2018 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovations

Proof of Disease: A Blockchain Consensus Protocol for Accurate Medical Decisions and Reducing the Disease Burden

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***Abstract*—Studies suggest that a significant proportion of the diagnosis in non-communicable diseases (NCD) is erroneous, unwanted, or unnecessary. To reduce the disease burden and improve public health, algorithmic support is essential. To realize this, health data must be computer understandable, secured, ubiquitous, and interoperable. Medical and disease data entered into computers are unstructured natural language texts with medical jargons which a computer normally cannot understand. EMR (Electronic Medical Records) are data silos in the hospital and do not interoperate. In this paper we present Ethereum based future ready *Proof of Disease* (PoD) consensus protocol with a computer understandable single instance of truth. It will solve many challenges that electronic health records (EHR) or health information exchange (HIE) have failed to address. This medical system will help achieve all the complex needs of P6 (Participatory, Personalized, Proactive, Preventive, Predictive and Precision) medicine and finally reduce the disease burden.**

Keywords— Blockkchain, Healthcare, Chatbot, IoT, Genomics, Precision Medicine, P6 Medicine, Proof of Disease.

I. INTRODUCTION

The growth in the scientific understanding of diseases in the last few decades has been unprecedented. Without automation and algorithmic support, it is humanly impossible for healthcare professionals to deliver timely medical care with the efficacy, consistency, safety, and accuracy that the full range of advanced technology and knowledge could support.

According to WHO (World Health Organization), 70% of deaths in the world in 2015 were due to non-communicable diseases [1] 42% of which were premature and avoidable [2]. Communicable diseases have distinguishable signs and symptoms and can be diagnosed at the early phase of the disease (acute onset). Eliminating the pathogenic agent and the discrete symptoms often cures the illness. Non-communicable diseases in contrast, are caused due to lifestyle, environment, or genomic causes over a long period of time (late onset) with confusing signs and symptoms. In a study, researchers found that 88% of such diagnoses at the primary care are erroneous that directly add to the disease burden [3].

The disease burden also includes unwarranted medical treatments and unnecessary laboratory tests. Studies find one-third of the medical interventions in the US are unnecessary [4] and often carry health risks. To address this changing medical care scenario, medicine needs to be ***participatory***, ***personalized***, ***proactive***, ***preventive***, ***predictive*** and ***precision medicine*** (***P6 Medicine***). P6 medicine will need algorithmic support of interoperable temporal and spatial data of health and disease of an individual (n=1) to be available for examination; and, that of the population (n=N) as evidence. P6 will reduce disease burden and promote the cause of ***evidence based medicine*** (EBM) and ***precision medicine***.

Health care data is stored in databases like ***electronic medical records*** (EMR) [5], ***electronic health records*** (EHR), or ***personal health records*** (PHR) in silos. They are used by hospitals for hospital administration, reimbursements, billing, claims processing, and clinical documentation. Sometimes they are also used to manage the procurement, inventory, and store management. These health records are proceedings of medical encounter between a patient and a provider primarily as clinical documentation. These medical records can be interpreted and consumed only by medical experts. None of these EMR/EHR or PHR systems is algorithm ready. They do not possess any intelligence and often fail to detect simple data entry errors.

Health data must have following properties:

1. Must include all health, disease, and treatment information of a person from the time of birth
2. Must be secured – must follow anonymity, privacy, confidentiality procedures
3. Must possess single instance of truth
4. Must have zero down-time or cannot be switched off

978-1-5386-9380-3/18/$31.00 ©2018 IEEE
DOI 10.1109/SmartWorld.2018.00079

5. Selective window of health data should be accessible to authorized stakeholders like payers, clinicians, proceduralists or advocacy groups
6. Integrity of the Health data must be ensured – it must be immutable
7. Must be ubiquitous –available anywhere anytime (outside of the home environment)
8. Must be machine understandable – should be able to exchange information with other systems and providers communications at the application layer
9. There should be resistance towards fraudulent attack or hacking
10. Must have recovery facility such that it is accessible when the data owner is unable to access the data (in case of trauma or loss of security key)

EMR or EHR are data silos that do not function outside of the home environment. To overcome this challenge there were attempts to store the health data in smartcards [6]. However, smart cards face challenges related to limited storage, along with access and interoperability issues. Independent ***patient portals*** like PHR offers ubiquity but possibility of health data misuse in PHR is very high [7]. In addition, PHR fails to provide anonymity and a peer-to-peer communication. In recent times, HIEs (Health Information Exchanges) are being promoted as a solution to health data interchange and interoperability [8]. In principle, an HIE will mobilize distributed health data as an aggregator and function as a centralized exchange. However, due to complexity in medical nomenclature and inherent challenges in medical system, HIEs often fail to normalize data and land up in duplicate, redundant, and orphan data. HIEs also fail to meet the basic requirements of data interoperability [9, 10]. The main challenge in HIE is to ensure a single instance of truth.

Blockchain being a P2P (Peer-to-Peer) network backed with distributed ledger system is ideal for health applications where any stakeholder can communicate with any other stakeholder without any intermediatary. This prompted the US Department of Health and Human Services (HHS) Office of the National Coordinator for Health Information Technology (ONC) to call for "Use of Blockchain in Health IT and Health-Related Research" challenge in July 2016. 15 solutions were chosen as winners from more than 70 submissions [11]. These applications looked into patient data privacy, health data security, interoperability of health records, claims processing, payer-provider communications etc. None of these applications however looked into the functional aspects of the health data – how to make the medical data clean, error free and computer understandable. None of these applications looked into the algorithm ready aspect of health data.

We classified medical records in three distinct generations. The First Generation (1G) had handwritten "human readable and human understandable" medical notes. Traditional EMR/EHR records still need human experts to understand the unstructured medical notes – these "computer readable and human understandable" notes are 2G (Second Generation). Third Generation (3G) health care systems in contrast will have computer readable and computer understandable algorithm ready medical notes. To best of our knowledge, this is the first time a machine understandable blockchain based medical care system is constructed that uses a ***Proof of Disease*** (PoD) as a consensus protocol that combines evidence-based medicine and AI/KM (Artificial Intelligence/Knowledge Management).

We present here our health system named Vibranthealthchain that overcome all shortcomings of the previous systems (Fig. 1). This is an integrated system based on Ethereum blockchain fabric. This system allows data from multiple 2G sources like EMR, EHR, PHR, diagnostic centers, radiology, proceduralist, clinicians, Genomics, Internet of Things (IoT), etc. This will interoperate with various healthcare stakeholders such as patients, doctors, hospitals, laboratories, diagnostic centers, advocacy groups, pharmacists, and insurers to access and interact with medical information with necessary security, privacy, and anonymity in a peer-to-peer (P2P) fashion. Each interaction in this system is accurate, immutable, auditable, transparent, secure, and machine understandable (controlled vocabulary/ontology based).

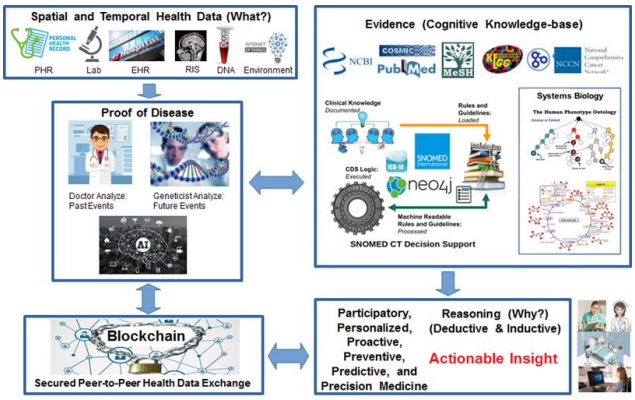


Fig. 1. The P6 Medicine (Future Medical Care) Architecture

II. OUR HYPOTHESIS (FUTURE MEDICAL CARE)

Effective treatment of any disease will need health related data of a person on a spatial and temporal basis from the day of birth. It will include illness and disease episodes as well as lab test and pathological test results that are outside of the normal range (hypo or hyper). It will need the genomic data to evaluate the genomic state of the individual. It will need environmental, health events, and lifestyle related data captured by IoT. It will need therapeutic data including toxicity or side-effects. And, finally the outcome analysis results of each disease episode. These data will be examined by a panel of experts to reach a ***consensus*** (***Proof of Disease***) to ascertain the current state of a person's health to avoid any misdiagnosis or overtreatment.

An accurate and necessary medical decision is possible only when this analysis result is combined with population and public health data as reference and evidence. Evidence is derived from literature and various biological, biochemical, and medical databases. The challenge with medical or clinical data is that they are unstructured data like clinical notes or discharge summaries that are not computer understandable. To make things worse, medical data uses jargons in many nomenclatures

that is specific to culture and geography. Unless this data is normalized and made algorithm ready – it is error prone. This requires active support from ***evidence based medicine*** facilitated by ***natural language processing*** (NLP) and ***big-data analytics*** as shown in Fig. 1.

III. Implementation Detail of Proof of Disease (PoD)

The overall architecture of Proof of Disease (PoD) is shown in Fig 1 and how it fits into the overall scheme of P6 Medicine. The implementation details of the same are as follows:

1. Mobile applications or desktops are used as user devices. The server is a cloud based application where client and server communicate through JSON objects.
2. Following standard authentication, the patient (or doctor) enters pathophysiological details of the disease in simple English. Server runs ***hunspell*** on the user text using customized medical dictionary (corpus). In certain cases, same is captured through IoT devices.
3. Using UMLS and ***metathesaurus***, we parse the user input and convert the unstructured English text into multiple UMLS CUI (Concept Unique Identifier).
4. We extract the diseases name and symptoms through masks like "Disease and Syndrome", "Finding" etc.
5. We convert the UMLS CUI into ICD10 and SNOMED CT Codes (Fig. 2a).
6. The vital information and the disease history are taken from the EMR/EHR. In case EMR/EHR data is not available, vital information is entered by user online.
7. The SNOMED CT codes obtained from Step#5 above are used to determine the disease network and the disease trajectory of an episode (Fig. 2b).
8. The overlapping (union) SNOMED CT subgraphs from different disease episodes of the past are the domain of morbidity and disease penetration.
9. Integrate SNOMED CT with phonemics databases to discover the core disease concepts in machine understandable ontologies using graph analysis.
10. In the final stage of PoD, the results from above phases are passed to a team of specialists. Medical specialists function as a ***medical miner*** (MM) in our blockchain system. A medical miner team will validate and confirm the results from above steps and finally commit into the blockchain. In principle, an MM will ensure a single instance of truth about the health state at certain instance of time.
11. In cases, when the proof of disease cannot be ascertained, additional biological databases are added and iterated over. These are ***big-data*** databases HPO (http://human-phenotype-ontology.github.io/), OMIM (http://bioportal.bioontology.org/ontologies/OMIM), HGVS (https://www.hgvs.org/), Gene Ontology (http://www.geneontology.org/), Virtual Metabolic Human (https://vmh.uni.lu/), KEGG (Kyoto Encyclopedia https://www.genome.jp/kegg/) etc.
12. Medical specialists will examine the disease results from Steps#1 to Steps#11 as a ***medical miner*** (MM). An MM validates the integrity of the illness or health data by comparing with population data, public health data and evidence based medicine knowledge body; then, identifies the likely trajectories of the disease with evidence and finally commits into the blockchain distributed ledger. In principle, an MM will ensure a single instance of truth about the health state.
13. In our system there are two types of medical mining activities; viz., (a) ***medical transaction or episode mining*** (MEM) and (b) ***health state mining*** (HSM). All the expert professionals that are part of the medical mining offering the service will be paid a fee for their services. Therefore, for the payment procedure, there is an additional mining activity in the blockchain network for the financial transaction as well. For the financial part of the consensus (payment for the PoD service), we use Ethereum's native coin consensus.

Fig. 2 shows an example of human understandable 2G medical text to 3G machine understandable SNOMED/ICD10 ontology translations. In Fig 2a user describes three diseases viz., "i have high blood pressure", "hypertension", and "high cholesterol". For computer, "i have high blood pressure" and "hypertension" are two different character strings. Following NLP driven normalization technique we resolved both of them as algorithm ready SNOMED CT code "38341003" and ICD10 code "I10". Fig. 2b shows the SNOMED ontology graph for "hypertension" (SONMED CT code 38341003) with diameter 3. In this graph, pink, yellow, and grey nodes are ***concepts***, ***descriptions***, and ***group*** nodes respectively. This is created in Neo4j (https://neo4j.com/) SNOMED graph database [12].

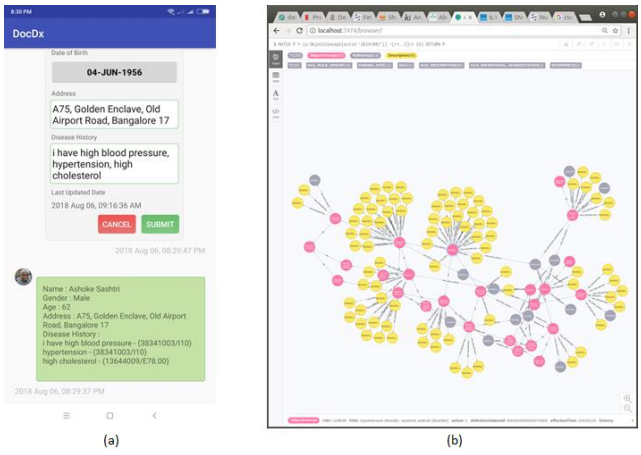


Fig. 2: Machine understandable disease ontology

IV. Health Transaction Types

As already mentioned, our blockchain network has three different types of mining; viz, (a) A medical episode mining (MEM), (b) A health state mining (HSM), and (c) A payment (financial/coin) mining. To meet these diverse mining needs, we implemented our Vibranthealthchain system using Ethereum ERC20 tokens.

A. Medical Encounter (Transaction) Data

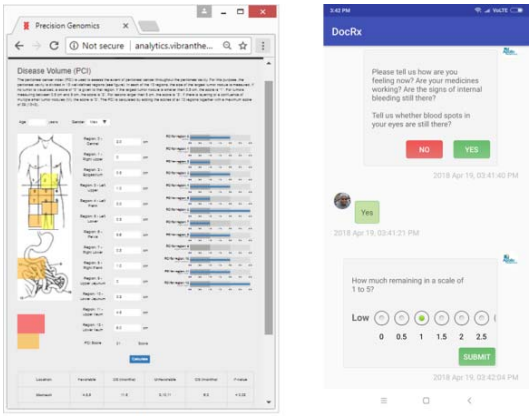
It is observed that the patient participation increases when patients have access to their health and lab records [13]. The very nature of health applications needs ubiquity of the health data with confidentiality, privacy, availability, interoperability, anonymity and peer-to-peer functions. Through blockchain and distributed ledger our system meets all these requirements.

B. Genomics and NCD

An NCD may be inherited at birth from parents' genetic material or somatic due to lifestyle or environmental factors. In precision medicine, the treatment and prevention approach of a disease takes into account the genomic variability. It includes individual mutations and variability in genes, and the population. The molecular marker as mutation in the genes or genome will be discovered through genetic tests [14]. Such genetic test results are stored in the blockchain as a transaction. While the mutation is stored in the blockchain, the pharmacogenomic risk factor is also stored in the blockchain.

C. Internet of Things

To transform reactive medicine into P6 medicine, we need integration of IoT (Internet of Things) [15] into the blockchain network. In IoT, devices with various sensors collect the health data real-time and send the data to the cloud storage connected to our blockchain network. The data collected by these sensors are analyzed by an AI (Artificial intelligence) system to determine the health events by correlating this data with the doctor's diagnosis and population data.



(a) (b)

Fig. 3. Transaction types (a) peritoneal cancer disease volume and Stage; (b) outcome assessments alert. These transactions will be entered into the blockchain by the MEM

D. Outcome of Interventions

Outcome of a medical encounter is the efficacy of endpoints when developing an intervention for a disease, condition, or procedure. Chatbot is the most effective tool for outcome assessments of a medical encounter because it empowers both patient and the clinician or the proceduralist. Communicable and non-communicable diseases both have issues with drug compliance. Our ***outcome assessment*** [16] measures volume of disease (Fig.3a), patient feedback (Fig 3b), drug compliance, and outcome that will be processed by an AI application and recorded as a transaction in the blockchain ledger.

V. BLOCKCHAIN DISTRIBUTED LEDGER

The Vibranthealthchain Blockchain Platform is an Ethereum (https://www.ethereum.org/) based blockchain technology deployed in the cloud. The medical miner validates the episode transaction, translates all clinical notes into structured ICD (International Classification of Disease) and SNOMED CT codes. These ICD and SNOMED codes are stored in a smart contract. For genomic data the MM uses our proprietary tools to determine the genomic mutations and convert it into HGVS (Human Genome Variation Society) nomenclature. During this process the medical expert validates whether the current onset matches with any clinical pathways [17].

A. Vibranthealthchain Medical Consensus Algorithm

The consensus protocol of blockchain is to ensure a reliable and single instance of truth. The consensus algorithm in our blockchain ensures that the disease and health information entered into the ledger is accurate – certified and validated by qualified medical miners. As already mentioned, there are two major types of miners in our consensus algorithm; viz., Coin Miners (CM) and Medical Miners (MM). The CM ensures that there is no double payment. The MM ensures that the medical transaction and health status entered into the ledger are accurate and warranted. The goal is to ensure best quality of medical care in least cost in least time. In our system the coin mining and medical mining are done by the same organization.

The consensus in MEM is about a disease episode; whereas, the HSM is about the overall health. HSM includes medical experts, statisticians, and evidences from literature and biological databases. It deals with illness, chronic, or acute medical conditions. It includes examination, recommendations, and referrals if necessary. From this evidence the panel identifies and analyzes the total path of care in terms of cost, quality, risks, and best possible actions. This always has a single goal – reduce the disease burden. The panel modifies the care continuum to reduce unwarranted diagnostic tests, treatments, hospital admissions and readmissions, decreases length of hospital stays, improve cost-effective prescribing. This step reduces variation in care and recommends advices that treat patients holistically.

B. Ledger

The ledger stores all transactions in the network. Transactions involving granting and revoking of access are stored in the ledger so that they can be audited. Patients' health events as well as results of laboratory tests are recorded in the ledger. In addition, the ledger also stores biomarkers and important events from genome and IoT devices respectively. No raw medical record will be stored in the ledger, instead only the health events in ontology terms will be stored in the ledger. The detailed documents, lab test records, radiology images etc. are stored separately in a secured repository (EHR/PHR) and the blockchain ledger contains a pointer to the repository.

C. Identity and Access Management

There is a layered Identity and Access management implementation for Vibranthealthchain. Provisioning of access will happen in many ways. When a patient goes to a doctor, he/she will assign temporary access to selective data from the ledger to the doctor. To assign access, the patient will perform the transaction to grant access to the doctor. This will execute a smart contract and the transaction (after consensus) will be stored in the blockchain ledger. When the doctor logs in to view the patient's record, the smart contract executes and provides access to the doctor based on the earlier provided access.

D. Anonymity

A patient may like to consult a peer who might have a disease similar to the current patient. In this case the patient may like to be anonymous but can add an arbitrary user to the network by providing access by means of smart contracts. For this, existing procedures will be used [18]. We however will use numbered system as used by financial institutions.

E. Key Recovery

A challenging scenario may occur when a person is in a situation where he or she is not in a position to use or share the secret private key (following a trauma for example). In such case the health record must be accessible. This kind of system needs a secret sharing feature [19]. We therefore implemented secret sharing for our Vibranthealthchain where at least two members are required to access the data. We assume the patient to be one user and two other parties to be trusted persons. There will also be the facility to revoke this privilege in case the trusted person becomes untrusted.

F. Registration Process

The registration processes in Vibranthealthchain includes a standard registration process similar to KYC (Know Your Customer). All stakeholders including the entities holding shared secret will be registered users. Following successful registration, the user (patient) will be prompted to add disease records of the past.

VI. BLOCKS

Blocks in a blockchain contain the transactions and are added to the distributed ledger. Every subsequent block contains a reference to the previous bock's hash, forming an immutable chain. Vibranthealthchain stores the Smart Contracts and the patient's diagnosis information in the block. Every block will consist of block header, the block metadata, and the transaction data.

a. Block Header – The block header contains the block number, current block's hash, previous block's hash and timestamp.

b. Block Metadata – The block metadata section contains the details about the block like the block creator, signatures, stakeholders that were part of the consensus.

c. Transaction Data – The transaction data section contains the details about all the transactions in the block. The transaction includes the entries written to the ledger by doctors or laboratories or genomic centers and the record of access provided and revoked by the patient. Since Blockchain is not suited for large data storage, detailed notes and lab results are not copied into cloud storage. The block will however store the ICD/SNOMED CT ontologies of the transaction. If the medical encounter was unnecessary, it is recorded in the block as well. Data stored in the cloud will be encrypted to secure the personal health records.

VII. SMART CONTRACTS

In Vibranthealthchain, we use Ethereum Smart Contract [20] for all transactions. For each type of transaction there are separate sets of actors (doctors) and algorithms. The medical miners will function like a distributed ***proof of disease board*** (PoDB). They will examine the diagnosis done by the primary care. The PoDB examines the clinical and medical signs and symptom recorded in the medical notes and their 3G equivalents (controlled vocabulary) in SONMED CT/ICD knowledge base. The geneticist members of the PoDB will look at the genomics and biological background of the disease and ensure that it maps with the patient's profile and previous encounters. During this process the PoDB refers to various evidence and recent research results. Once these experts reach a consensus about the current disease and agree on the transaction outcome, the transaction is added to the Blockchain ledger as ***instance of truth***. The consensus is at the knowledge level. This will eliminate the medical error and improves the accuracy of the transaction.

We intend to use Smart Contracts to implement our privacy control as well (future work). The Smart Contracts function as the Privacy Decision Point (PDP). The records in the Vibrahthealthchain ledger will have three levels of privacy –

a. Public – information that anyone can view (similar to Bitcoin network)

b. Semi-private – information that medical providers can view any time, but not open to public

c. Private – information that is not available for anyone to see, unless access is provided by the patient for a period of time and access is revoked at the expiry of that period

For providing access to the private information, the patient will assign access rights using a smart contract. The smart contract will generate a shared key and attach to the profile of the illness. The secret key will also contain information about which data is being share and the duration of validity. This will ensure that the patient data is available only to the appropriate people and only for the time required.

VIII. FEES

In our system, many doctors and geneticists participate in the consensus process whose services need to be paid for. Our blockchain includes Healthchain ERC20 tokens that will serve the purpose of payment of fees for doctors (Medical Episode Miners and Health State Miners). When users join the network, they will purchase these tokens. The payment will be done after the consensus has been archived after a doctor's service.

IX. PUBLIC HEALTH

"***Health*** *is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity* [21]". Public health is the science and art of preventing disease, prolonging life, promoting human health, productive workforce, and providing health for all. Our use case of blockchain in health addresses all issues of public health through proactive, preventive, and predictive health as well.

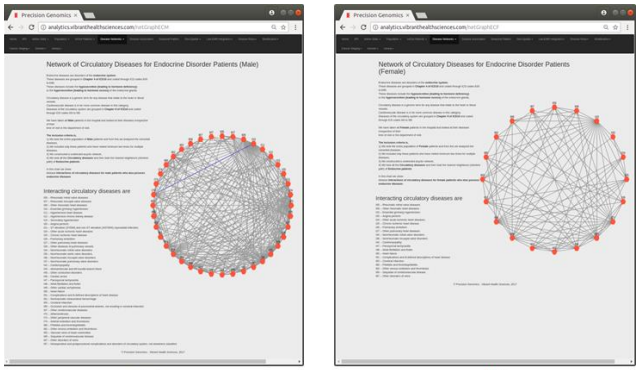


Fig 4: The network of co-occurring (comorbid) diseases of Circulatory diseases and Endocrine diseases. (a) Comorbidity in Male population; (b) comorbidity in Female population

Fetal origin of adult disease (FOAD) tells us that fetal insults are linked to genetic diseases at birth and lifestyle diseases at adulthood like hypertension, coronary artery disease, obesity, and insulin resistance diseases. We therefore use analytics to build a self-learning expert system to discover them. Fig. 4 shows the comorbid (co-occurring) disease network of Circulatory disease and Endocrine diseases in the male (Fig 4a) and female (Fig 4b) population mined from clinical data. This is a novel knowledge that was previously unknown. Such public health knowledge helps planning of resources and focus on disease management. This will help transform reactive medicine into proactive, predictive, and preventive. In Fig. 4, all diseases from unstructured medical notes are converted into computer understandable ICD10 ontology and then analyzed using artificial intelligence.

X. CONCLUSION

The disease demography along with health care costs are increasing combined with high level of errors and unwarranted treatments. We showed how a P2P network using blockchain overcomes the critical challenge of universal availability of medical and health data. We also showed how the 2nd Generation unstructured health data is converted into 3rd Generation computer understandable algorithm ready ontologies such that a consensus protocol can be implemented. We used Ethereum based ERC20 token compliant blockchain technology with smart contracts to realize Vibranthealthchain. Vibranthealthchain is a ubiquitous distributed application over P2P spatio-temporal distributed health information system. Data into this database is entered by experts following proper medical consensus (***Proof of Disease***). This data is clean and is used for accurate diagnosis and public health. This blockchain based distributed ledger is able to achieve all functionalities of health data interoperability that PHR, EHR, EMR, or HIE databases failed to achieve. In this paper we showed how it is possible to achieve P6 medicine comprising participatory, personalized, proactive, preventive, predictive and precision medicine through ***artificial intelligence***, ***blcockchain***, and ***big-data analytics*** and finally reduce the disease burden.

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