone accelerometers have received the most attention to date. Other digital biomarkers related to toxicity monitoring, such as sleep,[56] movement,[57] vital signs, and quality of life, are actively being researched by several groups.

Endpoints of early-phase trials should include feasibility of data collection and management as well as validation of device reliability. Validation studies may be particularly challenging, as 'gold standard' measurements may be unavailable or prohibitively challenging to acquire. It then becomes

Table 2 Clinical Studies in Cancer Patients Using Smartphone Apps With Embedded Sensors to Record PGHD

Patients	Smartphone Application and Supported Operating System (OS)	Purpose of Smartphone App	Patient Generated Health Data (PGHD)	Source of PGHD	Key Findings
72 patients with cancers who used a smartphone for 14 days[40]	App: Walkmeter OS: Apple iOS 10.2	Measure physical activity	• Step count • Distance traveled	Smartphone global positioning system (GPS)-signal	• Smartphones demonstrated excellent validity for step count when compared to a wearable accelerometer (ICC = 0.97, $P < 0.001$) and fair validity for fitness (ICC = 0.47, $P < 0.001$). • Excellent test-retest reliability for step count (ICC = 0.91, $P < 0.001$).
40 patients aged ≥65 y starting first-line chemotherapy for solid tumors who used a smartphone for 1 cycle[41]	App: GoogleFit OS: Android	Measure physical activity	• Step count	Smartphone accelerometer	• Mean pretreatment daily steps was 311 • 60% of patients had toxicities management over the phone • 27.5% of patients were sent for urgent medical attention and 15% were hospitalized
10 breast cancer survivors who participated in a 10-week pilot study with a smartphone app and health information delivery through Facebook[42]	App: MapMyFitness OS: Android or Apple iOS	Measure and enhance physical activity	• Distance traveled • Step count	Smartphone global positioning system (GPS)-signal	• Average daily moderate-to-vigorous physical activity and steps increased by 2.6 min and 1657, respectively • Average weight and body fat percentage decreased (2.5 kg, 2.3%, respectively)
Cancer patients in a tertiary hospital who used a smartphone app with sensor[43]	App: My Cancer Diary OS: Android or Apple iOS	Patient self-management	• Symptom management • Cancer education	Smartphone camera for patient log on	• Sensor usage by patients to log into smartphone app gradually declined in the first 3 mo.

Abbreviation: ICC, interclass correlation coefficient.

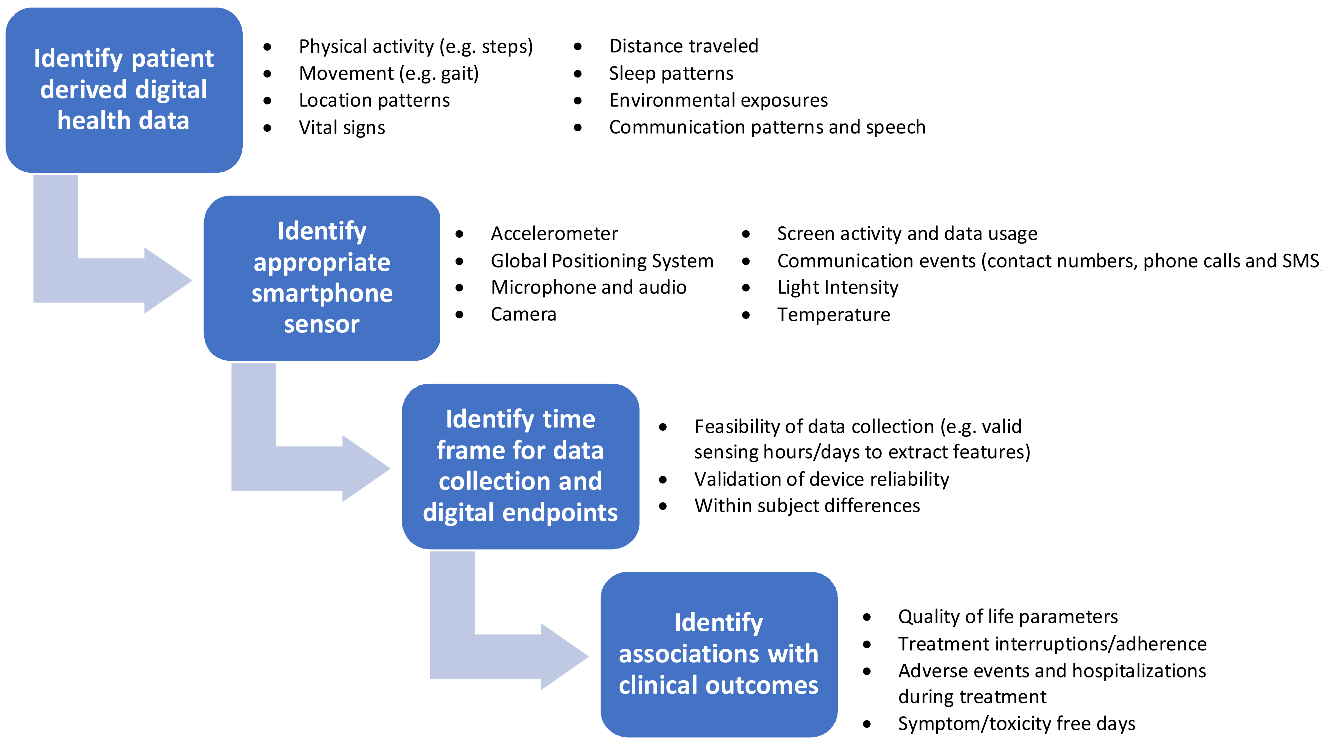

Figure 2 Designing cancer studies using smartphones to collect patient generated health data.

important to focus on within-subject differences, with the expectation that longitudinal changes throughout the treatment or post-treatment survivorship period may have clinical utility.

It will be important to consider the timeframe for PGHD collection with respect to the window when clinical events of interest are likely to occur. For example, when using smartphones to acquire PGHD to predict serious treatment-emergent adverse events, understanding of the physiology of the adverse events would facilitate identification of plausible prodromal periods within a dataset.

Data Collection: Smartphone App Design and Selection

As opposed to an ideal scenario where patients' mobile devices are standardized and provided for the specific purpose of collecting PGHD, many groups will pursue a practical approach, where participants' own mobile devices will be used to obtain PGHD. Allowing participants to use their own mobile devices,[37,42] rather than providing patients smartphones,[29] yields data with high fidelity and ecological validity, though one must be conscious of "a digital divide" among oncology patients and the resulting possibility for bias.

Disparities, including differences in technological availability, health literacy, digital health literacy, and Wi-Fi access may bias investigators to study patients with high socioeconomic status. Most apps available in the Apple mobile application marketplace are in English only,[58] written at reading levels that are too advanced for many patients.[59] Significant differences in digital health use by socioeconomic status for healthcare and health information-seeking items has been reported using data from National Cancer Institute's 2012 Health Information National Trends Survey.[60] Due to these factors, the introduction of technology-based solutions into routine clinical practice could theoretically exacerbate inequities in cancer outcomes. Alternatively, as the use of mobile technology is becoming widespread in low-income and diverse racial/ethnic populations, some have championed mobile health as a strategy for reducing health disparities.[61]

Data Storage

Data collected by an app from a series of sensors is sent to a portal server, where it is stored as part of the back-end component of application software systems. Many apps automatically transport data to their back-end servers when participants gain access to a Wi-Fi or cellular connection. If these data are deemed to represent protected health information, secure storage strategies will be required. Consolidated data should be stored by researchers in password-protected servers and in a deidentified fashion. To allow data to be collected from multiple apps, third-party data integration platforms for secure storage, monitoring, and analysis of PGHD have been developed.

Concluding Thoughts

Smartphones: Big Data, Big Promises

Smartphones are expanding the scope of data gathered in clinical trials and can facilitate the study of novel technology-based interventions for cancer patients. Additionally, mobile devices can provide novel forms of multidimensional data from large patient cohorts. Machine learning techniques, which have already been explored in the field of Radiation Oncology for the development of automated contouring, knowledge-based treatment planning, radiomics-based image analysis, and outcomes modeling, will also play a key role in transforming technical innovations related to mobile devices into clinical gains for our patients. Establishing a scalable infrastructure for collecting, storing, and analyzing information from mobile devices will be critical, as the breadth and depth of available data are expanding rapidly.

References

1. Satista. Number of Smartphone Users Worldwide From 2014 to 2020 (in Billions). https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/. Published by Statista 2019. Accessed April 10, 2019
2. Urwyler P, Stucki R, Rampa L, et al: Cognitive impairment categorized in community-dwelling older adults with and without dementia using in-home sensors that recognise activities of daily living. Sci Rep 7:42084, 2017
3. Silva de Lima AL, Hahn T, Evers LJW, et al: Feasibility of large-scale deployment of multiple wearable sensors in Parkinson's disease. PloS One 12: 2017:e0189161
4. Frias J, Virdi N, Raja P, et al: Effectiveness of digital medicines to improve clinical outcomes in patients with uncontrolled hypertension and type 2 diabetes: prospective, open-label, cluster-randomized pilot clinical trial. J Med Internet Res 19:e246, 2017
5. Shapiro M, Johnston D, Wald J, et al: Patient-Generated Health Data. White paper. Research Triangle Park, NC: RTI International; April 2012
6. Speck RM, Courneya KS, Masse LC, et al: An update of controlled physical activity trials in cancer survivors: a systematic review and meta-analysis. J Cancer Surviv 4:87-100, 2010
7. Ancoli-Israel S, Moore PJ, Jones V: The relationship between fatigue and sleep in cancer patients: a review. Eur J Cancer Care (Engl) 10:245-255, 2001
8. Champ CE, Ohri N, Klement RJ, et al: Assessing changes in the activity levels of breast cancer patients during radiation therapy. Clin Breast Cancer 18:e1-e6, 2018
9. Bennett AV, Reeve BB, Basch EM, et al: Evaluation of pedometry as a patient-centered outcome in patients undergoing hematopoietic cell transplant (HCT): a comparison of pedometry and patient reports of symptoms, health, and quality of life. Qual Life Res 25:535-546, 2016
10. Ferriolli E, Skipworth RJ, Hendry P, et al: Physical activity monitoring: a responsive and meaningful patient-centered outcome for surgery, chemotherapy, or radiotherapy? J Pain Symptom Manage 43:1025-1035, 2012
11. Lowe SS, Danielson B, Beaumont C, et al: Associations between objectively measured physical activity and quality of life in cancer patients with brain metastases. J Pain Symptom Manage 48:322-332, 2014
12. Maddocks M, Wilcock A: Exploring physical activity level in patients with thoracic cancer: implications for use as an outcome measure. Support Care Cancer 20:1113-1116, 2012
13. Ohri N, Kabarriti R, Bodner WR, et al: Continuous activity monitoring during concurrent chemoradiotherapy. Int J Radiat Oncol Biol Phys 97:1061-1065, 2017
14. Purswani JM, Ohri N, Champ C: Tracking steps in oncology: the time is now. Cancer Manag Res 10:2439-2447, 2018
15. Major MJ, Alford M: Validity of the iPhone M7 motion co-processor as a pedometer for able-bodied ambulation. J Sports Sci 34:2160-2164, 2016
16. Dey S, Sahoo S, Agrawal H, et al: Personalized cumulative UV tracking on mobiles and wearables. Conf Proc IEEE Eng Med Biol Soc 2017:2341-2344, 2017
17. Treehugger. Smartphone Case Protects Your Phone, While Its Built-in Sensors Help Protect Your Lungs. https://www.treehugger.com/gadgets/smartphone-case-protects-your-phone-while-its-built-sensors-help-protect-your-lungs.html. Published by Treehugger 2017. Accessed April 11, 2019
18. Nam Y, Lee J, Chon KH: Respiratory rate estimation from the built-in cameras of smartphones and tablets. Ann Biomed Eng 42:885-898, 2014
19. Alexander JC, Minhajuddin A, Joshi GP: Comparison of smartphone application-based vital sign monitors without external hardware versus those used in clinical practice: a prospective trial. J Clin Monit Comput 31:825-831, 2017
20. Lim J, Cloete G, Dunsmuir DT, et al: Usability and feasibility of PIERS on the move: an mHealth app for pre-eclampsia triage. JMIR Mhealth Uhealth 3:e37, 2015
21. Banos O, Villalonga C, Damas M, et al: PhysioDroid: combining wearable health sensors and mobile devices for a ubiquitous, continuous, and personal monitoring. Sci World Jo 2014: 2014:490824
22. Petersen CL, Gan H, MacInnis MJ, et al: Ultra-low-cost clinical pulse oximetry. Conf Proc IEEE Eng Med Biol Soc 2013:2874-2877, 2013
23. Duregger K, Hayn D, Morak J, et al: An mHealth system for toxicity monitoring of paediatric oncological patients using Near field communication technology. Conf Proc IEEE Eng Med Biol Soc 2015:6848-6851, 2015
24. Raghunathan NJ, Korenstein D, Li QS, et al: Determinants of mobile technology use and smartphone application interest in cancer patients. Cancer Med 7(11):5812-5819, 2018
25. El Shafie RA, Weber D, Bougatf N, et al: Supportive care in radiotherapy based on a mobile app: prospective multicenter survey. JMIR Mhealth Uhealth 6:e10916, 2018
26. Lyu KX, Zhao J, Wang B, et al: Smartphone application WeChat for clinical follow-up of discharged patients with head and neck tumors: a randomized controlled trial. Chin Med J (Engl) 129:2816-2823, 2016
27. Lee BJ, Park YH, Lee JY, et al: Smartphone application versus pedometer to promote physical activity in prostate cancer patients. Telemed J E Health, 2019. [Epub ahead of print]
28. Ormel HL, van der Schoot GGF, Westerink NL, et al: Self-monitoring physical activity with a smartphone application in cancer patients: a randomized feasibility study (SMART-trial). Support Care Cancer 26:3915-3923, 2018
29. Mayer DK, Landucci G, Awoyinka L, et al: SurvivorCHESS to increase physical activity in colon cancer survivors: can we get them moving? J Cancer Surviv 12:82-94, 2018
30. Uhm KE, Yoo JS, Chung SH, et al: Effects of exercise intervention in breast cancer patients: is mobile health (mHealth) with pedometer more effective than conventional program using brochure? Breast Cancer Res Treat 161:443-452, 2017
31. Rosen KD, Paniagua SM, Kazanis W, et al: Quality of life among women diagnosed with breast Cancer: a randomized waitlist controlled trial of commercially available mobile app-delivered mindfulness training. Psychooncology 27:2023-2030, 2018
32. Cheong IY, An SY, Cha WC, et al: Efficacy of mobile health care application and wearable device in improvement of physical performance in colorectal cancer patients undergoing chemotherapy. Clin Colorectal Cancer 17:e353-e362, 2018
33. Jibb LA, Stevens BJ, Nathan PC, et al: Implementation and preliminary effectiveness of a real-time pain management smartphone app for adolescents with cancer: a multicenter pilot clinical study. Pediatr Blood Cancer 64:10, 2017

34. Di R, Li G: Use of a smartphone medical app improves complications and quality of life in patients with nasopharyngeal carcinoma who underwent radiotherapy and chemotherapy. Med Sci Monit 24:6151-6156, 2018
35. Min YH, Lee JW, Shin YW, et al: Daily collection of self-reporting sleep disturbance data via a smartphone app in breast cancer patients receiving chemotherapy: a feasibility study. J Med Internet Res 16:e135, 2014
36. Langer SL, Romano JM, Todd M, et al: Links between communication and relationship satisfaction among patients with cancer and their spouses: results of a fourteen-day smartphone-based ecological momentary assessment study. Front Psychol 9:1843, 2018
37. Bae WK, Kwon J, Lee HW, et al: Feasibility and accessibility of electronic patient-reported outcome measures using a smartphone during routine chemotherapy: a pilot study. Support Care Cancer 26:3721-3728, 2018
38. Ferriolli E, Skipworth RJ, Hendry P, et al: Physical activity monitoring: a responsive and meaningful patient-centered outcome for surgery, chemotherapy, or radiotherapy? J Pain Symptom Manag 43:1025-1035, 2012
39. Zulueta J, Piscitello A, Rasic M, et al: Predicting mood disturbance severity with mobile phone keystroke metadata: a biaffect digital phenotyping study. J Med Internet Res 20:e241, 2018
40. Douma JAJ, Verheul HMW, Buffart LM: Feasibility, validity and reliability of objective smartphone measurements of physical activity and fitness in patients with cancer. BMC Cancer 18:1052, 2018
41. Soto-Perez-De-Celis E, Kim H, Rojo-Castillo MP, et al: A pilot study of an accelerometer-equipped smartphone to monitor older adults with cancer receiving chemotherapy in Mexico. J Geriatr Oncol 9:145-151, 2018
42. Pope Z, Lee JE, Zeng N, et al: Feasibility of smartphone application and social media intervention on breast cancer survivors' health outcomes. Transl Behav Med 9:11-22, 2019
43. Park YR, Lee Y, Lee G, et al: Smartphone applications with sensors used in a tertiary hospital-current status and future challenges. Sensors (Basel) 15:9854-9869, 2015
44. Lee H, Uhm KE, Cheong IY, et al: Patient satisfaction with mobile health (mhealth) application for exercise intervention in breast cancer survivors. J Med Syst 42:254, 2018
45. Bort-Roig J, Gilson ND, Puig-Ribera A, et al: Measuring and influencing physical activity with smartphone technology: a systematic review. Sports Med 44:671-686, 2014
46. Gresham G, Hendifar AE, Spiegel B, et al: Wearable activity monitors to assess performance status and predict clinical outcomes in advanced cancer patients. NPJ Digit Med 1:27, 2018
47. Basch E, Deal AM, Dueck AC, et al: Overall survival results of a trial assessing patient-reported outcomes for symptom monitoring during routine cancer treatment. JAMA 318(2):197-198, 2017
48. McCann L, Maguire R, Miller M, et al: Patients' perceptions and experiences of using a mobile phone—based advanced symptom management system (ASyMS) to monitor and manage chemotherapy related toxicity. Eur J Cancer Care 18:156-164, 2009
49. Maguire R, Fox PA, McCann L, et al: The eSMART study protocol: a randomised controlled trial to evaluate electronic symptom management using the advanced symptom management system (ASyMS) remote technology for patients with cancer. BMJ Open 7: 2017:e015016
50. Kloter E, Barrueto K, Klein SD, et al: Heart rate variability as a prognostic factor for cancer survival—a systematic review. Front Physiol 9:623, 2018
51. Collins KP, Geller DA, Antoni M, et al: Sleep duration is associated with survival in advanced cancer patients. Sleep Med 32:208-212, 2017
52. Ohri N, Rapkin BD, Guha D, et al: Predictors of radiation therapy noncompliance in an urban academic cancer center. Int J Radiat Oncol Biol Phys 91:232-238, 2015
53. Ohri N, Rapkin BD, Guha C, et al: Radiation Therapy Noncompliance and Clinical Outcomes in an Urban Academic Cancer Center. Int J Radiat Oncol Biol Phys 95(2):563-570, 2016
54. Pope Z, Lee JE, Zeng N, et al: Feasibility of smartphone application and social media intervention on breast cancer survivors' health outcomes. Transl Behav Med 9(1):11-12, 2018
55. Asensio-Cuesta S, Sanchez-Garcia A, Conejero JA, et al: Smartphone sensors for monitoring cancer-related quality of life: app design, EORTC QLQ-C30 mapping and feasibility study in healthy subjects. Int J Environ Res Public Health 16: 2019
56. Saeb S, Cybulski TR, Schueller SM, et al: Scalable passive sleep monitoring using mobile phones: opportunities and obstacles. J Med Internet Res 19:e118, 2017
57. Pepa L, Verdini F, Spalazzi L: Gait parameter and event estimation using smartphones. Gait Posture 57:217-223, 2017
58. Davis DW, Logsdon MC, Vogt K, et al: Parent education is changing: a review of smartphone apps. MCN Am J Matern Child Nurs 42:248-256, 2017
59. Kim C, Prabhu AV, Hansberry DR, et al: Digital era of mobile communications and smartphones: a novel analysis of patient comprehension of cancer-related information available through mobile applications. Cancer Invest 102(3):1-7, 2019
60. Kontos E, Blake KD, Chou WY, et al: Predictors of eHealth usage: insights on the digital divide from the Health Information National Trends Survey 2012. J Med Internet Res 16:e172, 2014
61. Vangeepuram N, Mayer V, Fei K, et al: Smartphone ownership and perspectives on health apps among a vulnerable population in East Harlem, New York. Mhealth 4:31, 2018