OpTrak: Tracking Opioid Prescriptions via Distributed Ledger Technology

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ABSTRACT

This paper describes the structure and functionality of OpTrak, which is a decentralized app (DApp) implemented using the Ethereum blockchain that targets the opioid epidemic currently plaguing the United States (US). The US has a severe problem stemming from the over prescription and distribution of opioids, costing the national healthcare system over $78 billion every year. Problems persist in every stage of the process, from doctors prescribing the medication to pharmacies fulfilling prescriptions. These problems arise from a combination of factors, including lack of accountability, transparency, and reliability in the current prescription drug monitoring programs.

This work provides three key contributions to research on a technical approach to mitigate the opioid epidemic in the US. First, we pinpoint key problems and loopholes that exist in the current opioid prescription system. Second, we propose an integrated approach for addressing these problems by leveraging the disintermediation, immutability, and network consensus characteristics of distributed ledgers, focusing on blockchain technology. Third, we describe the structure and functionality of a DApp, called OpTrak, that allows a consortium of healthcare providers to exchange patient prescription data securely. Our initial DApp prototype logs prescription data access requests and responses on a private configuration of the Ethereum blockchain and provisions access to patient data accordingly across a network of providers.

Keywords: Opioids, Opioid Epidemic, Blockchain, Ethereum, Smart Contract, Healthcare, Data Sharing, Interoperability, Prescription Drug Monitoring Programs

INTRODUCTION

Emerging trends and challenges. It is widely known that the United States (US) is in the midst of an opioid epidemic. Opioids are a class of drugs that consists of heroin, as well as legal pain relievers like oxycodone, hydrocodone, codeine, and morphine. Pain relieving opioids can be safe when prescribed for the right reasons and duration. These opioids can easily be misused, however, due to the production of euphoria and the relief of pain. Due to these effects, regular use (even through valid prescriptions) can yield dependence and addiction. In turn, the abuse of pain relievers often leads to overdose and death *(National, 2018)*.

Every day in the United States, over 115 Americans die after overdosing on opioids *(CDC/NCHS, 2017)*. Moreover, the DEA states that up to 80% of heroin addictions begin with the misuse of prescription opioids *(Bresnick, 2017)*. By calculating the costs of healthcare, addiction treatment, lost productivity, and criminal justice involvement, The US Centers for Disease Control and Prevention estimates that prescription opioid misuse has a total economic burden of $78.5 billion per year on the United States *(CDC/NCHS, 2017)*.

Many efforts are attempting to address this crisis, as shown by *The Drug Supply Chain Safety Act* (DSCSA) *(Center, 2013)*, the establishment of the *President's Commission on Combating Drug Addiction and the Opioid Crisis (Madras, 2018)*, and numerous prescription awareness campaigns *(CDC, 2017)*. Unfortunately, the current prescription tracking system in the US lacks the technical infrastructure to address this crisis effectively. In particular, the prescription opioid marketplace is rife with data hoarding, doctor shopping, provider ignorance, vulnerable and centralized data, and over-prescription *(Laxmaiah, 2012)*.

Attacking the opioid crisis in the US requires an approach to prescription monitoring that not only makes prescriptions safer, but also incentivizes providers to write fewer prescriptions. Providers today are economically incentivized to prescribe opioids to patients. As a result, providers often spend less face-time with patients, thereby lowerin costs associated with patient treatment, while increasing their financial returns. Similarly, pharmacies today are incentivized to produce and distribute opioids because the more opioids sold, the greater their revenue, which also increases shareholder value.

Patients themselves are also incentivized to consume opioids. For example, physical therapy in the treatment of pain can be extremely frustrating and filled with disappointment. Opioids provide short-term relief, though they often lead to patient addiction *(Van, 1999)*. This self-reinforcing cycle can be ameliorated by a technical approach that realigns incentives for providers, pharmacies, and patients.

Our contribution → The *OpTrak* decentralized app (DApp) that tracks opioid prescription using distributed ledger technology. To provide a technical platform for more effective sharing of opioid-related activities, we have developed OpTrak, which is a distributed ledger technology (DLT)-based DApp designed to operate within a networked consortium of healthcare professionals. OpTrak allows a trusted network of stakeholders (*e.g.*, hospitals and pharmacies) to store opioid transaction records in a secure and accountable manner. By securely disseminating knowledge that a prescription has been filled by a patient, OpTrak helps remedy various problems in the current US opioid system, such as lack of communications between providers causing duplicated opioid orders of the same patient *(Goldman, 2017)*.

Opioid data in OpTrak is shared with the networked consortium in a secure fashion with no single point of failure that could corrupt the entire system. Healthcare professionals, such as providers and pharmacists, are incentivized to participate in the consortium through access to data that will increase the quality and transparency of care. In turn, proper analysis of this data enables patients to receive care that is more appropriate to their condition(s).

OpTrak can also create personalized logs for each individual patient to help them identify past prescription activities. These logs can help steer patients away from the dangers of opioid addiction by encouraging them to adopt more effective long-term treatment actions. For patients who have genuine needs for opioid prescriptions, OpTrak helps make a safer marketplace.

Paper organization. The remaining of this paper is organized as follows: the *Background and Challenges* section describes the context of our work on opioid tracking via blockchain. The *Structure and Functionality of OpTrak* section describes the design and implementation of a prototype OpTrak DApp we developed using the Ethereum blockchain platform. The *Addressing Key Opioid Misuse Challenges via OpTrak* section presents key considerations we applied when developing our OpTrak DApp to address each of the challenges facing current opioid prescription tracking systems. The *Related Work* section compares our research on OpTrak with other work related to understanding drug prescriptions, as well as applications of distributed ledger technology in healthcare. Finally, the *Concluding Remarks* section summarizes key lessons learned from our work on OpTrak.

BACKGROUND AND CHALLENGES

This section presents an overview of blockchain technologies used by OpTrak and describes key challenges faced by current approaches to addressing opioid misuse.

Summary of Blockchain Concepts and Capabilities Used by OpTrak

A blockchain is an append-only ledger of a digital asset, such as digital currency or a piece of data. Transactions tracking the ownership of the assets are maintained by a number of nodes in a decentralized network. The ledger is not stored in a single location, but instead is replicated across the entire network and continually reconciled to present consistent and verifiable information. This distributed ledger achieves consensus through a process called mining, which has different implementations for different blockchains. The Ethereum blockchain, which underlies our OpTrak DApp, uses *Proof of Work* in its public incarnation, where network nodes compete to solving a difficult cryptographic puzzle, with the "winner" having their block be the first appended to the blockchain. Mining nodes are incentivized to complete the puzzle with some cryptocurrency award.

The Ethereum blockchain also provides a more generalized blockchain framework with its programmable "smart contracts" *(Buterin, 2014).* A smart contract is a piece of software that enables autonomous code execution when certain predefined conditions are met. It also supports data storage as state variables that can be updated based on access and conditions defined in the smart contract.

Interactions with an Ethereum smart contract are always deterministic and are recorded on the distributed ledger as transactions in a network-wide sequential order. All transactions are verifiable and are very hard to modify due to the decentralization nature of blockchain. These mechanisms render data and data operations on the blockchain immutable and non-repudiable, thereby attracting significant interest from healthcare IT researchers as a framework to enable more interoperable clinical exchanges without a third party intermediary *(Blockchain 2018)*. Below we describe how OpTrak leverages this decentralized blockchain technology to mitigate the challenges related to opioid misuse.

Key Challenges Faced by Current Approaches to Addressing Opioid Misuse

OpTrak is designed to address key challenges in healthcare related to accurately tracking prescription opioid medication. As described in the *Introduction* section, the United States currently faces a national epidemic involving the abuse and misuse of opioids. With the widespread problem of opioid misuse in the United States, federal, state, and local governments have begun efforts to implement prescription drug monitoring programs (PDMPs) *(Finklea, 2013)*. For example, according to the National Alliance for Model State Drug Laws (NAMSDL) *(National, n.d.)*, states are implementing PDMP electronic databases that collect designated data on substances dispensed in the state. The agency responsible for administration of the PDMP varies by state and includes state's regulatory, administrative, and law enforcement agencies. These agencies then distribute data to entities authorized by state law who use the information for their profession, such as physicians and pharmacies *(Diversion, 2016)*.

Despite the implementation of these programs in recent years, current evidence does not indicate that PDMPs are highly effective in combating drug abuse *(Office, 2013; US, 2016)*, due to a variety of factors, such as the fact that they still do not fix the fundamental problems with how doctors and others are incentivized regarding opioids *(Reuben, 2015)*. Some studies have shown improvement, such as the CDC's statement that the "Evaluations of PDMPs have illustrated changes in prescribing behaviors, use of multiple providers by patients, and decreased substance abuse treatment admissions" *(Center, 2017),* but there has not been clear and concrete highly successful outcomes. Despite these signs of progress, however, there is also substantial room for improvement in more timely responses of opioid prescription reporting, interoperability across states, and more accurate approaches to identify patients. Figure 1 shows the current status of prescription tracking, where providers within the same state may be able to exchange prescription history of a patient via statewide PDMPs.

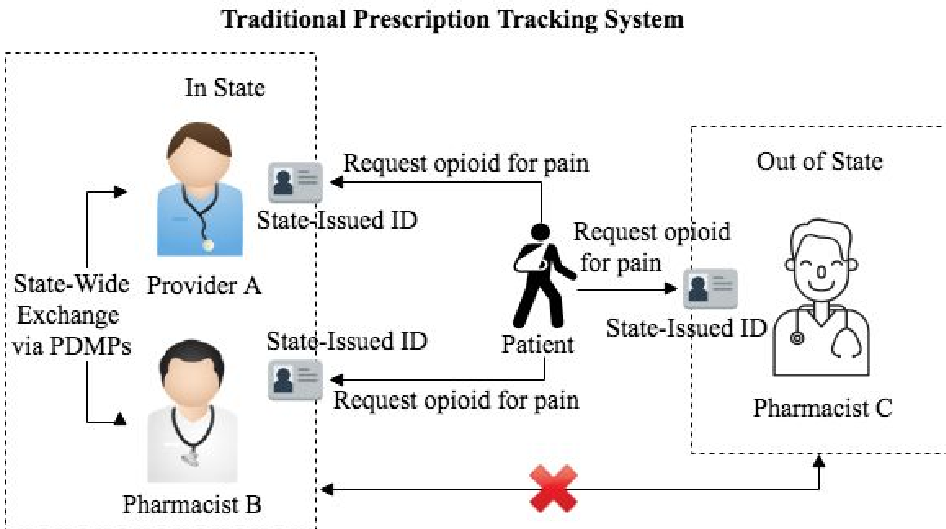

Figure 1. Traditional Prescription Tracking System with Little Interoperability across Different States

Figure 1 depicts a scenario where a patient attempts to request opioid prescription (*e.g.*, for pain management). In this conventional approach, the patient is required to present a state-issued ID as proof of their identity. Providers (Provider A and Pharmacist B) within the same state are able to exchange prescription data of the same patient using their provided ID through case reporting enabled by state-wide PDMPs. The state-by-state siloed implementation of PDMPs, however, limits interoperability across state lines. As a result, when the same patient visits another provider (Pharmacist C), Pharmacist C is unaware of the patient's previous prescription activities, which creates a loophole in the system that patients with opioid addiction can exploit to doctor shop across states and obtain more than the required opioid dosage.

Although PDMPs provide an important contribution in the fight against opioid abuse, therefore, the following challenges remain largely unresolved:

1. **Lack of interoperability between states:** PDMPs create one statewide electronic database to contain data related to the dispensing of particular substances *(Diversion, 2016)*. While these databases are a necessary first step, their state-by-state implementation restricts the interoperability of states. In particular, with states siloing their own data, there is a significant loss in potential sharing of prescription data across state lines. Physicians, pharmacies, states, and the federal government are therefore limited in the scope of data they can analyze to identify trends and draw valid conclusions.

2. **Vulnerability of centralized databases:** Maintaining one central database introduces the risk of losing all data in one incident or cyber-attack. Moreover, if any malicious actor succeeds in manipulating the database—*e.g.*, by supplying false information, changing information, or erasing information (Theoharidou, 2005)—the centralized database will be unable to remedy the information without cross referencing individual databases that have previously contributed to its information (if such sub-databases even exist). In conventional prescription monitoring approaches, states have the option to contract the responsibility of transaction recording to private organizations *(Appriss, n.d.)* who are utilized in many states and store information in a centralized system. If that centralized

database was compromised in some way, it would be hard to validate the correctness of its information.

3. **Identity Verification:** Conventional methods of prescribing and fulfilling prescriptions only require an individual to provide valid identification, typically through a state driver license *(National, 2013)*. These material licenses can be falsified, thus rendering the identity verification process inadequate. In cases where genuine identifications are provided by patients, errors (such as mismatching patients using aliases or failing to link prescriptions to the correct patients *(McDonald, 2013)*) may still surface due to the lack of interoperable medical identity management system.
4. **Reliability and Consistency of Information:** Physicians using current PDMP databases are often dissatisfied with data reliability and consistency *(Grossman, 2011)* due to several issues, including frequency and timeliness of data entry and the limited scope of the data. Different entities input their data at different intervals, *e.g.*, some states require monthly data entry while only one state provides real-time data reporting *(Prescription, 2012)*. Without a system that provides immediate entry of data related to dispensing medication, physicians will not have the proper real-time information to draw valid conclusions. Moreover, current databases typically only contain prescription data of patients within their state. It would thus be helpful to disseminate knowledge and increase physician awareness for authorized entities to access data from neighboring states.

Section *Addressing Key Opioid Misuse Challenges via OpTrak* describes how the OpTrak DApp applied blockchain technologies to address each of the challenges described above.

THE STRUCTURE AND FUNCTIONALITY OF OPTRAK

This section first provides an overview of our OpTrak prototype, which is a blockchain-based web app we developed to provide an opioid prescription tracking system. We then describe the functionality and technical components of OpTrak.

OpTrak Architecture Overview

OpTrak is designed as a web app built atop an Ethereum blockchain alongside existing provider databases (simulated for the prototype), as shown in Figure 2. OpTrak's smart contracts accept messages (*e.g.*, a prescription transaction or a request to view a patient's prescription history) from OpTrak web app. OpTrak then persists and/or delivers data (*e.g.*, data related to shared access or a specific data access request) used for prescription tracking.

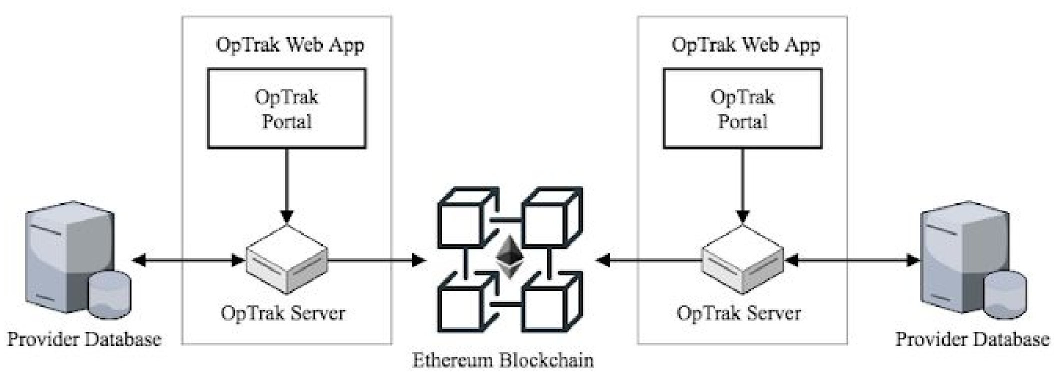

Figure 2. Components in the OpTrak Architecture

The Optrak web app provides a portal for care provider users, with its server component handling and encapsulating all blockchain communications. Each provider database is registered into the blockchain consortium if it sets up or connects to an OpTrack server. OpTrak's design enables the connection of traditionally siloed provider databases with each other in a decentralized manner, regardless of the physical location of the database owner entity. The OpTrak web app was written largely in Python and HTML and the smart contract was implemented with Solidity, which is the programming model Ethereum provides to write smart contracts. Two Postgres databases are used to simulate two provider databases.

Technical Components of OpTrak

OpTrak is comprised of three key components: (1) a standardized Postgres database simulator with API keys to permission access, (2) an Ethereum smart contract to log access requests and responses on the blockchain, and (3) a Python-based web app to provide users with familiar experience. As shown in Figure 3, each block contains a bundle of requests and responses and is chained in a network-wide sequential order. When a provider needs to access a patient's prescription information, a data request is sent to each provider in the registry with that patient's biometric-based identifier. Each provider responds with a binary (*i.e.*, "yes" or "no") message indicating whether they possess data for the corresponding patient. Each "yes" response will also contain an API access key that grants the requesting provider temporary access to that patient's data in the responder's database.

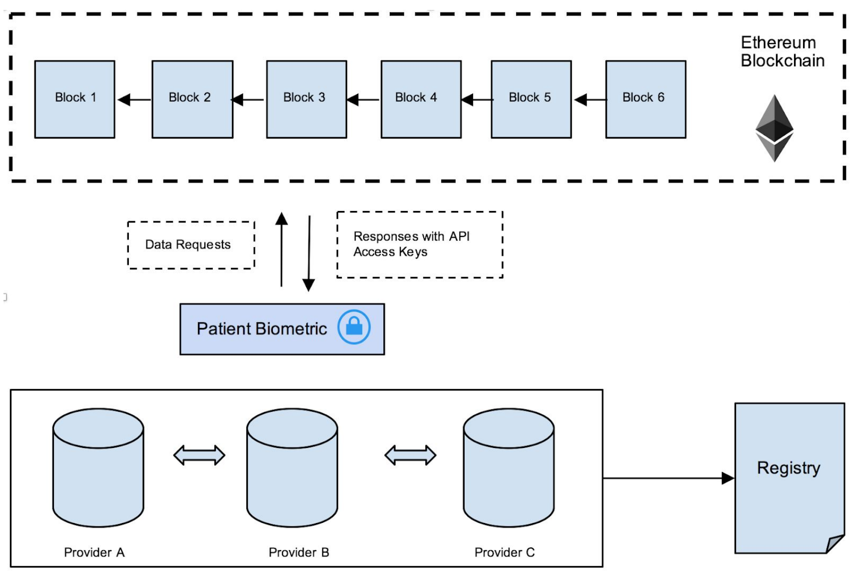

Figure 3. Detailed OpTrak Workflow Diagram and Technical Components

Standardized database. To facilitate the frictionless exchange of data between providers, OpTrack standardizes how prescription data is recorded. It can be costly to exchange data that is not uniformly recorded in a standardized manner. Fortunately, 43 of the 50 states in the US use the centralized Appriss database to centrally store opioid prescription data. Rather than rely on Appriss to provide central storage of prescription data, however, OpTrak works alongside each provider's local data server. When a provider in the system requests access to another external provider's database, a new API access key can be generated granting them temporary access *(Appriss, 2016; Controlled, 2018)*. Since data is standardized, this information can be easily understood by the receiving provider and thus leveraged to recognize a genuine patient request for opioid prescriptions.

Ethereum smart contract. We designed an Ethereum smart contract to log all data requests and responses on the Ethereum blockchain. When a provider requests data on a patient, it sends a data request to each provider in the registry, which is also simultaneously recorded on the Ethereum blockchain with a timestamp. Each provider then sends a response that is also logged on the blockchain. If the provider holds data related to the requested patient an encrypted API access key is attached to the response. Only the requesting provider can decrypt this key to retrieve the data. Maintaining the history of each data request and response on the blockchain allows OpTrak to track which provider has accessed another provider's database at any given time *(Buterin, 2014)*.

Python web app. All services offered by OpTrak are wrapped in a Python web app implemented via the Django web framework to provide users with familiar web experience *(Django, n.d.)*. We allow users to register or sign in to the system via a user-friendly portal according to their role (*i.e.*, patient or provider). This web service is responsible for all communications with the blockchain, thereby avoiding any additional technical burden to users. OpTrak's Python web app interacts with the Ethereum smart contract via the JavaScript *remote procedure call (web3.js, n.d.)*. Both patients and providers can be on-boarded to use the system to maximize awareness of prescription-related activities. The web app also allows providers to request data on a patient once the correct biometric-based identifier of that patient has been provided. When a data request has been transmitted through the web app portal, the web server instantiates a new request object in the smart contract component, which is in turn saved on the Ethereum blockchain. The request is then broadcasted to each provider registered in the system and their responses are logged into response objects saved in the same smart contract.

ADDRESSING KEY OPIOID MISUSE CHALLENGES VIA OPTRAK

OpTrak is designed to address the key challenges described in the *Background and Challenges* section above.. In particular, it creates a system for stakeholders to securely monitor and track patient opioid prescription data across state lines. It therefore increases provider access to prescription-related data and ensures the integrity of all parties involved in each prescription transaction and legitimacy of opioid prescriptions to prevent opioid misuse. Figure 3 presents the functionality of OpTrak that addresses the limitations of traditional system shown in Figure 1 using the same scenario, *i.e.*, a patient attempts to request opioid from different providers within and across state line.

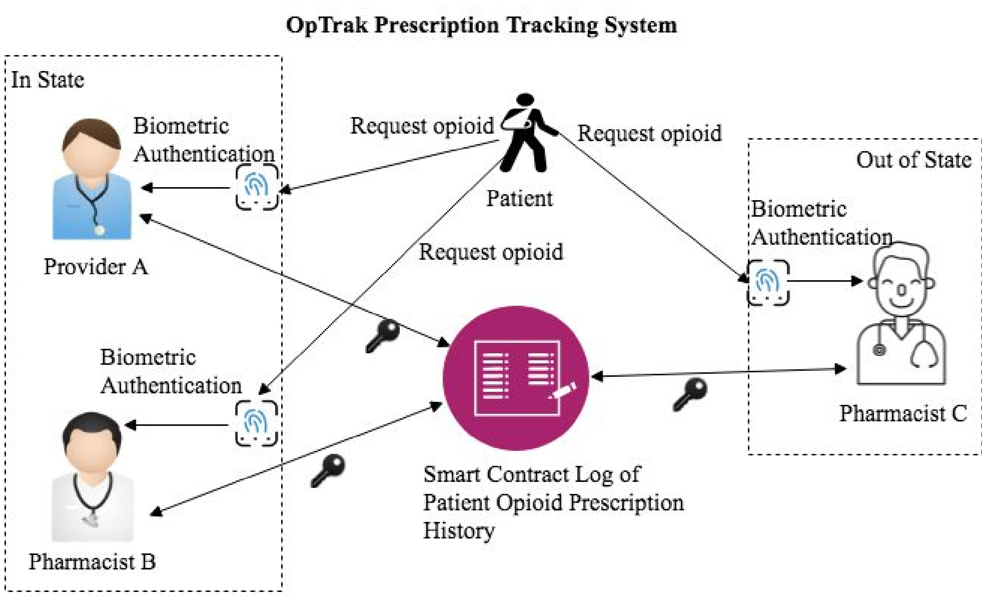

Figure 3. OpTrak Prescription Tracking System Creating Interoperability across State Lines

Figure 3 shows how OpTrak enables providers to verify patient identity via a biometric-based authentication mechanism that maps to a network-wide unique patient identifier. Upon authenticating the patient, all providers in this scenario can then securely share prescription activities of that patient (given proper authorization) through the smart contact log of OpTrak's decentralized design. This approach better equips providers with knowledge about the patient's prescription request and fulfillment history in (near) real-time, thereby helping determine whether it is safe to prescribe opioids to the patient.

The remainder of this section discusses how OpTrak addresses each of the four challenges facing current opioid tracking systems.

Addressing Problem 1: Lack of Interoperability Between States

OpTrak addresses the lack of interoperability between states, which is a key problem prevalent in current medical practice that partially fosters the opioid epidemic. The Drug Supply Chain Safety Act (DSCSA) was put into effect to improve drug security, and by 2023 the law requires that all prescription drugs are trackable across the supply chain via an interoperable system *(Center, 2013)*. The DSCSA, however, does not account for the need of an interoperable system regarding actual drug prescriptions.

Through lack of interoperability, patients can manipulate the medical system by doctor shopping across state borders, playing ignorant in writing scripts, *etc.*, thereby creating less collaborative and less effective medical practices. OpTrak improve interoperability through enabling providers residing in different states with a new way to share prescription information. In particular, rather than permanently sharing all data, OpTrak enables the distribution of temporary API access tokens. Data can then be supplied from the local provider via OpTrak's secure APIs, thereby enabling more interoperable data sharing.

To achieve these goals, OpTrak acts as a pipeline for the transmission of prescription data to appropriate and relevant parties within a consortium of providers, such as hospitals, insurance agencies, pharmaceutical distributors, *etc.* The membership of each additional provider (or their organization representative) must be approved by the existing consortium to ensure that they are a known and accountable entity, thereby ensuring that each network node is responsible for any action they perform.

Addressing Problem 2: Vulnerability of Centralized Databases

Rather than storing records of prescription transactions in a centralized global database, OpTrak allows providers to maintain control of the data they generate. Even if corrupted data enters a single local database, the collection of databases as a whole will remain untainted. This design minimizes the scope of any issue that jeopardizes the consistency of the overall database.

An alternative approach is to simply distribute each provider's database to the entire network, which would allow immediate remediation of any data corruption of data. We rejected this approach in OpTrak, however, for the following reasons:

- **Decentralization prevents mistakes in data records.** People quite often make mistakes. By distributing the entire database using blockchain, any modification of past recorded data will be impossible or hard due to blockchain's decentralized architecture and tamper-aware properties.. While one could update data, each update event is permanently and immutably recorded.

- **Authorization to access data may be bypassed that violates regulation.** To comply with healthcare information privacy and security regulations (*i.e.*, HIPAA, Health Insurance Portability and Accountability Act) *(US, 2003)*, data should only be viewable by relevant and authorized parties. Just because a patient has visited Hospital A, that transaction may not be permitted viewable by Hospital B unless authorization to view that specific information is granted or needed by the patient.

- **Market competition becomes disincentives to participation.** Medical data is a form of leverage. Providers within the consortium will likely not be incentivized to share their full datasets with each other or their competitors, which leads to OpTrak's permissioned viewing.

Instead of storing patient data in OpTrak's blockchain component, it only stores timestamped records of transactions. The fact that a transaction took place will be immutable and permanent, rather than storing actual information about what the transaction was (*i.e.*, some event occurred that was relevant to Patient X and Provider Y). This design enables OpTrak to grant providers permissioned viewing.

By distributing a record of transactions involving certain parties have taken place, OpTrak can alert any provider that pertinent patient information may exist and where it would be to retrieve the actual, detailed prescription information. Given that provider data is still locally stored, external providers in the consortium will not have access to that data unless it is granted by the provider that stores it locally. Through the use of temporary authentication tokens, each local provider can then grant temporary access to a patient's information if it is deemed appropriate via disintermediation with OpTrak's blockchain component. OpTrak ensures that request for patient data access is only deemed appropriate if that patient is indeed under the care of the external provider by an immutable log that can be verified by the patient and provider at any point in time.

Addressing Problem 3: Identity Verification

The decentralization property of blockchain technology can facilitate the identity verification process by standardizing identity representations. Smart contract=based public key infrastructure (PKI) has been proposed as a useful mechanism to create and manage identities *(Al-Bassam, 2017)* and has been preliminarily prototyped as a global registry *(Zhang, White, 2017)*. PKI *(Housley, 1998)* is widely used by Internet services and applications to secure communications, including authentication of client requests via Secure Socket Layer (SSL) *(Bhiogade, 2002)* and encryption of email messages using Secure/Multipurpose Internet Mail Extensions (S/MIME) *(Ramsdell, 2010)*. PKI uses a pair of mathematically linked public and private keys to encrypt data and verify digital signatures. The mechanism generating the key pair ensures it is computationally infeasible to derive the private key (which owners keep private and secure) from the public key (which owners are free to share with others to encrypt data and verify digital signature).

For provider users, OpTrak employs PKI-based identifiers in conjunction with a registry model created via a smart contract component to enable authenticated and encrypted communications between providers *(Zhang, White, 2017)*. The public and private keys can be managed by each provider's parent organization and encapsulated to the providers by using a traditional username/password authentication scheme on top of a key management software, such as a software wallet or key vault. To identify patient users, however, our design incorporates a biometric-based identity *(Pitt, 2012)* verification process because PKI-based key management would incur significant technical challenges (such as technical knowledge, management limitations, *etc*.) in this much larger population, thereby impeding wide-range adoption. OpTrak therefore uses otatient biometric data that are securely encrypted and stored with their provider(s), along with a hashed value of the data used to identify the patient.

Addressing Problem 4: Reliability and Consistency of Information

Many current Prescription Drug Monitoring Programs (PDMPs) suffer from the issue of providers submitting their data in a timely fashion *(Rutkow, 2015)*. By allowing local providers to store their generated data, OpTrak enables data updates as soon as it is recorded in the local system. thereby eliminating a step in submitting prescription records. In addition to streamlining the process by logging transactions, providers will now be more accountable for transactions that do occur., which will have a the following two-part effect:

- Prescribing doctors (or their surrogate) will feel more responsible for the transactions they sign off on. Providers will likewise be more precautious in writing a prescription for opioids if they believe each transaction can be observed and audited in a tamper-proof manner. The number and frequency of prescriptions can also be utilized to alert when doctors abuse their licenses.
- If doctors are more precautious in writing opioid prescriptions they may be less inclined to write as many opioid scripts. In turn, this reduction in scripts will lower the number of opioids in legal circulation and hopefully incentivize safer medical practices.

RELATED WORK

There are few discussions in the academic literature on systems for opioid prescription monitoring using a distributed and shared ledger, such as blockchain technologies. Given the opportunities that these technologies present, however, there are many projects underway aimed at revolutionizing the healthcare industry. Many of these projects are focused on solving problems including data fragmentation, interoperability, and audit tracking. This section describes the most relevant of these projects to characterize the current digital health landscape and understand how blockchain technologies can improve it.

MediLedger *(MediLedger, n.d.)* intends to utilize the blockchain to solve interoperability issues between drug manufacturers, distributors, and dispensers. Their platform aims to improve compliance of track and trace regulations, reduce the cost and effort involved in regulatory adherence, improve drug quality and security, and improve overall business operations of the pharmaceutical supply chain.

Appriss Health *(Appriss, n.d.)* aims to help providers, pharmacies, and state governments identify, prevent, and manage substance use disorders. They provide a suite of data analytics platforms that integrate with EHR workflows to identify at-risk patients and the resources necessary to support them.

MedRec *(Azaria, 2016)* applies smart contracts on the Ethereum blockchain to create a decentralized content-management system for patient's healthcare data. The authentication log, similar to OpTrak's permission management schema, governs medical record access, while providing means for auditability and data sharing. MedRec aims to integrate with providers' local EHR database solutions to give patients a "one-stop-shop" platform with access to all of their medical records. MedRec is being developed by researchers at the MIT Media Lab.

ScriptDrop *(ScriptDrop, 2017)* integrates a delivery service, a pharmacy focused EHR, and a blockchain backend to provide better prescription drug access to patients. ScriptDrop also aims to utilize daily medication reminders to provide a two-way communication with the patient, and identify which patients are not in compliance with adherence programs.

Our prior work focused on recommending design practice *(Zhang, White, 2017)* and evaluation metrics *(Zhang, Walker, 2017)* for creating and assessing blockchain-based healthcare apps. Moreover, we identified a number of plausible applications for using distributed ledger technology in healthcare, one of which discussed its potential for monitoring opioid prescription *(Zhang, Schmidt, 2018)*. We also recently proposed FHIRChain *(Zhang, White, 2018)* as a more generic health IT system for securely exchanging clinical data by analyzing a subset of technical requirements that would comply with security and privacy regulations.

CONCLUDING REMARKS

This paper motivated the need to address the problem of opioid misuse and abuse in the US and described how the blockchain technology used in the OpTrak DApp can serve as a promising solution. OpTrak is well-suited for a Prescription Drug Monitoring Program (PDMP) that tracks prescriptions at the national level. The blockchain technology underlying OpTrak enables any provider across the United States to exchange and access their patients' prescription records regardless of when or where they were prescribed, thereby helping to reduce prescription fraud. The following are key lessons we learned from developing and evaluating the OpTrak DApp thus far:

- **A decentralized and shared permissioned blockchain allows loosely coupled providers to access data silos without the need of centralized trust**. A consortium of providers that use the OpTrak technology act as an oracle, *i.e.*, external verifiable data feed to the smart contract for providing secure data retrieval service. The consortium must agree to add new providers to the OpTrak system. Stakeholders within the system (hospitals, government agencies, etc.) are incentivized to add new members to the consortium because with each additional member, they can form a more complete picture with a broader distributed dataset. Each patient's prescription record grows longitudinally as more time points are referenced by temporary access API queries. Likewise, the data becomes more layered as more information about the prescriptions are logged in a shared ledger.

- **OpTrak has no centralized data store, which provides some benefits compared with centralized architectures**. A key benefit is that providers using OpTrak do not actually have to give up rights to their coveted data sets. This benefit overcomes a common challenge in the healthcare industry: how does an organization facilitate beneficent data sharing between providers that do not trust each other? The answer comes in the form of a peer-to-peer API protocol that references a permissioned blockchain backend. With conventional prescription tracking technology, it is not feasible and too hard to expand past a local setting. In contrast, however, tracking and accessing prescriptions nationally with OpTrak would akin to tracking them on a local level and could be done with ease and speed. Moreover, a simple biometric-based identity approach is useful to look up a patient's information from any location that is part of the consortium. OpTrak provides a less expensive, more efficient, and more secure approach to facilitate prescription drug distribution.

- **The speed of blockchain technology provides a significantly more efficient method for tracking opioid prescriptions.** Today, the existence of any centralized form of tracking prescriptions necessitates the need for manual methods of input and updating. With these methods, the main source of tracking prescriptions is not updated as prescriptions are filled and are never really up-to-date. OpTrak would enforce and update tracking in (near) real-time across the entire chain, meaning that as soon as a prescription is entered into the system it is also entered into the chain and hence updated on every entity's system. This approach provides a more efficient, feasible solution to prescription tracking and the prevention of opioid abuse. Without real-time updates, it is easy to over-prescribe opioids to a patient with little opportunity for recourse.

- **OpTrak minimizes adoption overhead by working alongside existing systems.** The introduction of any new platform may cause changes in medical practice, thereby impeding adoption. The DEA, however, already requires the medical field to track and record every opioid that they prescribe. Allowing OpTrak to work side-by-side with existing systems in hospitals or doctor offices incurs minimal adoption overhead since opioid prescriptions can be entered onto the blockchain and provider databases simultaneously. Incorporating OpTrak into existing systems would therefore incur little additional time and would be easy to use since doctors would observe little/no differences from their existing systems. Opioid prescriptions would be entered onto the shared blockchain simply behind the scenes and would be unnoticeable to every participant. The provider themselves would never need to (1) see a private or public key, (2) understand how to run a node, and/or (3) learn an entirely new platform. OpTrak is thus an efficient solution to opioid prescription tracking that adds little/no overhead for entities adopting it.

In future work, we are exploring the practicality of OpTrak via a case study to evaluate various metrics in terms of real-time performance in addition to analyze the implementation effort required. These metrics include transaction throughput and turnaround time of a prescription transaction being available across the network. Moreover, we are extending the work presented in this paper to provide more patient-centric permissions that allow patient family members to access their prescriptions on demand and also consider monitoring adjustments for users with varying degrees of opioid dependencies, *e.g.*, new opioid patients versus patients with higher risks of addiction.

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