REVIEW ARTICLE

Quantum Cryptography for Securing Personal Health Information in Hospitals

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Abstract

Healthcare systems widely use information technology (IT) for system authentication (digital signatures), web surfing, e-mails, instant messaging, protecting data at rest, Voice over Internet Protocol (VoIP) telephony, and cellular telephony. To protect patient identification and healthcare information, cryptographic systems are widely used to secure these data from malicious third parties (adversaries). In our healthcare systems, we have had reasonable success in the efficient storage of the information of our patients and their families, in its timely retrieval, and in ensuring its safety from adversaries. However, the data are increasing rapidly and our current computational systems could be inadequate in the not-so-distant future. In this context, there is a need for novel solutions. One possibility can be seen in quantum computing (QC) algorithms/devices that can provide elegant solutions based on subatomic interactions. In this review, we have summarized current information on the need, current options, and future possibilities for the use of QC algorithms/devices in large data systems such as healthcare. This article combines peer-reviewed evidence from our own clinical studies with the results of an extensive literature search in the databases PubMed, EMBASE, and Scopus.

Keywords: Cryptographic systems, Health information, Healthcare, Hospital, Newborn.

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Highlights

- In our healthcare systems, we have had reasonable success in the efficient storage of the information of our patients and their families, in its timely retrieval, and in ensuring its safety from adversaries. However, the data are increasing rapidly and our current computational systems could be inadequate in the not-so-distant future.
- In this article, we have reviewed possible solutions based on QC algorithms/devices that can provide elegant solutions based on subatomic interactions.
- Quantum cryptography focuses on protecting patient health information (PHI). During the transfer, data are first encrypted (encoded) and the recipient then decrypts (decodes) the information.
- Details of various methods of encrypting and decrypting have been provided. Current information on various protocols for QC has been summarized, and future possibilities have been discussed.

Introduction

Healthcare systems widely use IT for system authentication (digital signatures), web surfing, e-mails, instant messaging, protecting data at rest, VoIP telephony, and cellular telephony.[1–3] To protect patient identification and healthcare information, cryptographic systems are widely used to secure these data from malicious third parties (adversaries).[4,5] Several strong encryption algorithms are well-known, such as the secure hash algorithm (SHA)-1, SHA-2, triple data encryption algorithm system (TripleDES), advanced encryption standard (AES), message digest (MD)-5, and Rivest–Shamir–Adleman (RSA, named after the last names of Ron Rivest, Adi Shamir, and Leonard Adleman).[6–9] Conventional cryptographic algorithms have been used in our healthcare system, but these systems are now beginning to show limitations with the ever-increasing amounts of private information being accrued and produced.[7] These difficulties are particularly important in mother–infant and neonatal intensive care units (NICUs) as there is a need to secure the personal health information (PHI) that has been obtained from the whole family.[10,11]

In our healthcare systems, we have had reasonable success in the efficient storage of the information of our patients and their families, in its timely retrieval, and in ensuring its safety from adversaries.[12] However, the data are increasing rapidly and our current computational systems could well become inadequate in the not-so-distant future.[13] In this context, there is a need for novel solutions. One possibility can be seen in QC algorithms/devices that can provide elegant solutions based on subatomic interactions.[14] These devices resemble classical computers in the need for a defined input, and processing of data, and show a recognizable output, but do not need conventional digital semiconductor processors with interface busses and external networks.[14] Unlike conventional devices, a fully-functional QC algorithm/device might paradoxically show an exponential increase in its capacity to process

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data.[15–19] These should be able to handle the increasing workload in progressively smaller intervals of time that might eventually become nearly immeasurable.[13,14,19–22] Many of these devices currently do show high margins of errors, but encouragingly, many potential solutions can now also be seen.[23]

The QC models have brought exciting possibilities for outcomes prediction in many situations with large datasets, such as in hurricanes, global warming, forest fires, and pandemics.[24] These non-canonical prediction models have shown new possibilities for improving the efficiency and prediction of outcomes in our healthcare systems.[14,24] The QC systems can help analyze large, private patient datasets without the risks of decryption.[7,25] A staggering number of implausible events could possibly be solved if we can develop mechanisms to manage entropy related to multiple concurrent events and lower the error rates to levels that we tolerate in our current electronic semiconductor systems.[13,26–28] The only dilemma is whether we are ready in our technological quest for solutions to accept probabilities instead of certainties.[29,30] In this review, we have described the need, current options, and future possibilities for the use of QC algorithms/devices in large data systems such as healthcare.

Need

In the last two decades, technological advances in electronic medical records (EMRs), continuous monitoring of vital signs, telehealth, and affordable at-home testing devices have improved neonatal care.[31–33] With families' consent, sharing of the data obtained from these devices can improve efficiency in patient care and minimize errors.[32,34] Healthcare providers can utilize these real-time data not only to improve patient care but also for clinical research focused on recording outcomes and drug trials.[35] Families' satisfaction can also be recorded, and education can be more focused and improved. Diagnostics can also be evaluated with greater conviction by an improved recording of data and coordination between various medical subspecialties. Findings can also be analyzed better using newer modalities such as machine learning (ML). The entire health sector can become more data-driven.[35]

The concerns are that all the above-mentioned datasets contain the PHI of the patients in electronic health records (EHRs)/EMRs, medical devices, computers, the cloud, emails, servers, databases, and other associated systems.[5,36] These detailed data make the healthcare sector easy prey to cyberattacks.[5,17,36] The hospital systems and medical companies need to retain the trust of the infants' families by focusing on patient security and access to their data. The Health Insurance Portability and Accountability Act (HIPAA) is one important example of legislation that outlines the maintenance of PHI and the protection of identity from fraud/theft.[37–39] The HIPAA journal[40] reports an unsettling trend, showing a conspicuous rise in the number of healthcare records getting exposed every year.[41] According to the data breach statistics published so far, 2015 has been one of the worst years with more than 113.27 million records being exposed. Nobody wants to remember the infamous "WannaCry" malware attacks of May 2017 with data breaches in the British National Health Service and many reputable medical companies in the USA information.[42] Investigations showed loss of information such as dates of birth, credit card information, social security numbers, addresses, email IDs, and phone numbers, which were sold on the dark web; some patient records fetched up to US$1000. According to the US Department of Health and Human Services, such deliberate hacking accounts for about 75% of healthcare breaches.[43] The affected people continue to face the brunt for the rest of their lives.

Mother–infant units and NICUs are high-priority areas in hospitals where the PHI needs to be secured.[44] Infants and their families are a heterogeneous population, with varying capacities to protect their identifiers and their social, financial, and health information.[45] Mothers and other family members are at risk of developing transient psychological conditions which might affect their employability even after they have fully recovered.[46] Infants are a uniquely vulnerable population because of limitations in their legal rights and capacities for autonomous decision-making.[47] This means that special provisions are needed to ensure their protection from these risks, which include, but do need to extend beyond parental proxy consent on their behalf.[47,48] We also need special considerations in the storage of biomedical information because of the sensitive nature of such data, and the potential immediate and longer-term implications of PHI in the context of family dynamics.[48] These require immediate determinations about who has access to, and control over, the infants' PHI that can alter the life course of these children.[48,49]

Cryptography

Overview of Modern Cryptography

The term cryptography was derived from two Greek roots, *kryptos* meaning secret, and *graphein* meaning to study/write. The composite word, cryptography, refers to the art of securing private communications in presence of an eavesdropper or adversary.[50] Messages are secured by first "encrypting" the plain text into a cipher (a way of disguising in code) in a message that is then sent to the recipient.[51] The recipient "decrypts" the message from cipher to plain text using a tool for back translation, usually referred to as a "key."[52] This process reduces the risk of loss of important information. Cryptography is broadly classified into two categories: Private/symmetric key cryptography and public/asymmetric key cryptography.[53]

- **Private/symmetric key cryptography:** In private systems, a single key is used for both encryption and decryption, hence the name symmetric. In one experiment, one of two members of the team wants to send a sequence of bits, 0110100 to another with the shared key 1110101.[54] She/he encrypts the message using a bitwise "XOR" operation (a logical operation that stands for "exclusive or"). The encrypted message looks like 1000001. An eavesdropper who does not have access to the key fails to comprehend the message while the original recipient can decrypt it by applying the "reverse XOR" operation, yielding the message sequence bits 0110100. This is a classic example of a one-time pad encryption technique.
- **Public key cryptography:** Public systems are more complex than private key cryptography.[55] The team members use more than one key for sending different messages to reduce the chances of hacking. The public key may include two mathematically-related keys, one (public) used for encrypting that can be made freely available, and another (private) key that is protected and is needed for decrypting. The private key is usually derived using complex, more sophisticated mathematical systems. Besides the Diffie–Hellman key exchange protocol,[56] two other public key encryption techniques are the RSA and the Elliptic

Curve Cryptography (ECC).[57,58] Trapdoor functions that are easy to compute in one direction but not in the other, are used extensively to build public key cryptosystems.[59,60]

Advanced Encryption Standard

Advanced encryption standard is a kind of symmetric block cipher that cuts input data into chunks of fixed length and encrypts using a key.[61,62] This is currently being used in government agencies to protect the data encryption standard (DES), another symmetric key encryption algorithm that uses a key of only 56 bits.[63] Even though it is vulnerable to quantum attacks, higher AES key lengths with compounded complexity increase its safety.

Rivest–Shamir–Adleman Encryption

In the RSA encryption systems, it might be possible to create a public key such as the product of two large prime numbers, p and q.[64] The encoding value may be large, c. Since the prime numbers are kept secret, most observers will be able to encrypt a message but only an operator who knows the primes will be able to decrypt it. The security of RSA relies on the practical difficulty of factoring the product of two large prime numbers, which serves as its trapdoor function.[65]

Elliptic Curve Cryptography

Elliptic curve cryptography is the study of mathematical properties of elliptic curves, which are a set of points (x, y), where $y^2 = x^3 + ax + b$.[58] The variables a and b belong to a field K that may be made up of real, rational, or complex numbers. Fields are important algebraic structures that permit the application of certain operations on the members of the field. Elliptic curves use shorter keys to optimize memory storage.[66] For example, the security provided by a 256-bit key in ECC is comparable to a 3,072-bit key in RSA.

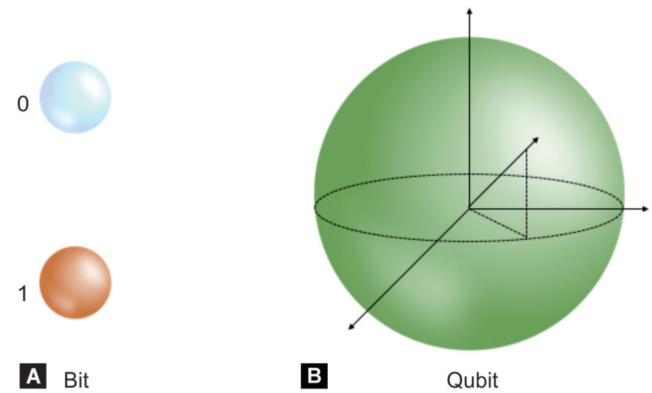
Quantum Computing

With the increasing number of transistors being used in a given chip, the speed of classical computers has increased but there are limits posed by the laws of quantum mechanics.[18,67] Classical computers are known to operate on a binary string of "bits," which are referred to as zeros and ones, and notated as "kets" (Dirac notations) $|0\rangle$ and $|1\rangle$.[68,69]

The key distinguishing feature of a quantum computer is referred to as a "qubit."[70] Figure 1 show a schematic representation of bits and a qubit. Each qubit is a superposition of two independent unit vectors in a 2-dimensional space and can be represented by the column vectors.[71] In other words, $|0\rangle$ and $|1\rangle$, which are independent unit vectors, would make our choice for the bases of the 2-dimensional vector space.[71] A $2n$ dimensional vector space would be having $2n$ basis vectors. In summary, a qubit state is a superposition of the two basis vectors such that the vector is normalized.[72]

Tensor Product

Tensor product (TP) results from an interaction between ≥2 qubit states. This concept helps us mathematically characterize the phenomenon of quantum entanglement (QE) (*vide infra*).[73] This needs to be differentiated from TensorFlow quantum (TFQ), which is a quantum ML library for rapid prototyping of hybrid quantum–classical ML models.[74]



Figs 1A and B: (A) A classical binary bit can only represent a single binary value, such as 0 or 1, meaning that it can only be seen in one of two possible states (off or on, false or true, low or high). Classical computing devices manipulate those bits with the help of logical gates (AND, OR, NOT); (B) In QC, a qubit or quantum bit is the basic unit of quantum information. It is a two-state quantum-mechanical system, represented by a superposition to achieve a linear combination of two states. Information is stored in quantum bits, or qbits. A qbit can be in states labelled |0> and |1>, but it can also be in a superposition of these states, a|0> + b|1>, where a and b are complex numbers. If we think of the state of a qbit as a vector, then superposition of states is just vector addition. Every extra added qbit can help store twice as many numbers. For example, with 3 qbits, it is possible to get coefficients for |000>, |001>, |010>, |011>, |100>, |101>, |110> and |111>

Quantum Entanglement

Quantum entanglement is a physical phenomenon seen in quantum physics, but not in classical mechanics. QE is seen when the physical properties of two particles such as position, momentum, spin, and polarization are perfectly correlated, even when these particles are separated by a large distance.[75] In this situation, the total spin of these two particles will be predictable.[76] Measurements of a particle's properties will result in an irreversible wave function collapse of that particle and will change the original quantum state, affecting the entangled system as a whole.[76]

Measurement Postulate

The MP in quantum mechanics pertains to the degree the wave function collapse occurs.[77] According to the Schrödinger equation, which describes the wave function in a quantum-mechanical system, the wave function evolves deterministically as a linear superposition on different states.[78] In other words, after one initial observation, all subsequent measurements remain consistent with these first-time observations.

No-cloning Theorem

This admits our inability to clone any arbitrary quantum state into multiple copies of itself.[79] If we could, this would have informed us about the behavior and properties of the state by applying different measurement operators to the state countless times. Despite all the measurements, we would always have information about the initial state.

Quantum Algorithms

Quantum algorithms are a set of instructions run on quantum computers similar to how classical algorithms are meant for classical computers.[80] The two most popular quantum algorithms are Shor's algorithm and Grover's algorithm.[81,82] Shor's algorithm is an algorithm for finding the prime factors of an integer using a specific unitary operator. Unfortunately, this algorithm can undermine the security of RSA and ECC due to program-related issues.

Modular arithmetic can provide insights into these algorithms. Grover's algorithm, also known as the quantum search algorithm, is a quantum algorithm that can reduce the time needed for an unordered search.[83,84] Simply put, an unordered search refers to searching for a particular element in a random list of elements such that no guess would bring us closer to the element we are looking for. The obvious way to do this would be to start from the first element and move onwards. Grover's algorithm can improve these searches as it is based on the properties of superposition, entanglement, and interference.[82] There is a special qubit gate called oracle which takes the input state and flips the phase of the chosen ket we are looking for and another gate which inverts the amplitudes of all the component kets about the mean of all the associated amplitudes.[85] However, all problems are still not resolved, and some limitations might appear when full-fledged quantum computers become a reality. Many algorithms such as Deutsch–Jozsa, Bernstein–Vazirani, Simon, quantum Fourier transform, quantum phase estimation, quantum counting, quantum walk search, and dense coding are being investigated.[86–91]

Quantum Key Distribution

The quantum key distribution (QKD) is a secure channel for encryption and decryption using the principles of quantum mechanics. The main tenets of quantum mechanics that makes QKD secure is the measurement postulate, where measurements of an unknown quantum system lead to a change in its state and any information about the initial state is lost after the measurement.[92] There are also possibilities of changes related to the no-cloning theorem and entanglement.

The BB84 Protocol

Named after its creators, Charles Bennett and Giles Brassard, BB84 is a quantum protocol used to generate a private key.[93] In this protocol, the first observer takes a series of qubits and performs any one of two orthogonal measurements on each qubit, such as the measurement of spin in the x and z directions. The first then send those to the second, who repeats the same job. The first operator, however, does not inform the second about which measurements were made and so the second operator will likely measure 50% of the qubits in the same manner as the first operator. After performing the experiments, they could publicly announce their readings and discard the measurements where they differ. The remaining set of measurements becomes their private key. An eavesdropper could then make major efforts to intercept the message qubit but due to the measurement postulate, she/he will be changing the qubit nearly 50% of the time. The no-cloning theorem suggests that she/he will not be able to copy these either. The original two operators will be able to publish a subset of their results and using the correlation they will be able to determine whether there has been any meddling with their key.

The E91 Protocol

This is a slight variation of the BB84 protocol and uses entanglement.[94] The first operator prepares several entangled qubits[95] and sends those to the second; she/he will keep one qubit and send the entangled partner to the second operator. The rest of the protocol resembles BB84. However, it is worthwhile to note that the first operator will not have to tabulate the measurements as the "correlatedness" of the entangled pairs will be certain.

Future Possibilities

Shor's algorithm suggests that many public key encryption techniques like ECC and RSA that are based on factoring and discrete logarithmic problems will remain considerably insecure in the face of QC.[96] However, there are a few quantum-safe encryption techniques today that would last at least for the next century, even if QC becomes a reality in the next 2–3 decades. The National Institute of Standards and Technology had recently listed four encryption methods that are ready for the post-quantum world: Cryptographic Suite for Algebraic Lattices (CRYSTALS)-Dilithium (a lattice-based signature scheme), a cryptographic signature algorithm FALCON, SPHINCS+ (a stateless hash-based signature scheme, which advances the SPHINCS signature), and CRYSTALS-Kyber.[97–99] Active research is going on developing lattice cryptography, multivariate cryptography, code-based cryptography, supersingular isogeny key exchange protocol, and symmetric key systems like AES and SNOW- 3G.[100–104] Campagna recently postulated that there will be three main questions about the number of years needed to fulfill our health sector needs: (a) Our encryption to be secure; (b) to make our IT infrastructure quantum-safe; and (c) before a large-scale quantum computer will be built.[105] The physical hardware required to build qubits includes transmons and superconductivity traps, and we will also need insights into cavity quantum electrodynamics.[13,106,107] Significant efforts are also being propagated toward developing topological quantum computers. On a positive note, researchers have recently built the world's largest functioning QKD network using photons and relay optics.[108]

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