
Research and Applications

The REDCap Mobile Application: a data collection platform for research in regions or situations with internet scarcity

Paul A. Harris ^{1,2,3,4}, Giovanni Delacqua², Robert Taylor², Scott Pearson², Michelle Fernandez², and Stephany N. Duda^{1,2}

¹Department of Biomedical Informatics, Vanderbilt University Medical Center, Nashville, Tennessee, USA, ²Vanderbilt Institute for Clinical and Translational Research, Vanderbilt University Medical Center, Nashville, Tennessee, USA, ³Department of Biomedical Engineering, Vanderbilt University, Nashville, Tennessee, USA, and ⁴Department of Biostatistics, Vanderbilt University Medical Center, Nashville, Tennessee, USA

Corresponding Author: Paul A. Harris, PhD, Department of Biomedical Informatics, Vanderbilt University Medical Center, 2525 West End Avenue, Suite 1500, Nashville, TN 37203, USA; paul.a.harris@vumc.org

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ABSTRACT

Objectives: To share our approach for designing, developing, and deploying the Research Electronic Data Capture (REDCap) Mobile Application, details about its dissemination and support through the REDCap Consortium, and a set of lessons learned and guidance recommendations for others developing mobile platforms to support research in regions or situations with internet scarcity.

Materials and Methods: We defined minimum viable product requirements centered around Android and iOS platform availability, data capture specifications and project initiation workflow, study data synchronization, and data security. After launch, we added features based on feedback from end-users and REDCap administrators. We prioritized new features based on expected impact, difficulty, and anticipated long-term cost for sustainability.

Results: We chose Apache Cordova, a combined iOS and Android development framework, based on targeted end-user technology expectations, available programmer resources, and the need to provide solutions for resource-limited settings. The REDCap Mobile Application was launched in 2015, has been enabled at over 800 REDCap Consortium partner organizations, and has supported diverse scientific studies around the world.

Discussion: Apache Cordova enabled early software releases for both iOS and Android, but required ongoing optimization efforts to improve software responsiveness. Developing a robust and efficient mobile device synchronization architecture was difficult without direct access to global network infrastructures for testing. Research teams in sub-Saharan Africa helped our development team understand and simulate real-world scenarios of intermittent internet connectivity.

Conclusion: Guidance recommendations based on designing, developing, deploying, and disseminating the REDCap Mobile Application may help other teams looking to develop clinical research informatics applications.

Key words: clinical trials, database management systems, medical informatics, translational medical research, mobile applications

LAY SUMMARY

We created the Research Electronic Data Capture (REDCap) Mobile Application to allow research teams the option of using a non-internet-connected mobile device for field data collection, with synchronization to a “parent” REDCap database project whenever internet connectivity could be established. Tight integration with the REDCap web application platform, coupled with a large existing REDCap user community, contributed to rapid adoption. The REDCap Mobile Application is now an established platform with a successful track record supporting research teams conducting diverse scientific studies around the world, especially in regions or situations with internet scarcity. This manuscript provides a synopsis of our approach for designing, developing, and deploying the REDCap Mobile Application, and details about its dissemination and support through the REDCap Consortium. We also include a set of guidance recommendations for others developing mobile platforms to support clinical and translational research in rural or global health environments.

BACKGROUND AND SIGNIFICANCE

Data collection represents the first stage of the research data life-cycle and is crucial for the conduct of investigation and ultimately the dissemination of findings in clinical and translational research.¹ Inadequate access to data management resources can present a barrier for individual clinical and translational investigators.² In supporting the research enterprise at Vanderbilt University Medical Center (VUMC), we recognized in 2004 the need for a secure, web-based data collection and management platform suitable for use across diverse medical domains. We created REDCap (Research Electronic Data Capture) to give researchers a self-service platform for data planning, collection, and sharing.³ In 2006, we began the REDCap Consortium, allowing any academic, nonprofit, or government organization to use the REDCap software at no cost for local hosting and support of local research teams.⁴ Since that time, the REDCap Consortium has grown to support over 1.6M research team members at nearly 5000 licensed partners in 141 countries.⁵ Through our work at VUMC and in the REDCap Consortium, we have observed that providing research teams with easily deployable tools for data planning, capture, and management leads to a wide diversity of innovative use cases. Through common bibliometrics from Google Scholar⁶ and Web of Science,⁷ we have discovered more than 12 000 citations of REDCap use between 2009 and 2020. During this time period, citations were noted from 2460 highly diverse research journals, including the *New England Journal of Medicine*, *Lancet*, *British Medical Journal*, *Journal of the American Medical Association*, and the *Australian Veterinary Journal*.

REDCap is a web-based system and can be easily deployed in on-premises data centers or cloud environments. End-users require only a web browser and internet connection to do their work. Advantages of this approach over traditional software that is installed on a single computer (eg, Microsoft Office) includes ease of deployment, centralized security, scalability, and the ability to deploy and support new versions and features over time without requiring a system administrator to support device management. A disadvantage of the web-based approach is dependency on internet connectivity. In countries with pervasive high-speed internet availability, there remain specific geographic (eg, rural) and organizational (eg, schools, prisons) environments where clinical and translational research is conducted, but internet connectivity cannot be assumed. Reliable internet connectivity in resource-limited countries presents a greater challenge. According to a 2019 World Bank report, nearly every country in the world has a growing percentage of its population using the internet, but a real digital divide persists among high-income (86% of population using internet), middle-

income (47%), and low-income (16%) countries.⁸ In our work distributing and supporting REDCap across more than 140 countries, we have observed that academic medical centers, hospitals, and government organizations often have reliable internet connectivity and can therefore take full advantage of a web-based system as long as researchers are working within the organization’s digital environment. That said, internet connectivity may be largely unavailable for researchers conducting field visits to capture information needed for clinical and translational research studies. As illustrated by a 2017 State of the Internet report on Connectivity, speeds and reliability vary greatly by region and by country.⁹

In 2014, we sought to create the REDCap Mobile Application to allow research teams the option of using a non-internet-connected mobile device for field data collection, with synchronization to a “parent” REDCap database project whenever internet connectivity could be established. This manuscript provides a synopsis of our approach for designing, developing, and deploying the REDCap Mobile Application, and details about its dissemination and support through the REDCap Consortium. We also include a set of guidance recommendations for others developing mobile platforms to support research in regions or situations with internet scarcity.

MATERIALS AND METHODS

Designing the platform

In keeping with our established approach for creating new REDCap features and functionality, our goal in developing REDCap Mobile Application was to “build small, evaluate, and evolve.” Based on feedback from local and Consortium-based research teams, we defined the following minimum viable product requirements:

Platform requirements:

- Provide native applications for use on iOS and Android devices.
- Avoid internet dependency except when downloading and setting up REDCap Mobile Application for a specific project and periodic synchronization of data preceding and following field data collection.
- Build capability to use a single REDCap Mobile Application-enabled mobile device to support simultaneous REDCap field collection projects on multiple projects.

Data security requirements:

- Ensure encryption-at-rest data storage on local REDCap Mobile Application devices and encrypted transmission during study metadata and data synchronization processes.

- Empower REDCap Administrators to remotely remove and clear out any saved data on any REDCap Mobile Application device associated with their local REDCap environment.

Study setup and data capture requirements:

- Support rapid setup of new data collection projects on REDCap Mobile Application-enabled devices through Quick Response code or alternate numeric code.
- Replicate REDCap's web application data collection functionality for case report forms, file uploads, and survey instruments, with per-project instructions defined by importing the parent REDCap project metadata (fields, instruments, events, arms) into REDCap Mobile Application.
- Develop setup procedures using human factor design principles to ensure diverse research teams across the REDCap Consortium can initiate and manage research projects using the REDCap Mobile Application with little or no support from local REDCap Administrators.

Study data synchronization requirements:

- Develop reliable and intuitive synchronization processes to ensure seamless transfer of collected data between REDCap Mobile Application devices and the REDCap project database.
- Maintain a local log of all project data activity on the REDCap Mobile Application device until synchronization has occurred and log all data imported back to the REDCap web server after synchronization.
- Support mid-study modifications to data collection forms. REDCap Mobile Application project-level metadata updates should be recognized and refreshed on REDCap Mobile Application devices any time internet connectivity is established for data synchronization so that field collectors are always equipped with latest study data collection instruments as defined in the parent REDCap project database.

Technology selection and initial development

After defining minimum viable product requirements and confirming plans with potential research end-users at VUMC and the REDCap Consortium, we investigated and chose a mobile application technology stack and began development. REDCap Mobile Application uses the Apache Cordova Framework, which is an open-source mobile development JavaScript framework.¹⁰ The core of an Apache Cordova application uses CSS3 and HTML5 for rendering and JavaScript for logical operations, and it allows cross-platform development for iOS and Android platforms. Applications execute within a wrapper targeted to each platform, and rely on standards-compliant application programming interface (API) bindings to access each device's capabilities such as sensors, data, and network status. REDCap Mobile Application extends the basic Apache Cordova functionalities by using plugins, allowing additional functionality that can be called from JavaScript, making it communicate directly between the native layer and the HTML5 page. These plugins allow access to mobile application functions like camera, compass, file system, and microphone.

We began REDCap Mobile Application development in Q1 2014, shared the initial offering with VUMC researchers for testing and feedback in Q4 2014, and released the application to the global REDCap Consortium in Q2 2015. Initial development and deployment to the REDCap Consortium required approximately 6 person-months for programming, approximately 2 person-months for de-

velopment of documentation and training materials, approximately 2 person-months supporting publishing of REDCap Mobile Application to iOS and Android Application stores, and approximately 3 person-months for project socialization and feedback exercises (eg, weekly consortium calls refining requirements, technical office hours), and full utilization of our REDCap Consortium support team and information exchange resources.⁴

Evolution of the REDCap Mobile Application platform

We deployed REDCap Mobile Application as an optional REDCap module to the REDCap Consortium in May 2015. Since that time, we have added many features and functions in response to direct feedback from end-users or indirect feedback through communication with local REDCap administrators. Prioritization was typically based on 4 factors: expected impact in terms of new projects or research teams supported; implementation difficulty level; anticipated long-term cost for sustainability; and anticipated ability to add features and functions in a manner allowing autonomous use by diverse research teams with little or no support from local REDCap Administrators.

One example of platform functionality added after initial product launch included the development of a crowd-sourced language translation methodology that allows the entire REDCap Mobile Application framework to be rendered in any language desired by a local study team. The REDCap Consortium currently supports REDCap Mobile Application translations in English, Spanish, simple Chinese, traditional Chinese (Taiwan), French, Japanese, German, Vietnamese, Brazilian Portuguese, and Russian. Other new features focused on simplifying study setup, streamlining data collection workflow for field data capture, maintaining data type and collection instrument feature parity with the REDCap web application, and optimizing data synchronization and logging support processes.

Our release cadence for new features and functions for the REDCap Mobile Application is approximately monthly. Estimated VUMC annual resources required to continually maintain and evolve the REDCap Mobile Application platform and disseminate to the REDCap Consortium include 120 person-hours per month for application development and maintenance, 50 person-hours per month for REDCap Consortium support (eg, office hours, weekly assistance webinar, documentation, committee organization for language translations, end-user FAQ documentation), and 10 person-hours per month for strategic development and new innovation planning.

RESULTS

The REDCap Mobile Application was launched and disseminated to the REDCap Consortium as an optional module in May 2015. A summary of our local VUMC utilization metrics in January 2021 showed 296 REDCap projects with data imported from devices running REDCap Mobile Application and 1004 end-users utilizing either iOS or Android devices for data collection in support of these projects. While these numbers are modest in relation to the overall number of active REDCap data collection projects (~31 000) and end-users (~38 000) currently supported at VUMC, they are surprisingly high given the availability of internet connectivity in our home city of Nashville, Tennessee, and surrounding areas. A closer look at the projects utilizing REDCap Mobile Application at VUMC indicated that many are supporting studies where VUMC is acting as a central data coordinating center with data collection in rural or international settings.

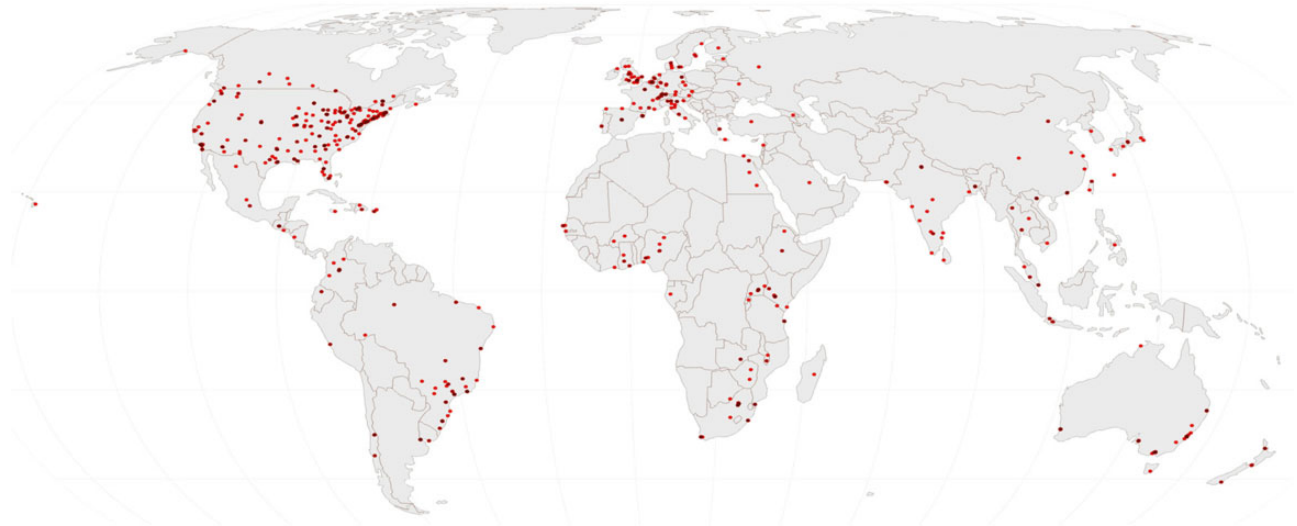


Figure 1. Geographical location of REDCap Consortium partner institutions enabling use of the REDCap Mobile Application (January 2021).

Based on consortium metric reporting, we are aware of 802 REDCap Consortium partner organizations that have enabled REDCap Mobile Application for use by local research teams as of January 2021. **Figure 1** provides a geographic representation of these organizations and clearly illustrates global adoption of the platform. Reinforcing this point, **Table 1** provides partner institution metrics and summary use statistics by world geographic region. **Figure 2** provides a graphical view of REDCap Mobile Application end-users registered to REDCap Consortium partner organizations in low- and middle-income countries (LMICs).¹¹ This is undoubtedly a conservative estimate of LMIC field collection use because we are not reporting on projects where a central data coordinating center might be in a high-income country with field collectors operating in other countries.

Distribution of REDCap Mobile Application to individual devices is typically performed through either the Google/Android Application store or through the Apple/iOS Application store. **Figure 3** provides a temporal view of the Android downloads for the top 10 countries over time.¹² Although US installations are proportionally high, relative growth of installations in LMICs has contributed significantly to the Android REDCap Mobile Application user base population over the last 4 years. **Figure 4** provides similar counts of REDCap Mobile Application downloads for Apple iOS devices.¹³ Apple REDCap Mobile Application downloads skew toward high-income countries.

REDCap is a distributed platform, and we generally only know crude count metrics from our partner institutions rather than project

specifics. Given this, real-world impact measures of the REDCap Mobile Application are limited. A January 2021 Google Scholar search for “REDCap Mobile” yielded 85 references.⁶ Based on this published body of work, information about projects from our local REDCap support team, and anecdotal feedback from collaborators in the REDCap Consortium, we compiled a short list of vignettes highlighted in **Table 2**. This is not an exhaustive list of projects utilizing the REDCap Mobile Application, but rather a single vignette in each continent region of the world selected to illustrate use case diversity and suitability for use of the platform across the globe.

DISCUSSION

Our primary goal in developing the REDCap Mobile Application was to provide research teams a means of collecting data in the field where internet connectivity is nonexistent or unreliable. Strong uptake of the application globally indicates the software addresses a need for mobile data collection in both high-resourced and resource-limited settings.

We accepted a clear tradeoff in our selection of the Apache Cordova framework for application development. Apache Cordova packages a JavaScript application in an iOS or Android wrapper to deliver a browser-based rendering of applications on a mobile device.¹⁰ By maintaining a single code-base that runs on both iOS and Android, we reduced the number of developer and programming language requirements to support the REDCap Mobile Application. We were also able to develop simultaneously for Android and iOS to accommodate our global user base. However, running code through Apache Cordova can reduce software performance compared to native operating system development frameworks. Time saved at the outset may have been lost later, as our team spent considerable effort optimizing performance to ensure research end-users a reliable and responsive data collection experience.

Our greatest challenge was developing a robust and efficient mobile device synchronization architecture without ready and direct access to a variety of global network infrastructures for testing. Research teams in sub-Saharan Africa were our most valuable collaborators in refining synchronization procedures, connected to us through local REDCap administrators in South Africa, Kenya, Rwanda, Nigeria, Ethiopia, Malawi, Ghana, and Sudan. These indi-

Table 1. Geographical breakdown of REDCap Consortium partner institutions using REDCap Mobile Application, including number of projects receiving data and end-users associated with REDCap Mobile Application projects (January 2021)

Geographical region	Partners	Projects	End-users
East Asia and Pacific	118	1153	1818
Europe and Central Asia	136	740	1556
Latin America and Caribbean	113	897	2005
Middle East and North Africa	8	25	60
North America	306	4913	9281
South Asia	23	236	357
Sub-Saharan Africa	98	1907	4559
Total	802	9871	19 636

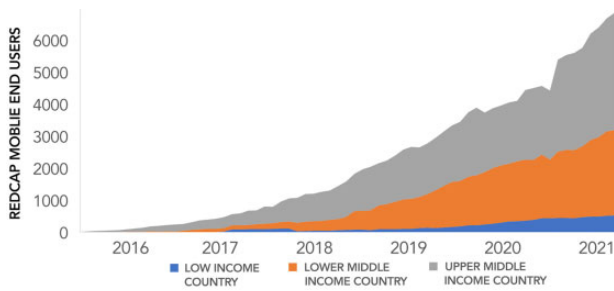


Figure 2. REDCap Mobile Application end-user counts spanning May 2015 to December 2020 from all REDCap Consortium partner institutions located in low- and middle-income countries as defined by the World Bank June 2020 country income classifications.¹¹

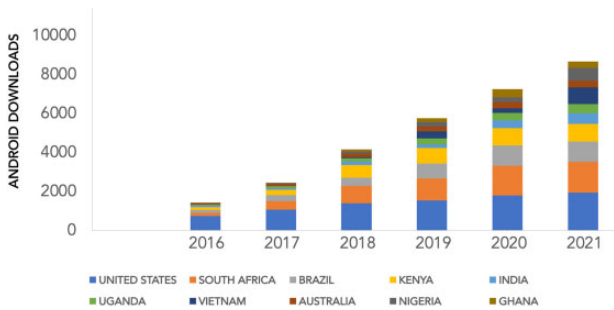


Figure 3. REDCap Mobile Application installations per year on Android devices by country-level download location. Data obtained from Google Play Console (January 18, 2021).¹²

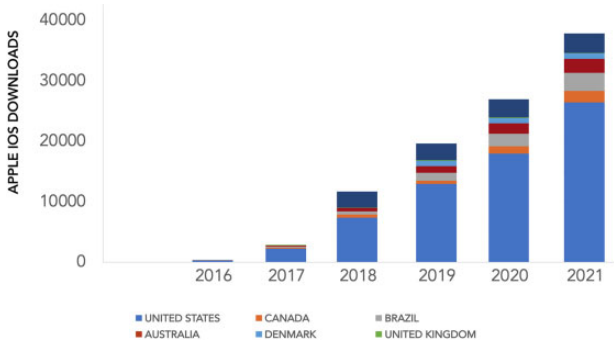


Figure 4. REDCap Mobile Application installations per year on Apple devices. The graph includes metrics for 7 countries. We were only able to obtain metrics for highest download countries each year and these were not always the same list of countries each. In cases where a country count was previously present, but not in the top 5 countries for the next year, we assumed zero downloads for reporting purposes. Metrics were obtained from Apple Application Store Connect.¹³

viduals helped our development group at VUMC understand and simulate real-world scenarios of intermittent internet connectivity. Specifically, we learned that even when internet connectivity is available, within-session bandwidth constriction and intermittent connection loss must be anticipated during data synchronization operations. Based on these findings, we reworked back-end technical methods to reduce the number of client-to-server API calls to avoid potential disconnections and data loss. We also built user-friendly data transfer remediation workflows to ensure failover pro-

cesses were available and that sufficient redundancy was built into the synchronization process to ensure lossless transfer. Figure 5 provides a high-level block architecture diagram and description of the synchronization process. Through these active collaborations and real-world early adopters, we were able to refine our processes and build a better product for other research teams across the world.

Other mobile platforms and technologies are available for field-based research data collection, including open-source and commercial solutions like Open Data Kit, Kobo Toolbox, Comcare, and Magpi.^{19–22} We were also aware of teams using the web version of REDCap in regions of internet scarcity by installation of the entire technology stack (web server, database server, and REDCap source code) on standalone laptops.^{23,24} Our goal in creating a native REDCap Mobile Application solution was not to compete with these or other data collection products, but rather to build a product that integrated well and complemented our REDCap web application platform. This philosophical construct helped us solidify initial scoping requirements in defining a minimum viable product for launch and also in subsequent features added to maintain parity between the REDCap Mobile Application and the REDCap web platform. Tight integration with the REDCap web application platform, coupled with a large existing REDCap user community, contributed to rapid adoption by diverse research teams around the world. Continuous input from REDCap researchers and administrators has proven invaluable in prioritizing the development and deployment of a useful product intentionally designed to support global biomedical research.

We include below a list of lessons learned and guidance recommendations for others developing mobile platforms to support research in regions or situations with internet scarcity:

- Designing and deploying a general use mobile application platform to support diverse clinical and translational research studies across a large number of geographic regions is more challenging than building a targeted platform for use by a single team supporting a single project. Engaging global partners to help test the device in diverse, real-world settings was essential.
- Mobile application data synchronization is difficult and requires time and planning. This is especially true in anticipated projects where data collections may change over time.
- Choosing a mobile application development framework is important and should be based in part on targeted end-user technology expectations. Android solutions are essential for LMIC deployment.
- Managing expectations for end-user support is challenging. Direct end-user engagement has been proportionally higher for our REDCap Mobile Application development team than our REDCap web-based application development team due in part to the fact that there are fewer “experts” in the REDCap Consortium who can provide direct advice for other administrators. We do not charge for our platform and provide *pro bono* support for a very large end-user community, so minimizing our support investment means we can spend more time and resources can be used for development. One strategy that has worked well to minimize support investment included establishment of a common access email inbox with an automated reply that sends users a listing of the options available for assistance and technical support. Examples include how to report a bug or software issue, reminders for embedded in-Application or online frequently asked questions, reminder of local REDCap administrator expertise, and information for scheduled weekly direct support call times.

Table 2. Selected REDCap Mobile Application vignettes from around the world

South America (Brazil)	A study in Botswana reported that the new antiretroviral drug used to treat HIV, dolutegravir, might cause neural tube defects in infants born to women exposed to dolutegravir during pregnancy. As the dolutegravir rollout had begun earlier in Brazil than in other countries, the Brazilian government conducted a rapid chart review of pregnant women exposed to dolutegravir around the time of conception and matched controls ($n = 1427$). To conduct the country-wide chart review, which included remote villages in the Amazon, the Brazilian Ministry of Health prepared 74 tablets with the REDCap Mobile Application and trained data abstractors during a multi-day, hands-on workshop ¹⁴
Oceania (Fiji)	A research team with collaborators in Fiji and Australia used the REDCap Mobile Application to measure and compare the incidence of scabies and impetigo in young children, the elderly, and iTaukei (Indigenous Fijian). Their findings highlighted skin and soft tissue infections as an important public health concern and increased awareness for additional research funding to alleviate ¹⁵
Africa (Ghana)	A research team in Ghana used the REDCap Mobile Application to study health supply chain worker's capacity and competency to perform supply chain functions. Findings were useful in informing workforce development strategy ¹⁶
Asia (Vietnam)	The mobile REDCap Mobile Application has been used in Vietnam for data collection and management of several epidemiological research projects. These include the Vietnam Breast Cancer Study (a hospital-based case-control study of 500 cases and 500 controls); a 1000-participant community-based survey for diabetes and metabolic condition in urban and rural districts of Vietnam; the Vietnam Colorectal Polyps and Cancer Research (VinCAPR); and a randomized clinical trial studying the influence of peanut consumption on cardiovascular risk factors and the gut microbiome
Europe (England)	A group in London is using the REDCap Mobile Application to assess the feasibility of conducting a future trial in further education colleges to investigate if frequent, rapid, on-site testing and treatment reduces chlamydia rates in sexually active male and female students ¹⁷
North America (United States)	A team in Tennessee examined severity of food insecurity, interrelatedness of social determinants of health, and ways that physicians and community food banks are addressing the topic. The research team collected data using the REDCap Mobile Application on an iPad without Wi-Fi and uploaded after daily site visits ¹⁸

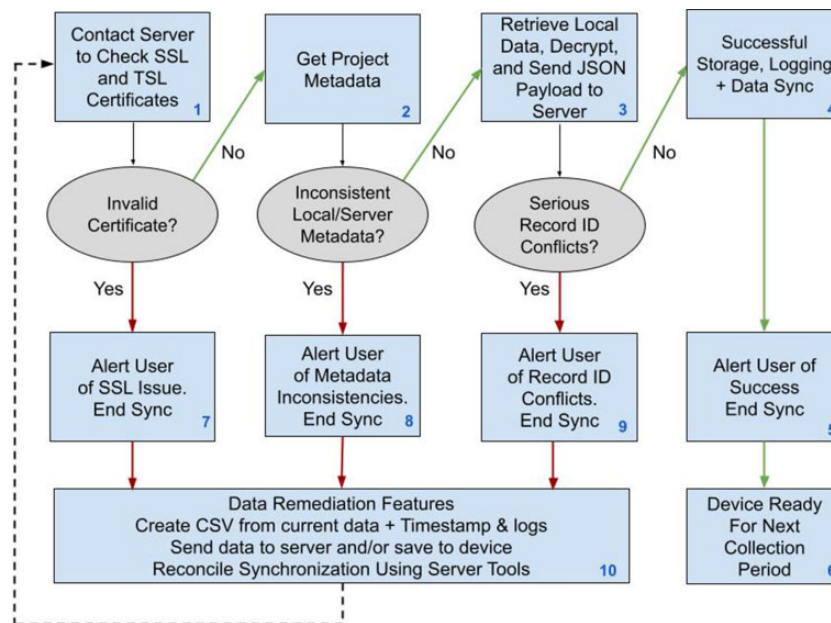


Figure 5. The synchronization process begins with an end-user selecting a function on the REDCap Mobile Application (RMA). Once initiated, the RMA device contacts the REDCap server through secure, wireless internet connection and checks SSL and TSL certificates (1). If certificates are valid, RMA retrieves project metadata from the REDCap server (2) and checks for consistency, a necessary step given data instruments may have changed since last synchronization. If metadata are similar, the RMA runs a function to decrypt all locally stored data records for transfer (3). A server-side synchronization algorithm then checks for record ID conflicts, a necessary step given new records may have been collected and transferred from other RMA devices or REDCap web user interface tools since last RMA synchronization. If record ID conflicts are nonexistent or record IDs can be automatically renamed by algorithm, the RMA uploads all data to the REDCap server (4) and then alerts the end-user of successful synchronization (5) and readiness of RMA device for continued field-level use (6). If errors or issues are detected at any point in the RMA synchronization process, the end-user is notified (7–9) and instructed to take remediation steps for data and device synchronization using server-side tools (10).

CONCLUSION

The REDCap Mobile Application is an established platform with a successful track record supporting research teams conducting diverse scientific studies around the world. The platform has evolved over time, and we anticipate future enhancements as we strive to maintain parity between REDCap web application and REDCap Mobile Application products, evaluate new development framework options for enhanced performance, and further optimize bi-directional synchronization options between local REDCap servers and the REDCap Mobile Application.

Tight integration with the REDCap web platform is a distinguishing strength of the REDCap Mobile Application, reducing the need for clinical research informatics teams to support multiple software platforms while also minimizing software training time for research teams already familiar with REDCap. Our model of developing, launching, and disseminating a minimum viable product to the REDCap Consortium, then listening to the community of adopting researchers for evaluation and evolution has produced a widely adopted application. Guidance recommendations based on designing, developing, deploying, and disseminating the REDCap Mobile Application may help other teams looking to develop clinical research informatics applications.

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AUTHOR CONTRIBUTIONS

PAH, GD, and SND conceived and designed the study, participated in data analysis and interpretation, drafted the manuscript, made critical revisions to the manuscript, and approved the final version for submission. RT, SP, and MF conceived and designed the study, drafted the manuscript, and approved the final version for submission.

CONFLICT OF INTEREST STATEMENT

None declared.

DATA AVAILABILITY STATEMENT

The data underlying this article are available in the article.

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