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Technology optimization for patient safety: a blockchain-based anesthesia record system architecture

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Patient safety is acknowledged as a primary aim of anesthesiology. Anesthesia records constitute the main document of the intraoperative course of anesthesia administration. In this paper, we postulate that anesthesia record systems should be based on an integral tamper-proof design and provide specific technology characteristics to ensure data immutability, accessibility and transparency. Issues and limitations regarding current anesthesia record technologies are reviewed. We introduce a novel anesthesia record system designed for patient safety optimization which integrates dedicated hardware, blockchain technology and decentralized storage solutions. We propose an oracle network in which anesthesiologists run independent Sybil-resistant nodes which broadcast biosensor time series to decentralized storage systems and generate proofs of existence on public blockchains. Records are biometrically signed and incorporate information on the temporo-spatial relation between the anesthetized patient and the professional in charge through a unique personal-transponder wearable device. Compatibility for data science and machine learning implementation are discussed. Finally, we evaluate future impact and technological potential.

KEYWORDS

anesthesia record, blockchain technology, machine learning, patient safety, decentralized storage, control systems, soulbond tokens

1 Introduction

Intraoperative anesthesia procedures can be considered a "control system" from a cybernetic perspective (Aström and Murray, 2008). The patient can thus be contemplated as a complex system controlled by the anesthesiologist who performs as a non-deterministic controller.

Anesthetized patients are peculiar components of this system as they remain in a state of maximum vulnerability: they are unable to take care of themselves, delegating their safety to professionals and medical institutions.

The aim of anesthesia records is to register measurements and interpretations for research or audit purposes. They have evolved from manually confected paper sheets to electronic records registered by anesthesia machines and monitors. However, current technology implementations are based on models that are vulnerable to data tampering, destruction, and access limitation, and therefore provide suboptimal mechanisms for ensuring data integrity.

Although individuals and institutions are expected to comply with safety regulations and standards, we believe that anesthesia record systems should operate with trustless and independent mechanisms in order to provide immutable data from sampling and transmission, to the storage and recovery processes. A simple heuristic is: if someone had to choose between boarding one of two identical aircrafts for the same price, one lacking a flight recorder, the other having one installed onboard; it is logical to assume that the latter would be the best choice as it relies on mechanisms that provide evidence regardless of any outcome. In this way, data transparency and availability is guaranteed by a system which is independent of pilots and flight companies.

Anesthesiologists are on the forefront of ensuring the highest possible quality and safest care for every patient (Gaba, 2000). A cornerstone of the discipline is continuous improvement based on iterative reevaluation of metrics, review of processes, and learning from mistakes (Valentine and Falk, 2018). In this context, we believe that performance analysis has the potential to improve the outcomes of dynamical systems and should therefore be a pivotal implementation for control systems in which human life is at stake.

We propose a record system architecture based on two fundamental principles: "data integrity" and "data completeness". "*Data integrity*" refers to the preservation of accuracy, consistency, transparency and immutability throughout the data lifecycle. "*Data completeness*" refers to the presence of necessary information that must be incorporated within the register to contextualize the recorded time series. A scientific record system should bolster data analysis and the exchange of standardized information between anesthesia providers on a global level (Colquhoun et al., 2020).

2 Outline

In **Section A**, we begin by framing the anesthesiological scenario as a control system. We continue by elucidating the meaning of "safety", reviewing the causes of suboptimal performance and the limitations for record rebuilding. Next, we expose the drawbacks of current recording methods.

In **Section B**, we introduce our proposed solution. We first describe what we consider to be the necessary features of an ideal anesthesia record system. We define its components and delineate their interactions. We then describe methods for generating, updating and rebuilding anesthesia records. The section culminates by recapping how this architecture addresses each proposed feature of the ideal system.

In **Section C**, we discuss the innovation and future vision of this technology. We highlight how the system can proliferate a decentralized oracle network and describe its potential applications. We point out emerging characteristics that are expected to benefit patients, anesthesiologists and the global community. Internal details about the system´s governance, sustainability and self-audit are illustrated. We explain how the proposed system can be coordinated with different fields such as artificial intelligence, neuroscience and anesthesia simulation. Finally, we conclude by mentioning expected limitations.

3 Section A: Background

3.1 The control system model approach

We propose to analyze the intraoperative scenario in a reductionist way by considering it as a cybernetic model (Novikov, 2016).

The set of the anesthetized patient being controlled by the anesthesiologist can be interpreted as a control system consisting of four basic components:

1) *A controlled component*, represented by the patient, which can be considered a complex dynamical system (Ladyman et al., 2013).
2) *A controller component*, represented by the anesthesiologist who is in charge of observing the patient, interpreting measurements, and making decisions to maintain or correct patient variables within safe limits (Klocke et al., 1986). Anesthesiologists can be considered non-deterministic controllers as they may exhibit different reactions to identical situations at different times.
3) *A channel from the controlled component towards the controller*, which transmits the sampled measurements.
4) *A channel from the controller to the controlled component*, composed of the collection of interfaces through which the anesthesiologist can intervene over the patient, such as endovenous lines, infusion pumps, ventilators, pacemakers, or direct contact with the patient.

3.2 Safety

We consider a "safe performance" to be the active maintenance of the patient's physiological and biochemical parameters within ranges considered normal by scientific consensus (Joyce et al., 2017). To achieve this, anesthesiologists must take effective action to recover parameters when they deviate from these reliable limits. Lack of timely correction of such deviations can threaten the integrity of the patient and generate potential harm.

The concept of "harm" is broad and can range from general eventualities such as hypoxia, hypoperfusion, pain, acidosis or hypothermia; to specific damage caused by burns, cuts or compressions. Harm can be reversible, irreversible (generating sequelae or disability) or even cause death.

As a controller, the role of the anesthesiologist is to preserve situational awareness (McIlvaine, 2007; Schulz et al., 2013; Schulz et al., 2015) to efficiently prevent harm and ensure patient safety during the entire anesthetic procedure until self-control is regained or exerted by another controller (such as an intensive care service).

3.3 Causes of suboptimal performance and suboptimal record rebuilding

Similarly to pilots, anesthesiologists are in charge of detecting anomalies and resolving complications efficiently (Toff, 2010). To understand the causes of suboptimal performance and undesired outcomes during intraoperative anesthesia, failure scenarios should be outlined. The term "anomaly" refers to any actual or potential inconsistency, irregularity or deviation of parameters which could expose patients to risk or harm.

From the controller perspective, suboptimal performance can be framed in four main failure scenarios:

A) ***Detection Failure***: an anomaly is not detected or detection is delayed.
B) ***Diagnostic Failure***: an anomaly is detected but incorrectly identified or categorized.
C) ***Failure in Therapeutic Selection***: an anomaly is detected and correctly identified, but there is an erroneous choice of the treatment to be applied.
D) ***Failure in Therapeutic Implementation***: an anomaly is detected and correctly identified; the correct treatment is recognized but executed inefficiently or incorrectly.

The root causes of main failure scenarios can be traced to:

1-Controller Absence
2-Controller Distraction
3-Controller Inexperience
4-Insufficient Professional Training
5-Ineffective Supervision of Trainees
6-Resource Unavailability
7-Resource Malfunction

Within this framework, causes of suboptimal record rebuilding must be also recognized:

A) Incomplete/Interrupted Registration
B) Record System Failure
C) Record Adulteration
D) Record Destruction
E) Record Access Limitation

Anesthesia records should enable easy contextualization of any outcome of the control system. Although record immutability is an intimidating concept, technology should protect professionals and institutions from liability risks by providing objective evidence of compliance with quality and safety standards (Feldman, 2004). Genuine commitment to patient safety must involve full transparency for patients and society. Record rebuilding should be guaranteed by a solid tamper-resistant architecture.

3.4 Drawbacks of current anesthesia records

Paper-based anesthesia records present several disadvantages: difficult legibility of handwritten information, asynchrony between measurement and data registration, susceptibility to inaccuracies, loss of relevant data, and user distraction from the environment surveillance (Reich et al., 2000; van Schalkwyk et al., 2011; Edwards et al., 2013; Anderson and Merry, 2015). Paper sheets are easy to tamper, their authenticity relies on sensitive mechanisms such as handwritten signatures or classic stamping. Finally, being physical objects, they are prone to damage or loss.

Prevailing electronic anesthesia records provide many advantages over handwritten registers (Ehrenfeld and Rehman, 2011), however, some aspects of their design can still be improved. For example, data is locally stored on the sampling devices or in centralized institutional networks, which can lead to data vulnerability or access limitation. Authentication relies on local mechanisms such as passwords for the monitor hardware or for local networks. User profiles can generally be created readily and can also be issued and withdrawn by individuals or centralized administrations, providing a technologically weak mechanism for validating user legitimacy.

Current record traceability and timestamping do not depend on public networks, nor do they count on mechanisms to generate public proof of existence or immutability. Data provenance is not endorsed by network-based geolocation.

Finally, there is a general lack of compatibility and interoperability between electronic systems for the integration of data in real time.

4 Section B: Solution

4.1 Proposed anesthesia record features for system optimization

In order to optimize the "control process", the quality of the generated data should be maximized. An ideal record system should provide unbiased data and ensure the immutability of information, precluding the influence of particular interests of individuals or institutions. In addition, mechanisms to generate evidence about the performance of the system components and their interactions must be provided by the architecture itself.

We propose a model based on the application of open-source hardware and software for the registration of sensor time series as a fundamental principle for case analysis and reconstructions. Decentralization and technological independence ensure an impartial and immutable data outflow. The records integrate real-time information on the spatio-temporal relation between the patient and the anesthesiologist, generating evidence of the entire anesthesia control system. To enhance the interpretation of the time series, manual incorporation of supplemental data related to the anesthesia case is invited by the system.

A global anesthesiologist ecosystem can be assembled over a record technology based on specific features to ensure scientific rigor in the data generation process. While these characteristics define the system as a whole, we divide them into three main categories for an intelligible exposition:

a) Features of the data generation process
b) Features of the system network
c) Features for interacting with data

4.1.1 Features of the data generation process

1- **Automaticity:** Data sampling and registration should be automated in order to eliminate bias and prevent legibility issues or ambiguity resulting from manual data transfer. An automated record should avoid distractions for the anesthesiologist (Dutton and DuKatz, 2011; Kadry et al., 2012; Tse et al., 2020).

2- **Synchronicity:** Asynchrony between real events and their registration may lead to inaccuracies and loss of information. Sampled data should be recorded simultaneously (or with minimum delay) with respect to the sensors' measurement process (Vigoda and Lubarsky, 2006).

3- **Decentralized Storage:** Relying on local hardware or centralized services for record storage may lead to potential vulnerabilities such as access limitation, data tampering or permanent loss.

We believe that data integrity and accessibility can be ensured by delegating the storage to decentralized systems. This would maximize fault tolerance and attack resistance, and would also avoid reliance on critical points of failure related to hardware malfunction and central control over databases. While "architectural decentralization" would enable data to be saved and distributed globally, "political decentralization" would avoid dependence on the control of individual organizations over data storage (Buterin, 2017).

Storage redundancy should be manageable according to the ecosystem requirements.

4- **Accessibility:** Records should be permanently available for consultation worldwide. Data retrieval must be guaranteed avoiding any type of territorial or institutional access restriction. Patients can thus benefit from the availability of previous records for use in prospective anesthesiological procedures or emergency scenarios.

5- **Encryption:** Data must be transmitted securely between nodes, the protection from decryption in the case of malicious interception must be technically ensured (Fernández-Alemán, 2013).

6- **Real-Time Transmission:** To minimize record vulnerability at data generation sites, sampling should be transmitted to remote storage systems instantly or with minimum delay.

7- **Biometric Authentication:** Record systems should count on signatures or authentication mechanisms to validate that the data has been generated by whoever claims to have done so. Biometric authentication, such as fingerprint reading, provides a reliable method for the identification of the anesthesiologist and also generates an active proof of proximity to the patient. Biometric signatures would provide objectivity in determining anesthesia times, eliminate inaccuracies in billing systems, and provide a formal method for handovers between professionals. Furthermore, these would impede fraudulent authentication and discourage simultaneous anesthesia procedures.

Ideally, the patient's consent to record their data should also be obtained through a biometric method. We propose a raw voice recording system to document the patient's authorization before the anesthesia procedure begins. This would allow its incorporation into the anesthesia record without compromising privacy.

8- **Traceability:** Information on procedure geolocation and timestamps should not rely on manual labeling. This must be automatically generated by network connectivity and embedded within the register as evidence of the data origin.

9- **Confidentiality/Privacy:** Paper anesthesia records can easily be mishandled, compromising sensitive data. Most electronic records from anesthesia machines and monitors rely on manually introduced passwords which can be easily revealed or shared. Biometric authentication certifies signer legitimacy and ensures data protection through a non-shareable mechanism. It also enables the implementation of ledgers containing chronological data of biometrically-signed access to records.

To ensure privacy, records should not contain personally identifiable information about patients (Coorevits et al., 2013; Kayaalp, 2018). If necessary, records could be paired to specific cases using codes owned by the patients, or by matching tracking tags (previously authorized by them) such as geolocation, timestamps, type of intervention or medical history.

10- **Availability of Data on the Interaction between System Components:** The performance record of a control system should include information about the dynamic interactions of its components. In addition to the sampled data from patients and the equipment interacting with them, anesthesia records should include measurements of the spatio-temporal relation between the patient and the anesthesiologist.

In order to prevent record discontinuity or the generation of unsupervised datasets, the system should provide incentives to maximize data completeness and should discourage the absence of the anesthesiologist in the operating room.

Spatio-temporal data from professional trainees should also be available in the form of peer-to-peer dynamic interactions between the trainee, the main anesthesiologist and the anesthetized patient.

11- **Data Immutability:** Measurements should be invulnerable to adulteration from sampling to retrieval processes. Modification or addition of new data should be implemented in a "persistent data structure", preserving historical data entries (Kaplan, 2018).

12- **Blockchain Data Stamping:** Proof-of-existence can be generated by registering information of the anesthesia record on blocks from public blockchains. Stamped information should encode: anesthesiologist ID, record identifier, version, time window of its creation and geolocation. It should also include a content hash and the storage addresses of the record and its previous versions.

4.1.2 Features of the system network

13- **Universal Instrument Identification:** System components and sensors should be universally identifiable by an electronic method. Technical identifiers must be transmitted within the record to allow the performance evaluation and quality of its components. Also, as a policy to ensure scientific reproducibility, data compression and processing should be performed by open-source algorithms.

14- **Technology Independence:** In order to provide an impartial architecture, the record system should be a dedicated and independent technology implementation. Instrument electronic-identifiers and open-source design should be technically required for external device compatibility.

15- **Bidirectional Communication Support for Wearable Devices:** Current anesthesia monitoring systems lack mechanisms to measure and record the proximity of the anesthesiologist.

Neither do they provide remote communication between the professional and the monitors.

Two-way communication between wearable devices and the record system can generate spatio-temporal data between the anesthesiologist and the patient. Additionally, wearables can allow users to manipulate system parameters remotely, generate biometric signatures, and create voice recordings.

The wearable should be able to alert users through vibration or sound, when the system measurements are interpreted as unsafe conditions for the anesthetized patient (such as anesthesiologist motion inactivity or continuous absence within a safe surveillance distance). Wearable devices should be able to self-alert users even when no connection to the record system is available.

Wearables can also be used to unlock system functions and accredit system manipulation by the actual user through very close radio frequency communication.

Data generated from wearable devices should be integrated into the anesthesia record.

16- **Anti-Sybil Backed System[1]:** The system should count on a mechanism to prevent the creation of arbitrary, fraudulent or duplicate user profiles (Douceur, 2002). Integration of blockchain unique human identity proposals (Liu et al., 2020) and the implementation of biometric signatures can lead to a globally interoperable anesthesiologist reputation system (Hoffman et al., 2009).

17- **Decentralized Governance:** Consensus for system implementations should be managed by a distributed network with no central control (Reijers et al., 2016). Decentralized governance is important for optimizing patient safety as a global anesthesiologist community can reach consensus on standards, guidelines and protocols in an open and transparent way, eliminating any potential risk for institutional coercion. On this basis, compliance with safety protocols, monitoring guidelines, professional certification requirements, and procedure classification for billing systems could be globally assessed by a decentralized community of professionals.

Decentralized governance would also contribute to safety by providing a democratic way for the system community to evaluate its users' compliance with the established standards. Finally, a network of self-audited users can openly report and alert the global community about labor regimes that may compel anesthesiologists to work in conditions in which patient safety is undermined or deviated from the scientific approach.

18- **Output Data Interoperability:** Records should facilitate the organized data exchange between diverse information systems, in this context, data must be ideally structured for effectively feeding blockchain oracles (Al-Breiki et al., 2020). Datasets should be easily tokenizeable and embeddable in programmable environments such as smart contracts (Mohanta et al., 2018; Buterin, 2022a).

19- **Synchronizable Records:** Data streams should be easily synchronized with data from third party devices. In the same way that clapperboards are used in filmmaking to adjust and integrate recorded audio with video, anesthesia records should provide a mechanism for self synchronization with any type of external data gathered from peripheral devices. For example, video from the surgical field could be integrated with the time series to generate multimedia content for research, educational or legal purposes.

Although video recordings of the operating room could be a valid solution for registering events and team performance, this type of information entails potential issues concerning privacy. Native video recording falls outside the scope of this architecture. However, since the system logic seeks to achieve scientific interoperability, synchronization mechanisms for external video must be provided.

20- **Dedicated System:** The system should be exclusively tailored to patient safety, performance analysis and quality improvement in the field of anesthesiology. In order to mitigate errors and improve the safety of human tasks, it should facilitate the use of checklists and the easy access to protocols and guidelines (Phipps et al., 2008). The architecture should support real time consultation with colleagues worldwide through the system's professional network.

21- **Open-Source Framework:** Medical devices can be potentially overpriced in relation to their provided technology. Programmed obsolescence can be used immoderately to maximize profitability by electronically limiting usage time of technological supplies. Closed-source developments restrain the community from auditing hardware and software. This also limits performance evaluation and benchmarking of internal components and processes. The technical design of system components should remain openly available for the community to review, report issues, and suggest improvements.

4.1.3 Features for interacting with data

22- **Predictive Analytics and Machine Learning Compatibility:** Generated datasets should provide a quality standard for applied research in technology. Extracted statistical information from big data can be used for real-time performance evaluation and predictive analytics (Liem et al., 2018). Sampling and recording processes should generate optimized data streams for feeding artificial intelligence-driven technologies and also for enabling their continuous surveillance. Closed-loop anesthesia infusion systems are examples of emerging technologies that could leverage this system as a data source (Connor, 2019).

23- **Compatibility and Interoperability for Supplementary Data Incorporation:** Users should be able to integrate supplementary data to the time series records. This feature should be available during the anesthesia procedure or in deferred scenarios such as the preanesthetic visit or extra operative medical consultation.

The input of supplementary information is considered to support the interpretation of time series and should therefore be encouraged. Supplementary data should be incorporated manually and may include patient medical information, device settings, medication details, intraoperative comments and voice notes. In addition, electronic interoperability with authorized third-party devices and extrinsic software platforms

1 https://en.wikipedia.org/wiki/Sybil_attack [Accessed 12 November 2022].

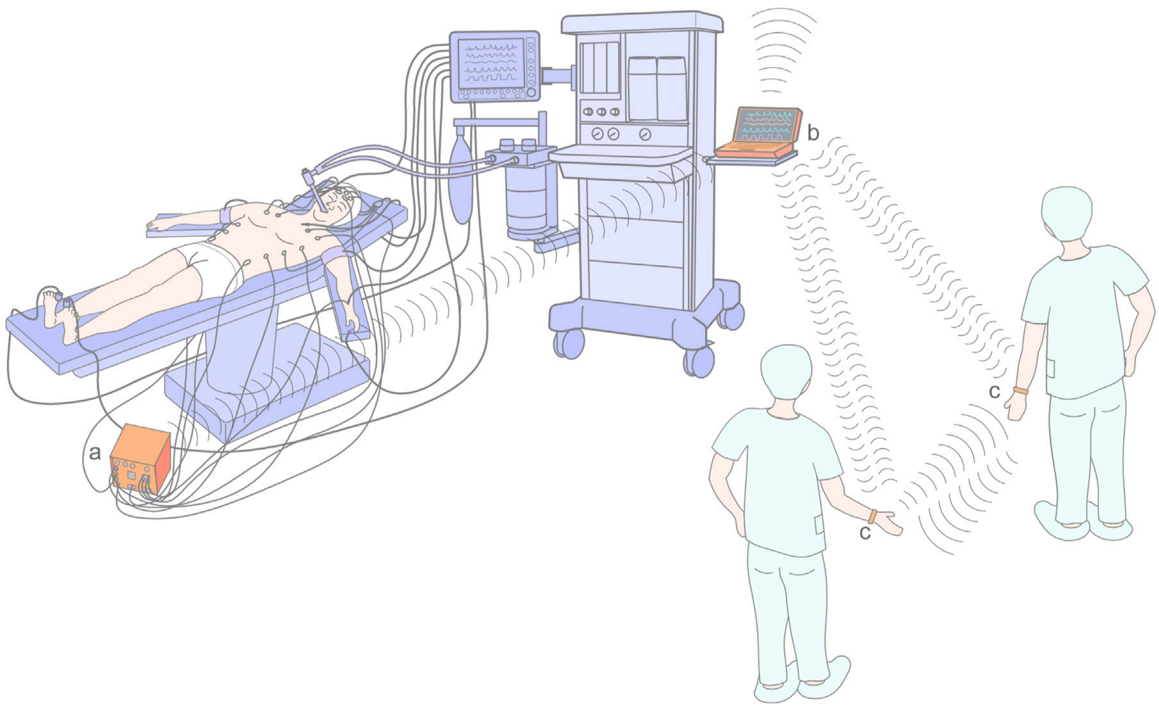

FIGURE 1
Interaction between system components. **(A)** ***Sampling unit***, **(B)** ***specific application computer device***, **(C)** ***wearable transponders***. The computer device (connected to the peer-to-peer governance network) transmits the collected data in real time to the decentralized storage systems.

should allow the embedding of external data such as video, images, or files containing valuable information (Weininger et al., 2017).

24- **Customizable Screen System Interface:** A front-end interface should enable users to customize the data flow representation for efficient real-time data analysis (Simpao and Rehman, 2020).

A standardized display configuration must be available through a fast switching mechanism to facilitate the communication of critical information between colleagues during handovers (Saager et al., 2014; Jones et al., 2019) or in emergency scenarios.

25- **Software Tool Compatibility:** Predictive analytics software is expected to improve decision making-processes (Nair et al., 2017; Rozental and White, 2019). Current anesthesia monitors do not admit the installation of accessory applications. The system should allow users to install and implement their preferred data extraction tools. Also, individuals should be free to develop and deploy their own applications. Audited open-source software validated by scientific consensus can be made available to the ecosystem for use, continuous testing and improvement.

4.2 Implementation

We introduce a model to resolve current issues and comply with the proposed features. In the following section we describe hardware components and their interactions (Figure 1). We outline the aim of the system software and the integration of blockchains with decentralized storage systems. We also describe methods for generating, updating and retrieving anesthesia records.

The descriptions refer to what the authors consider to be the best system configuration, but since various possibilities in component design and connectivity are compatible with the main objective, alternative implementations are mentioned.

We envision that this proof of concept should be initially implemented as a physically independent system from the anesthesia ventilator and multiparameter monitor. This is because it is a technically simpler way to evaluate its performance and adoption during early stages. It should be noted that the initial implementation as a stand-alone system can contribute to safety by being available as a second multiparameter monitor in the operating room, providing backup in complex scenarios where sensor malfunction, disconnection or interference may hamper decision-making processes.

5 Hardware

5.1 Sampling unit

The device consists of a module that contains an array of sockets into which cables from different sensors are connected. Its function is to collect data from sensors and deliver it to a dedicated computer device that broadcasts the data streams to remote storage systems. To provide a mechanism for tracking and measuring instrument performance, the sensors are equipped with an electronic identifier through which the system is able to register their specifications such as model, developer, serial number and time of use. Since the system is intended to be suited for research purposes, several sockets may be present for the same type of sensors.

Each channel receives a specific type of input consisting of biosignals from patients or data from electromechanical devices connected to them. These may include signals from pulse oximetry, electrocardiography, noninvasive blood pressure, invasive pressure, electroencephalography (EEG), near-infrared spectrometry, temperature, and data from the respiratory circuit (capnography, flow, volume, pressure, and gas analysis). Signals that require invasive instruments, such as intravascular sensors, can be electronically split and delivered to the sampling unit and main multi-parameter monitors from a unique transducer.

Data streams are preferably transferred to the computer device via wireless connectivity in order to prevent cables interfering with staff circulation in the operating room.

To maximize electrical safety for patients, this device is ideally powered by rechargeable batteries.

5.2 Specific-application computer device

This module is a personal specific-application computer, equipped with a screen and input devices such as keyboard, moused, knobs and buttons for easy user interaction. It contains the front-end software that allows the anesthesiologist to log into the system, authenticate, generate case registers, consult them and introduce supplementary information to the records.

This device receives the sensors' time series from the ***sampling unit*** and transmits data streams to the remote storage systems via Internet connection. The sampled data is displayed in real time enabling users to interact with it through visualization tools and analytics software.

It is equipped with a fingerprint reader for generating biometric signatures during the anesthesia procedure. Geolocation and synchronization with universal coordinated time (UTC) is established through Internet connectivity.

A set of antennas built into the unit allows bidirectional connectivity with other devices maintaining constant communication with the ***wearable transponder***[2]. In addition, an integrated very short-range radio frequency identification system (RFID) allows the detection of the wearable device in close proximity, providing a mechanism to validate operations on the computer device performed by the transponder holder.

5.3 Wearable transponder

This device consists of a unique personal smart bracelet equipped with accelerometers, fingerprint reader, vibration motor, sound emitting system, microphone and a magnetic clasp with an electronic contact. Its function is to provide the anesthesiologist with a self-authentication mechanism and generate evidence on the active vigilance of the anesthetized patient. This is done by measuring irregular acceleration patterns on the wearable and estimating the distance between this device, the computer, and the sampling unit through the wireless connectivity.

A very short-range RFID verifies the close proximity of the wearable during the computer device operation.

Bidirectional communication enables the user to remotely interact with the computer device through buttons and a touch-sensitive scrolling surface on the smart bracelet. The device is also able to receive signals from the computer which can trigger vibrations or sound alerts on it.

The built-in microphone allows the incorporation of voice notes to the records. Although the system is not conceived to incorporate personally identifiable information from patients, brief timestamped voice statements from individuals consenting to have their data recorded, can be integrated into the anesthesia record to provide a biometric proof of voluntary acceptance for their data processing.

5.4 Video synchronizer

This is a complementary device designed to synchronize third-party video recordings with the sampled data. It provides a precise mechanism to create multimedia content integrated with anesthesia data streams.

The device consists of an array of lasers which are pointed toward the surgical field or a site of interest. It is connected to the sampling unit or to the computer device and synchronized with the system´s native chronometer. A variable dot pattern is generated intermittently and projected by the lasers in synchrony with the time series clock. The dot pattern code embedded within the record, provides a way for any video content that includes the dynamic pattern in the filmed plane to be synchronized with the data streams by matching the visual time pattern with the one in the time series (Figures 2, 3).

6 Software

The system software interconnects the hardware with distributed storage systems, blockchains and decentralized computing services. It provides a front-end interface on the computer device for logging into the online system and for interacting with the "governance layer": a peer-to-peer network which coordinates the system components and in which decisions about the system infrastructure, flow of data and permissions are resolved by consensus.

The software facilitates data management and communication between devices. It allows users to customize data visualization and run applications to explore sampled information. In addition, it provides the interface to interact with machine learning tools such as artificial neural networks. Global data statistics are delivered for real-time visual juxtaposition with time series enhancing surveillance through trend extrapolations, Bayesian inference or the application of deep learning predictive models (Emmert-Streib et al., 2020).

7 Blockchain technology

Blockchain technology is implemented to provide a public register of the anesthesia records. Information such as record ID, anesthesiologist authentication, personal blockchain address signatures, record content hash, storage addresses, versioning, geolocation and timestamping; is embodied on blocks of public blockchains generating an immutable proof of record existence.

2 https://en.wikipedia.org/wiki/Transponder [Accessed 12 November 2022].

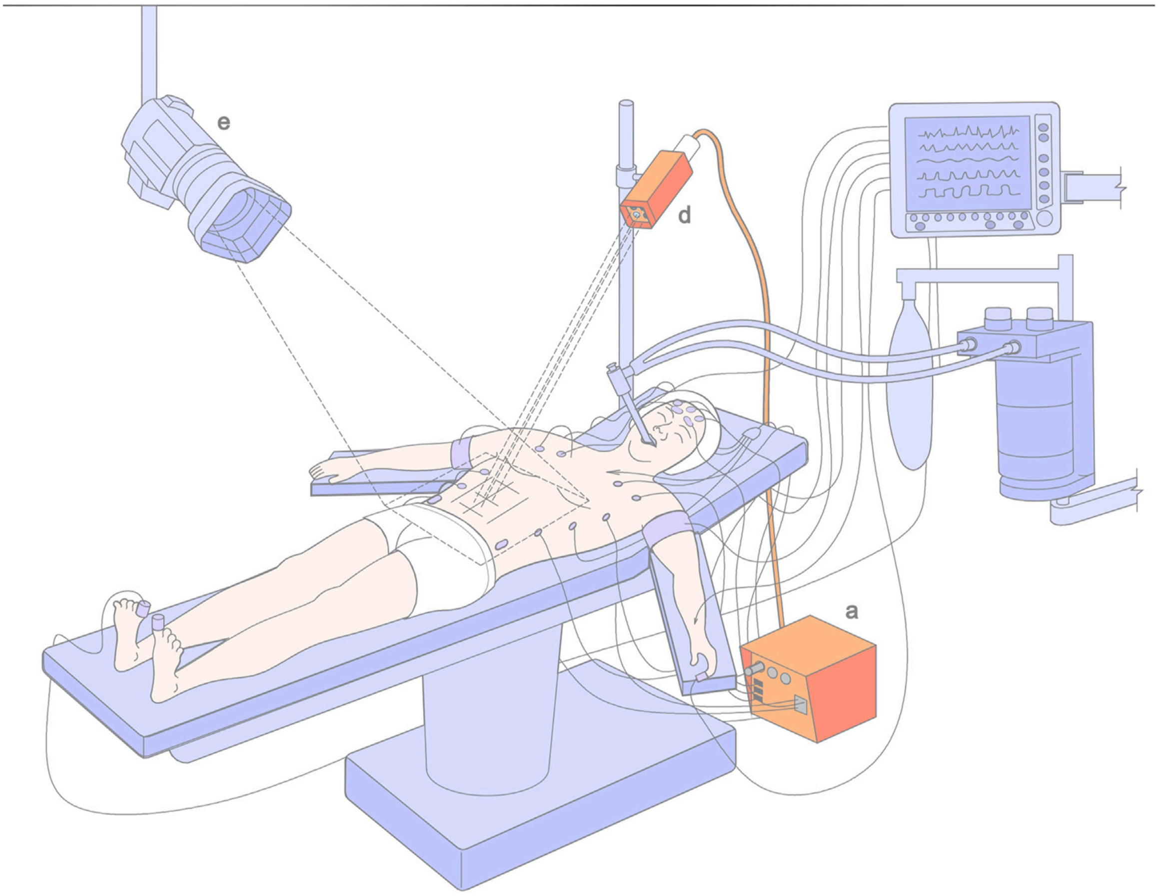

FIGURE 2
Method for synchronizing third party video. The **(d)** ***video synchronizer*** is connected to the system timer through the **(a)** ***sampling unit***. It projects through its lasers a dynamic dot pattern synchronized with the system´s internal chronometer to the area being filmed by a **(e)** ***third party video camera***.

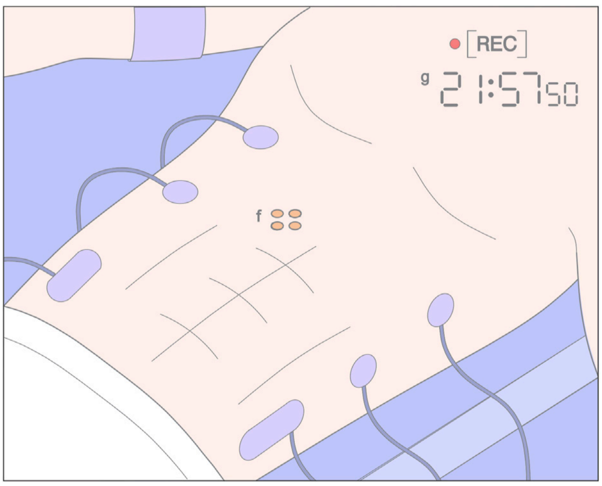

FIGURE 3
Filmed plane recorded by a third party video camera. The **(f)** ***dynamic dot pattern*** projected by the video synchronizer enables synchronization of the system internal timer (and therefore, the recorded time series) with the **(g)** ***third party video chronometer***.

Users connect to the system through their unique accounts based on blockchain addresses (wallets) that provide proof of personhood and possess certain useful features such as Sybil attack resistance and community recovery (Siddarth et al., 2020). These accounts are also referred to as "Souls" in the context of Web 3.0 (Chohan, 2022) and are used to hold the professional´s commitments, credentials and affiliations in the form of "soulbond tokens" (Weyl et al., 2022). The application of this methodology is expected to be consistent with the future global adoption of universal identity systems based on distributed ledger technologies (Goodell and Aste, 2019; Zwitter et al., 2020). Anesthesiologists can thus take advantage of blockchain use cases to prove provenance, reputation and establish decentralized governance through innovative polling mechanisms such as quadratic voting (Lalley and Weyl, 2018).

8 Decentralized storage

Data streams are directly transmitted to distributed remote storage systems, initially saving the anesthesia records relying on architectural decentralization. To ensure data integrity and permanent accessibility, records are then retransmitted to one or

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more distributed storage networks structured on political decentralization.

Although an optimal implementation would involve transmitting data streams directly to politically decentralized storage networks, current technologies present slow upload and download speeds and do not allow information to be recorded in real time. To overcome this limitation, we propose to apply a remote storage system consisting of one or more architecturally decentralized (but politically centralized) databases for efficiently receiving the transmitted data in real time.

Once the anesthesia case is over and the record transmission to the remote databases is completed, it is integrated into a unique register and automatically retransmitted to architecturally and politically decentralized storage systems for permanent and immutable preservation.

Multiple types of databases can be implemented simultaneously to deliver streamed data: regular SQL, NonSQL or databases built specifically for time series (such as InfluxDB[3] and TimescaleDB[4]). These can also provide efficient data access for machine learning model training, real-time analytics and data mining. Selected data can be filtered, categorized and saved in repositories in order to be readily available and interoperable for data science (Sessler, 2014; Epstein and Dexter, 2018).

"Content-addressable storage" (CAS) qualifies as an optimal scalable approach to store and reference permanent anesthesia records in architecturally and politically decentralized systems (Hinsen, 2020; Kumar and Tripathi, 2020). CAS delivered by peer-to-peer networks (as proposed by IPFS[5]) can further contribute to persistent data structures by providing logical decentralization (Benet, 2014; Buterin, 2017). This technology allows the long-term immutable storage of electronic objects using cryptographic hashes (calculated from the object content) as references to retrieve the original data. Hash-based IDs are unique identifiers that provide a permanent and unalterable address for future record reconstruction. Content-addressing guarantees that the links always return exactly the same content even though it may be redundantly partitioned and replicated onto arrays situated at different locations. Even if someone destroys all the copies on the network, it would only take one node adding the content in order to restore the global availability.

The CAS system is impervious to technological changes since the data remains accessible as long as an application server is able to map the address of the original content. It also prevents the data from being duplicated or modified once stored, therefore guaranteeing its legitimacy and integrity. A CAS-based end storage can simplify data communication between different software used in research and facilitate distributed computations.

In order to keep records always available, the content must be stored at least at one location. This is referred to as "pinning" in the IPFS protocol (Guidi et al., 2021). Objects can be pinned on local nodes or delegated to third-party pinning services. To provide scalable, cost effective and permanent storage, diverse storage services could be implemented concurrently or alternated if necessary; in this way storage redundancy can also be dynamically regulated according to the ecosystem´s needs.

Although native blockchains could theoretically be used to store data within blocks, the method would be impractical due to the extreme block size that would be required.

Since a primary goal of the system is to save an immutable copy of the record with the lowest possible latency in politically decentralized (and ideally, logically decentralized) storage networks; intermittent transmission of partial data sets could be considered as an alternative strategy.

9 Hyperscale computational network

The internal hardware of the specific-application computer devices, connected through a peer-to-peer network, may deliver a suitable computational power for coordinating the data flows according to the instructions on the governance layer. However, processing power may be limited as the system and data throughput scalate. Specific tasks regarding high-performance networking, big data processing and deep learning will require large-scale computations (Panda et al., 2022). To meet the needs, computing power, communication, memory and storage can be outsourced to decentralized services orchestrated from the governance layer.

9.1 System architecture

The network of peer-to-peer specific-application computer nodes, integrates into a governance layer. This structure exerts parallel control over the different system components: storage services, blockchains, and outsourced computational networks (Figures 4, 5).

Its functions are:

Data Management:

- Verify the legitimacy of its users
- Certify the generated records
- Direct the data transmission to the storage systems
- Coordinate the flow of data between different storage systems
- Write the blockchain registers

Coordination for the Participation of Nodes:

- Conduct the voting system for: network consensus, use of the decentralized-treasury funds, improvement proposals, community consultation, insurance resolutions.

System Administration:

- System maintenance
- Accountability
- Outsourcing relationship management (for data storage, computational power, machine learning model training, and blockchain fees)
- Quality control of the generated information
- Accreditation of its members' compliance

3 https://www.influxdata.com/
4 https://www.timescale.com/
5 https://ipfs.tech/

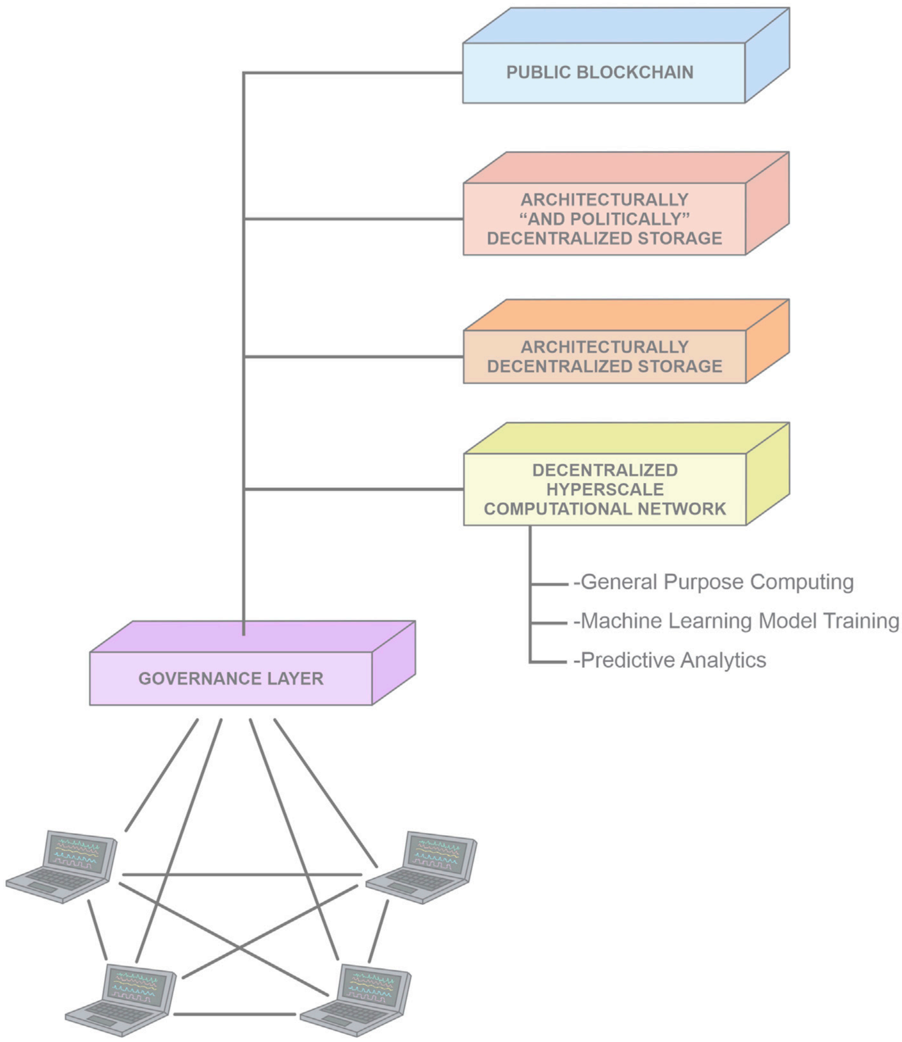

FIGURE 4
System Architecture: Component Diagram. The Governance Layer exerts parallel control over each component and coordinates the flow of the data.

- Custody of internal system data (for example,; the distribution of split keys, information about members, internal registry of anesthesia records, history of queries to registers).

An inherent value of the system is that as a result of its processes, anesthesia records (which are encrypted and certified by the system) are stored and always available through content addressable storage, evidencing their existence on a public blockchain.

This implies that even if the system architecture ceases to exist, the records and the evidence of their generation and immutability would remain available. In this hypothetical case, since the system´s treasury is aimed to cover the costs for the pinning services of the records though smart contracts; these would remain pinned for a considerable period, allowing anesthesiologists and patients to download their records and pin them themselves to ensure their permanent availability.

Access to the content of the records, and thus the preservation of their privacy, would rely on the holders of their respective decryption keys. Interestingly, techniques for content erasure have been proposed for CAS in order to meet the "right to be forgotten" requirement for personal data protection regimes (Politou et al., 2020).

While the application of a second set of sensors connected to the patient could be considered as an over-engineering approach, it should be understood that this is implemented in this way to allow the gradual operation and testing of the concept without affecting the validated monitors of the operating room. We foresee that, if adopted, some components of future versions of the system could be simplified or even dispensed with. For example, the sampling unit could be reduced to a small module which may capture raw data wirelessly from multiparameter monitors and anesthesia machines. These in turn, should be able to transmit their raw data and the technical identifiers of their components. The wireless sampling unit could be further integrated into the specific application computer device, which may become a main multiparameter monitor in the operating room.

9.2 Methods

9.2.1 How is a record generated?

- Certified anesthesiologists use the specific-application computer, connected to the Internet, to log into the system through their password and biometric authentication. A blockchain-based personal identification account can also be paired to the system. This can be done by connecting a software cryptocurrency wallet (such as Metamask[6]) to the user interface or by signing a specific message with the private key of a proof of personhood wallet: for example, generating a signature containing the case record ID and its geolocation with the private key of a Proof of Humanity[7] (PoH) Ethereum[8] address (Buterin, 2014).
- The sampling unit is wirelessly paired with the computer device. Cables from sensors needed for the procedure are connected to their sockets. Each channel sampling rate is configured according to specific needs. For example, higher temporal resolution may be required for EEG channels in surgical procedures that generate useful data for neuroscience research.
- The wearable device is paired with the specific-application computer and sampling unit. The user puts the device on their wrist, closes the electronic clasp and self-authenticates using the fingerprint reader.
- Sensors are connected to the patient. A case register is created in the system using the specific-application computer device. Information related to patient medical history, procedure plan and professional team is introduced.
- A brief recording of the patient's voice is obtained through the microphone on the wearable device. This provides a biometric consent declaration which is incorporated within the anesthesia record.
- Checklists are run to verify procedure details and check resource functionality and availability.
- Geolocalization and UTC synchronization are established.
- The user starts the recording by generating a fingerprint signature on the computer and wearable device. Sampled data is transmitted from the sampling unit to the computer device where time series are displayed on screen.
- Datasets are streamed in real time to the remote storage system via Internet connection. An internal memory stores the sampled data within the device to provide a buffer for transmitting deferred data in situations where Internet connection quality becomes low or interrupted.
- Generated information from the wearable and sensors is streamed in a time series format. Supplementary data expected to enhance the interpretation of the anesthetic procedure is manually incorporated into the register through the computer device. These data may include: sensor placements, medications administered, infusion rates, ventilator settings, comments, observations, voice recordings and photos or videos from authorized devices.
- At the conclusion of the anesthesia procedure, the anesthesiologist confirms the end of the recording with a new biometric signature.
- Once the complete set of data from the anesthesia procedure is received by the remote databases, it is then integrated, packed and retransmitted with the lowest possible latency to an architecturally and politically decentralized storage system (such as IPFS[3], Arweave[9], Storj[10], Sia[11]) where they are permanently stored.
- Blockchains are implemented to automatically generate a public timestamped proof of record existence, certifying the provenance and authenticity of purported factual recordings. An automatic register is generated on a block of a public blockchain consisting in a digital signature encoding specific information such as:
  - anesthetic case record identifier
  - anesthesiologist identifier
  - signature from an anti-Sybil personal address (or from a related dedicated address)
  - record version
  - timestamps (defining case time interval)
  - geolocation
  - addresses of the decentralized databases in which the record is stored
  - hash of the record content (to validate data immutability and to retrieve records from CAS)
- Keys for decrypting the stored files containing the records are generated for the anesthesiologist and the patient. Additionally, a special split key, such as a Shamir key (Shamir, 1979), is randomly and redundantly distributed among users to provide a mechanism for record decryption through the system consensus. This enables a democratic community retrieval of the record information in situations where neither the patient nor the anesthesiologist can provide the decryption keys (Benzekki et al., 2017).
- On completion of the anesthetic procedure, the system generates an electronic certificate which is sent to the anesthesiologist´s computer device. It incorporates the record identifier, the encoded register uploaded to the blockchain and the block header. This certificate can be attached to the hospital medical record and delivered to the patient.
- As a result of the described processes, a register for each case is generated in a public blockchain certifying the existence, storage and authenticity of the anesthesia record. Blockchain scanners can be used to verify registers and are therefore essential to support a universal logbook containing blockchain-certified professional cases. A system internal ledger available off-chain can facilitate data accesibility avoiding the need to scan entire blockchains to search and retrieve records.

6 https://metamask.io/
7 https://www.proofofhumanity.id/
8 https://ethereum.org/
9 https://www.arweave.org/
10 https://www.storj.io/
11 https://sia.tech/

- Anesthesia records authorized by patients can be made available for use in data science and research. Patients can provide customs permissions to use or restrict specific types of information from their records.

9.2.2 How is new information added to an existing record?

The system architecture is conceived so that the original data cannot be modified or deleted. Amendments and additions are allowed to the creator of the record, in a timestamped and layered structure, preserving the historical data always accessible.

Data can be corrected or added by recovering the record from the decentralized databases through the system software. Once modifications have been made, the new complete record is uploaded to the architecturally and politically decentralized database and a new blockchain register is generated. As an alternative implementation, the system could upload just the new record layer, referencing in the blockchain register the entire set of layers prior to the original.

9.2.3 How is a record retrieved?

Records can be retrieved autonomously using their blockchain identifiers which specify versions, storage addresses, and content hashes. Decryption is performed using the keys of the patient or the anesthesiologist.

Retrieval can also be done through the system by requesting the data recovery from the computer device of the record creator. After verifying the identity of the user, data packages are downloaded, and the record content is decrypted. Anesthesiologists can thus consult and review previous anesthesia records from their patients without the need to handle the specific decryption keys. A history of record queries is automatically generated by the system.

Community recovery can be achieved with the randomly distributed key through the consensus of users. These are randomly selected and subjected to consultation in order to establish whether the retrieval and decryption of the anesthesia record for each particular case is justified and in accordance with ethics and law.

9.2.4 Wearable device operation

The interconnection between the wearable transponder, the sampling unit and the computing device allows the dynamic estimation of distances between them and, therefore, the extrapolation of spatio-temporal information between the patient and the anesthesiologist. Accelerometers built into the wearable device sample acceleration patterns which are expected to be irregular when worn by a person. Movement patterns can be automatically detected by the system but also efficiently verified using artificial intelligence. Measurements from the wearable sensors are transmitted along with the time series, thereby generating an automated proof of active permanence within a safe distance from the patient.

As a routine protocol, the system stochastically requests biometric authentications on the wearable. To improve the verification mechanisms, the device can be linked to a personal-identity blockchain address (such as the proposed by PoH) so that when a biometric authentication is produced, signatures or non-interactive zero-knowledge proofs[12] (Blum et al., 1988; Buterin, 2022b) are delivered to the system.

To avoid the risks of dealing with private keys of a personal ID public address, the user can link it to a dedicated address. For example, the governance layer can issue a soulbond token (ideally a non-transferable token) which exhibits: a) a PoH address (or similar service), where this soulbond token is delivered and expected to be held; b) an anesthesiology dedicated address (generated by the user) and; c) a signature emitted from a system official address (as a membership certificate) having both addresses (a+b) as the input content of the signed message. The user incorporates the secret key of the dedicated address into the wearable transponder which enables it to generate off-chain signatures or zero knowledge proofs (ZKP). This method would provide evidence that the fingerprint signer is in physical possession of the cryptographic seed of the dedicated address. This public address has an inherent value for the user as it is used as a unique account for the system and as the identifier for the professional log, the generation of reports, and the issue of certifications (Figure 6).

To ensure that the wearable device is worn by its legitimate owner, biometric authentications are requested each time its contact is closed. This is because it is expected that the anesthesiologist may need to take the bracelet off during certain procedures, for example, when placing a central line. Successive openings may increase the frequency of stochastic authentication requests.

Alerts on parameters outside normal ranges transmitted from the computer can trigger vibrations and sounds in the wearable device. Also, circumstances automatically interpreted as suboptimal patient surveillance generate alerts and response requests on the wearable. These may include: lack of response to consecutive requests, failure to detect the wearable within a safe distance for a time considered to imply risk for the anesthetized patient, prolonged accelerometers inactivity and, detection of continuous regular motion in the wearable. In these cases, the algorithm may increase the frequency of stochastic authentication requests on the device. Requests and authentications are recorded in real time.

The smart bracelet can be used to remotely interact with the computer device allowing to silence alarms and navigate through menus via a touch-sensitive surface. It can be programmed to generate vibration patterns to indicate attributes of the sampled signals such as heart rate, oxygen saturation, blood pressure and airway compliance among others.

As a safety feature, the wearable device can autonomously alert the user through vibrations or sounds when it senses permanent motion inactivity or loses connection with the computer device due to excessive distance or poor signal quality.

The very short-range radio frequency system, integrated in the wearable and in the computer device, functions as an automatic proximity detector that differentiates computer manipulations done by the user carrying the wearable. This connection can be used as an additional mechanism for unlocking special functions by close proximity such as alarm settings and display customization.

12 https://en.wikipedia.org/wiki/Zero-knowledge_proof [Accessed 12 November 2022].

10.3389/fbloc.2023.1116124

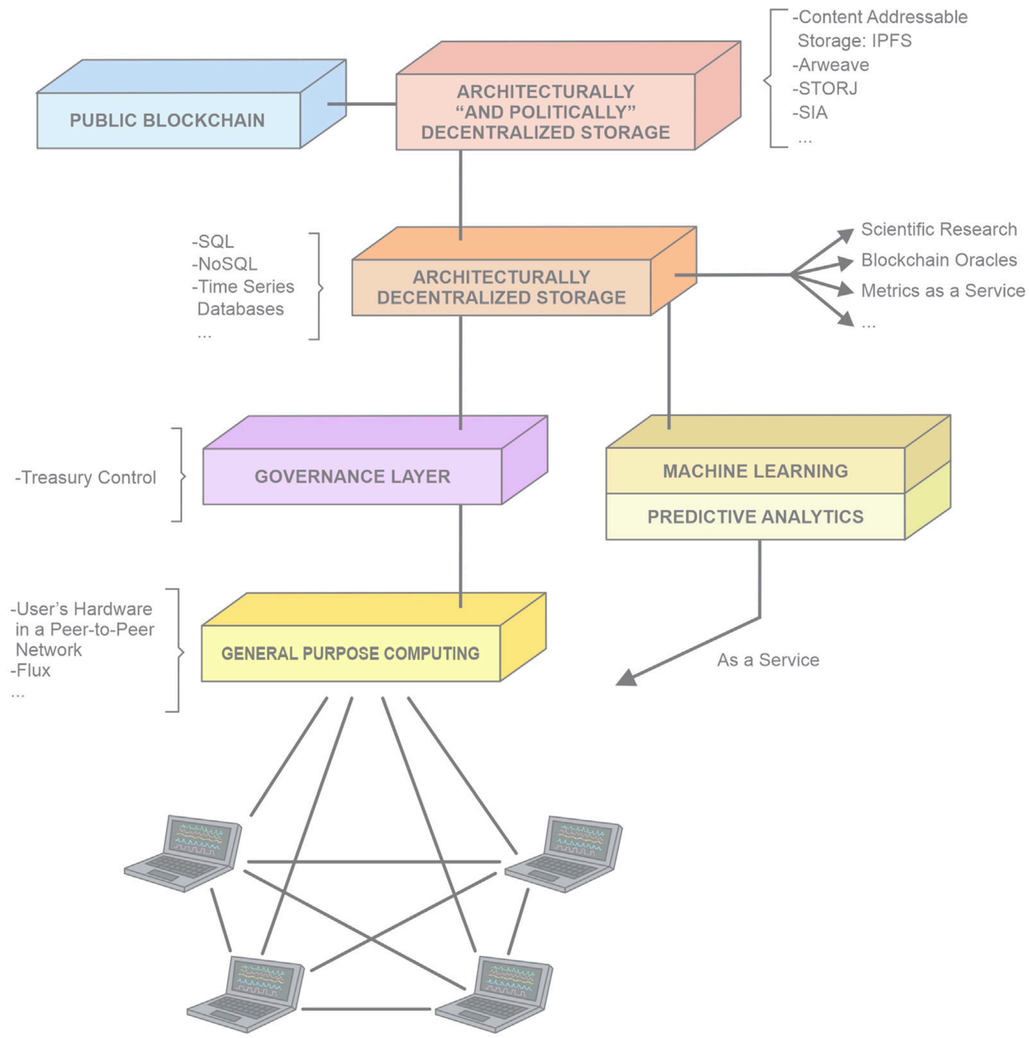

FIGURE 5
Interaction Diagram: the scheme represents a simplification of the data flow. It should be noted that every interaction is coordinated through the Governance Layer. The computational power is segregated into different independent systems which perform specific tasks.

9.3 Overview

The proposed system architecture addresses the aforementioned features in the following way:

1) **Automaticity:** Sampling and recording is done automatically, reducing distractions and allowing anesthesiologists to focus on patient care. Sensor measurements are transmitted directly avoiding the inaccuracies of manual data transcriptions.
2) **Synchronicity:** Data is simultaneously recorded in the electronic system as it is sampled by sensors, eliminating asynchrony between what is happening and what is being registered.
3) **Decentralized Storage:** Definitive storage of the records takes place in architecturally and politically decentralized databases. The system is able to delegate the storage to the most convenient services and regulate data redundancy based on needs.
4) **Accessibility:** Record availability is ensured through storage decentralization allowing censorship-resistant data retrieval worldwide. Patients benefit from having their anesthesiological history instantly available globally.
5) **Encryption:** Data is encrypted from sampling to storage processes. Different decryption keys are delivered to the patient and the anesthesiologist. A special redundantly partitioned key is randomly distributed among users to enable community recovery of records.
6) **Real-Time Transmission:** Data received by the computer device is transmitted immediately or with minimal latency to remote databases.
7) **Biometric Authentication:** Anesthesiologists sign their records through the fingerprint readers on the computer and wearable device. Patients incorporate their consent to sample and save their data through a short recording of their voice (not mentioning personally identifiable information) via the microphone built into the wearable. Instantly hashed, time-stamped raw audio verifies that voice recordings are not

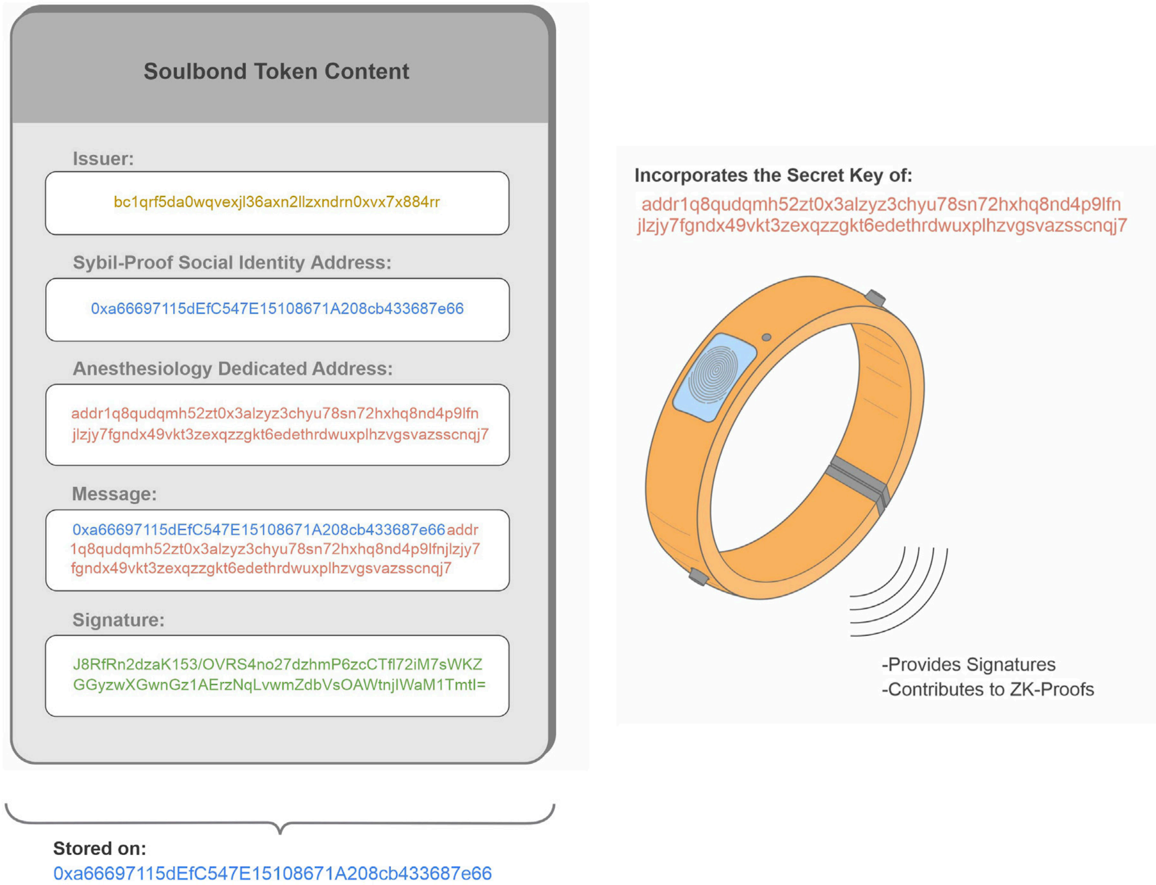

FIGURE 6
Soulbond Token containing a signature[13] (in green) emitted from a system official address[14] (in yellow: a bech32 Bitcoin address). The message contains a personal ID address[15] (in blue: an Ethereum Externally-Owned account such as used in PoH), and an anesthesiology dedicated address[16] (in red: a Cardano Shelley address). The token is stored in the user's personal ID address. The secret key of the dedicated address is incorporated in the wearable device, allowing it to provide signatures or generate non-interactive zero knowledge proofs. Different blockchains were used to demonstrate the implementation versatility. The signature can be verified at https://www.verifybitcoinmessage.com/.
[13] J8RfRn2dzaK153/OVRS4no27dzhmP6zcCTfl72iM7sWKZGGyzwXGwnGz1AErzNqLvwmZdbVsOAWtnjlWaM1Tmtl=
[14] bc1qrf5da0wqvexjl36axn2llzxndrn0xvx7x884rr
[15] 0xa66697115dEfC547E15108671A208cb433687e66
[16] addr1q8qudqmh52zt0x3alzyz3chyu78sn72hxhq8nd4p9lfnjlzjy7fgndx49vkt3zexqzzgkt6edethrdwuxplhzvgsvazsscnqj7

generated at a later time. In addition, open source signal processing facilitates the application of synthetic-speech detection methods to ensure that recordings are not created by a voice generator or impersonator software (Dinkel et al., 2017; Borrelli et al., 2021). In this way, each anesthesia record incorporates a biometric signature of its creator and a biometric proof of the patient's authorization and permissions for the generation and processing of their data.

It should be noted that biometrically generated information is enclosed within the encrypted records and is not made publicly available as part of the metadata.

8) **Traceability:** Data is recorded with a certification of their respective geolocation and UTC timestamps which are determined through the network connectivity. This information is also embedded and publicly available on the blockchain register.

9) **Confidentiality/Privacy:** The identity of the patients remains confidential since the records do not contain personally identifiable information. However, if a patient register ID is forgotten or lost, it can be traced back by matching previously patient-authorized tracking tags such as type of procedure, anesthesiologist ID, date, geolocation or specific patient characteristics. The implementation of smart contracts to support data usage consent can further ensure the confidentiality of personal information shared with multiple data controllers and processors (Kaaniche et al., 2020).

10) **Availability of Data on the Interaction between System Components:** Anesthesia records contain information on the dynamic interaction between the anesthesiologist and their patient, which is extrapolated from distance and acceleration data from the wearable transponder.

Wearable devices provide trainees with a mechanism to record and certify their actively supervised anesthesia cases. Data collected throughout the anesthesiologist career can support an updated interoperable register to provide proof of training and proficiency worldwide (Simpao et al., 2011). Similarly professionals who supervise anesthesiologists in training can provide objective evidence of their involvement and expertise as instructors through their personal records.

11) **Data Immutability:** Content hashes certify the immutability of records. A persistent data structure ensures access to historical information by adding corrections and new data without overwriting the original entries. Modifications to records are incorporated in a layered structure, on top of previous data, so that information from all versions is preserved.
12) **Blockchain Data Stamping:** Proof-of-existence is available on-chain embedded on blockchain blocks as public evidence of the generated records. It encodes information about:
    - record identifier
    - record version
    - anesthesiologist identifier
    - hash of the content (for retrieval of records saved as CAS and for verifying record immutability)
    - geolocation
    - time window within which the record was generated
    - file storage addresses (path for file reconstruction)
    - blockchain block headers containing registers from previous versions
    - file storage addresses of previous versions
13) **Universal Instrument Identification:** Sensors and system components provide their electronic identifiers which are incorporated in the record and enable the tracing of their use time and their performance evaluation. Signal processing algorithms are also electronically referenced and transmitted within the records.
14) **Technology Independence:** System sensors are independent and autonomous from those provided by the anesthesia machine and its multiparametric monitors.

Alternative third-party sensors may be compatible with the system as long as they are based on open-source technology and provide electronic instrument identifiers.

15) **Bidirectional Communication Support for Wearable Devices:** Wearable transponders maintain two-way communication with the computer device enabling remote operation, self-authentication and voice recording.

Users can be alerted through the wearable via vibration or sound whenever the system interprets measurements consistent with situations of risk for the patient. The wearable can alert the user autonomously even when it has no connection to the computer device.

Short-range RFID validates computer manipulations carried out in close proximity to the transponder worn on the wrist of the user.

Information generated by the wearable is included in the anesthesia record.

16) **Anti-Sybil Backed System:** Blockchain-based "unique human identity systems" can be integrated by linking blockchain accounts to the user profile or by incorporating signed messages within the anesthesia record. As an example of the latter case, signatures can be generated with the private key of a personal identity blockchain address and embodied in the record. Alternatively, a system dedicated address, linked to the user´s personal identity address can be utilized to generate signatures or ZKP.
17) **Decentralized Governance:** System improvements, planning and policy making can be decided through system community voting. Blockchain based user profiles provide trustless mechanisms for democratic consensus.
18) **Output Data Interoperability:** The system advocates the exchange of electronic information. It generates an organized information outflow ready to provide off-chain data to blockchain oracles (such as Chainlink[17]). Records can be tokenized and integrated into smart contracts for automated execution of programmable agreements.
19) **Synchronizable Records:** An output channel is available for synchronization with the system´s internal timer. A mechanism to synchronize third party video recordings is provided through the projection of lasers in the vicinity of the surgical field.
20) **Dedicated System:** The system is custom designed for the exclusive use of anesthesiologists. Soulbound tokens can be issued (and potentially removed) by a decentralized community of anesthesiologists as a method for certifying membership and ethical compliance.
21) **Open-Source Framework:** Hardware, firmware, and software components are open-source by default and therefore technically auditable.
22) **Predictive Analytics and Machine Learning Compatibility:** Statistical information generated by the system is available for real time juxtaposition with sampled data during anesthesia procedures. Machine learning delivered as a decentralized service (as proposed by Gensyn[18]), can potentiate system data analysis.

The scientifically rigorous data generated by the system is technically ideal for feeding artificial neural networks. In this framework, it should be noted that the system could leverage the application of "federated learning" and "federated analytics": machine learning techniques that train algorithms for generating models and predictions across multiple decentralized nodes without the need to exchange or centralize data sets (Rieke et al., 2020; Short et al., 2022). These may become essential implementations in the field of anesthesiology, as they would address critical issues concerning data privacy, data security, and access rights while taking advantage of distributed computation.

Interestingly, distributed learning may coexist with decentralized storage as nodes could train their local data while permanently storing it on politically decentralized storage systems. In this way, each node could retain governance rights over its generated data while preserving a

17 https://chain.link/

18 https://www.gensyn.ai/

mechanism for the system community to access it through the consensus of the decentralized governance layer.

Since reliance on data is essential to generate accurate models; the need for a governance layer to ensure data integrity and filter out unacceptable nodes seems critical.

Live-streamed data can be used for modeling, calibrating and auditing technologies based on artificial intelligence such as automatic closed-loop infusion systems.

23) **Compatibility and Interoperability for Supplementary Data Incorporation:** Users are incentivized to generate rigorous and exhaustive records as these are cataloged according to their completeness. Datasets incorporating accurate supplementary information are expected to be valuable for researchers from different fields. Records utilized for scientific research can be publicly certified by the system. These can be used to establish a reputation of users as research contributors.
24) **Customizable Screen System Interface:** The computer interface enables anesthesiologists to customize the screen according to personal preferences. Sampled data can be displayed with innovative visualization modes such as tridimensional representations or tunnel navigation. A rapid, standardized display mode is available for emergency consultation with colleagues who may not be used to a personalized screen configuration.
25) **Software Tool Compatibility:** Software tools run over a failsafe firmware layer allowing users to perform measurements on the data shown on-screen and to apply predictive analytics algorithms.

Users are able to create their own applications and share them with the system community for testing. Innovative software tools that prove useful and are validated by scientific consensus can be made available to the ecosystem.

10 Section C: Innovation, future vision and limitations

10.1 Innovation

Blockchain technology is increasingly gaining adoption in several environments. Aviation (Ahmad et al., 2021), robotics (Lopes and Alexandre, 2019; Strobel et al., 2020), agriculture (Xiong et al., 2020), healthcare (Saeed et al., 2022; Thakur, 2022) and supply chain management (Munir et al., 2022) are examples of activities where this technology is explored. The idea of blockchain applicability in the field of anesthesiology has been proposed (Bellini et al., 2019; Jain, 2019). While specific implementations to use blockchain for the anesthesia records have been suggested (Figar Gutiérrez et al., 2021), our technology concept differs in two fundamental aspects: a) the proposed architecture seeks to not depend on monolithic private services and instead, use them if needed, as replaceable modules; and b) we propose to rely on layer-one blockchains to take technological advantage of the security and decentralization of their consensus mechanisms. That is, implement "real blockchains" and "real politically decentralized storage systems" and not depend on "storage services with blockchain characteristics".

Conceptually, we seek to develop an integral architecture that minimizes systemic over encapsulated complexity (Buterin, 2022c) while preserving decentralized governance, data immutability and accessibility. On this basis, fully decentralized computing networks (as proposed by Flux[19] and Internet Computer[20]) should be conceived as a plausible implementation to allocate the computing power infrastructure of the system. Also in this context, decentralized wireless networks (as proposed by Helium[21]) should be considered as an ideal global communication technology for the devised architecture.

10.2 Anesthesia records as a blockchain oracle

The work of anesthesiologists within health systems is exceptional since they objectively measure multiple parameters related to patients, machines, medications, and diverse technological resources. The proposed system provides continuous data streams whose inherent characteristics make them suitable for feeding analytics systems and for supplying off-chain data to blockchain oracles (Caldarelli, 2020; Ezzat et al., 2022). The generated data is technically valuable as it originates from a complex control system in which many variables are measured and whose different components have distinctive reasons to support the quality of the registration process. These components are naturally coordinated to generate a robust and coherent data flow. The concept should be explained from four different perspectives, each of which presents specific incentives for preserving data integrity and for preventing other parties from colluding against the system:

Patients: Patients logically demand safe anesthesia and quality of care. They expect their anesthesiologist to be qualified and trained to resolve any potential complication. Patients are aligned with the preservation of data integrity, since it prevails as evidence in cases of harm or death. Records are also valuable as documentation of their anesthesiology history for future interventions.

Anesthesiologists: Although practitioners are naturally motivated to provide safe anesthesia to their patients, they are also expected to benefit from data integrity and legitimacy as it feeds their professional log and builds their reputation in the system. In addition, the recorded evidence of compliance with safety standards is a technological protective factor against liability risks.

Society: Data integrity contributes to society by improving anesthesiology outcomes and quality through scientific research. Data tampering is expected to be repelled and reported, as adulterated data can undermine patient safety.

Companies: Companies are expected to appreciate transparent data as they can leverage metrics, supply chain analytics and pharmacovigilance. Rigorous data drives free and fair competition and provides a major incentive for companies to oppose data fraud.

The described system components interact so that each party is encouraged to take advantage of legitimate data and motivated to verify the reliability and validity of the other components. This

19 https://runonflux.io/
20 https://internetcomputer.org/
21 https://www.helium.com/

mechanism of cross auditable interactions provides a collusion resistant system optimized to provide accurate data flows.

10.3 Safety of human life as a measurable asset

Human life can be considered the worthiest asset. Estimating its intrinsic value is analytically complex and objectively unfeasible due to the myriad of variables that should be taken into consideration. However, anesthesiology provides scenarios in which human life is in a standardized state of potential vulnerability due to the lack of self control. Here, the costs and performance associated with the safe care of human life can be objectively measured.

The value of human "health" is also difficult to calculate due to the subjectivity of considering the specific characteristics of patients and of measuring isolated variables from health systems. For example, it would be impractical to establish a standard health value based on a surgeon's skills, or on a tangible item such as a specific medication or treatment. Both approaches would result in deviations due to interindividual skill disparities in the former, and medication price volatility over time in the latter.

We propose that real-time multivariable recordings can be used to objectively determine the costs related to intraoperative anesthesia procedures through the integration of biosensor time series (and hence data on the performance of the anesthesiologist) with information related to case complexity, medical resource requirements, pharmacological consumption and use of technology. Global statistics can reduce variability and eliminate bias and inconsistencies.

A decentralized blockchain oracle can rule an open-access standard price in health systems which can be used as a financial reference value. This can provide a mechanism to scientifically determine minimum ethical wages for anesthesiologists (and extensively for other health professionals). The latter should be understood as the minimum payment rate that professionals should ethically receive during a specific procedure for health systems to coherently guarantee compliance with safety standards. This can prevent detrimental consequences from unfair or distorted billing systems which, through professional overload (West et al., 2018; Afonso et al., 2021; De Hert, 2021), can lead to decreased situational awareness (Schulz et al., 2017), sleep deprivation (Howard et al., 2003; Neuschwander et al., 2017; Wong et al., 2018) or indirectly induce unsafe practices such as simultaneous anesthesia (Burns et al., 2022), absence from the operating room, or protocol circumvention.

Oracles can automatically classify anesthesiological procedures based on analytical criteria such as patient characteristics, case complexity, procedure duration, incidence of complications, professional proficiency and training requirements. An updated categorization of anesthesiological procedures can improve patient safety by establishing a scientific scale for professional fees, so that cases that are more sophisticated or require more complex skills, are higher ranked. We believe that anesthesia billing structures should position the economic incentives to reward continuous professional education, training and deliberate practice (Hastings and Rickard, 2015), overcoming schemes that can potentially lead to academic outdating or competency obsolescence.

An "anesthesiology blockchain oracle" fed with continuous multivariable data streams can theoretically engender a token tied to healthcare. Global intraoperative sampling could provide a formal way to estimate the value of assuming the responsibility for taking care of human life.

Interestingly, the performance evaluation of intraoperative anesthesia through the proposed measurement system may contribute to practical solutions for some crypto-economic problems termed as "*Proof of Excellence*" and "*Decentralized Success Metrics*" (Buterin, 2019). The former refers to token distribution and involves creating a task that only humans can do (or are the only ones authorized to do) but that computers can easily verify. The latter problem consists in implementing a decentralized method for measuring numerical real-world variables.

Finally, it should be noted that an anesthesiology oracle could provide a useful source of entropy (such as League of Entropy[22] and Random.org[23]), operating as a publicly verifiable randomness beacon (Stipčević and Koç, 2014).

10.4 Professional interoperable CaseLog

The interrelation between blockchain technology and distributed storage should provide anesthesiologists with a universal professional record. A personal logbook can be made globally available supplying interoperable evidence of professional proficiency and expertise. Quantities, types and performances of cases carried out during an anesthesiologist´s professional career could be verified on the decentralized and immutable register.

Wearable transponders enable professionals in training stages to formally register their actively supervised cases. Similarly, those in charge of academic training are able to accredit their activity as supervisors.

The envisaged system should contribute to the anesthesiologist community by providing a transparent tool to issue evidence of professional suitability and thus facilitate transnational interoperability. Work experience involving geographical exchanges should enhance the spread of knowledge and professional development.

10.5 Academic incentives

The system aims to foster individuals to seek excellence in their generated data. Records can be categorized according to the quality of their measurements and their completeness. Targeted incentives can be granted for provenance-rich data, uninterrupted sampling, interference-free datastreams, continuous proximity to the supervised patient and for the quality of the supplementary information. Users can be referenced according to the suitability of their records for use in scientific research. Greater demand is expected for high-quality data generated by better referenced users.

10.6 Governance

User profiles linked to unique blockchain anti-Sybil identities provide the means for a voting system, enabling affiliates to reach

22 https://www.cloudflare.com/leagueofentropy/

23 https://www.random.org/

consensus and take decisions collectively without relying on a central authority (Honkanen et al., 2021). Decisions on the direction of the ecosystem, such as improvement proposals and technology implementations can be achieved through the decentralized polling mechanism (Zwitter and Hazenberg, 2020).

A scheme of challenges can incentivize the network to verify the professional performance, accreditation fulfillment, and safety compliance of its participants, thus ensuring the scientific and ethical integrity of the system. In this way, the admission and rejection of users is constantly determined by the consensus of the ecosystem. Scalability and global adoption can drive a "network state" (Srinivasan, 2022): a translational online community of anesthesiologists organized around the values of Science (Bunge, 2018).

10.7 Sustainability

The costs of system maintenance, processing power, data storage, audit incentives and blockchain fees must be covered by a sustainable contribution mechanism. While a payment system analysis is beyond the scope of this paper, potential implementations of blockchain technology should be considered.

We believe that from an ethical perspective the system's cost should be covered by users themselves and patients should not be charged. A real-time blockchain micropayment system (Klein and Stummer, 2021) applied during the data transmission process can provide a fair alternative to the subscription model, such that users are charged only by their transmitted data and can freely decide whether to record their specific cases on the system.

Taking advantage of blockchain transparency and traceability, a cryptocurrency treasury can be established and controlled by the governance layer through the voting system. Smart contracts can be programmed to automatically pay the costs for storing and pinning services directly from the system reserves. The treasury can provide funds according to the ecosystem´s investment interests such as scientific research, production of educational content, simulation training, technology development and provision of resources for anesthesiologists in areas of need (Warner et al., 2022). Also, in return for generating the anesthesia record, patients and anesthesiologists can be insured by the system treasury (Shetty et al., 2022). In this way, costs of potential legal demands and compensation for injuries or sequelae during recorded anesthesia procedures can be covered directly by the system.

Users can be randomly requested to audit anonymous records in order to interpret cases which need clarification. Worldwide users with diverse professional backgrounds can determine through recorded measurements whether the execution of the audited anesthesia was carried out competently in accordance with safety protocols. Through this mechanism, the ecosystem consensus can resolve the release of funds for each particular case in a fair and impartial way.

Part of the system liquidity can be collectively managed to generate income through the investment in projects or protocols enabling users to reduce (and potentially eliminate) their system usage expenses. Not only this could result in a feasible cost-free service and professional insurance, but also in a potential retirement fund system (Sarker and Datta, 2022). Furthermore, utility tokens can be minted by the system mechanics contributing to its sustainability through the application of strategic tokenomics (Freni et al., 2022).

10.8 Record audit structure

It is expected that any anesthesia record may require an audit or an expert opinion emitted by a third party or legal entity. The system can contribute by providing a mechanism for cooperative issuance of formal interpretations.

Users with different backgrounds and diverse professional expertise can be incentivized to review records and submit their findings and conclusions. Sustainability of the audit structure can be achieved by paying contributors according to professional expertise.

In order to guarantee confidentiality and impartiality throughout the entire review process, traceable content is hidden and records are kept anonymous. Reports on records are authenticated by their reviewers and made openly available enabling the ecosystem to audit and object to the review process. Users can be randomly incentivized to create and inject fake records with incorrect, imprecise or unreliable information in order to reward reviewers who consistently detect inaccuracies.

In addition to auditing purposes, a report system should be available to communicate accidents, near misses and rare events related to patients, medications, surgical procedures, or equipment performance. In this way colleagues can evaluate, provide suggestions and validate data for its correct interpretation. A library of scientific case reports selected by the ecosystem can be created for educational purposes.

10.9 Artificial intelligence

Feedback control systems have potential application in the field of anesthesiology. Artificial intelligence algorithms can integrate datastreams in real time and efficiently anticipate the physiological and biochemical evolution of patients (Hashimoto et al., 2020).

Upcoming technology will likely provide automated control of drug infusion systems and anesthesia machine parameters, leading to more precise and accurate performance (Zaouter et al., 2020). Although from a safety perspective automated systems are not expected to replace human anesthesiologists, new technologies will probably expand their tasks and require professionals to operate and supervise automatic control systems (Lonsdale et al., 2020). This will propel professional development of future anesthesiologists into formal science fields such as mathematics, computing and engineering.

The development of control systems driven by artificial intelligence will require implementation stages in real scenarios (Magrabi et al., 2019; Canales et al., 2020). The immutable, authenticated and timestamped data generated by our proposed architecture is theoretically applicable for optimally feeding these systems and for providing continuous technological surveillance of innovative implementations (Parvinian et al., 2018). We believe that systems which exert control over humans through artificial intelligence should be auditable through an open science framework (Paton and Kobayashi, 2019).

10.10 Neuroscience and neurotechnology

Intraoperative anesthesia provides exceptional opportunities for the sampling of EEG data. Diverse cases require different types of anesthesia; from sedation to deep hypothermic circulatory arrest (Mavroudis et al., 2018; Alkhatip et al., 2021). Open source neurotechnology and standardized protocols can provide vast datasets for neuroscience research.

We believe that anesthesiology should play a leading role in addressing fundamental problems of neuroscience. There is arguably no medical specialty better positioned to pursue a comprehensive explanatory framework for understanding how the electrochemical activity of the brain generates perception; also known as “the hard problem of consciousness” (Chalmers, 1995). Assessment of the activity and interactivity of neural structures during different states of anesthesia can elucidate the core requirements for conscious experience.

Coordinating efforts through a collective “laboratory” composed of operating rooms around the world measuring information processes about conscious state transitions is expected to generate valuable data to consolidate physiological knowledge of neural encoding (Mashour, 2022). Making foundational scientific contributions to understanding the neural basis for consciousness is important for anesthesiology since solving this challenge will provide insights into what brains are naturally engineered to do (Alkire et al., 2008). Ultimately, this knowledge will help in understanding how to improve patient safety.

10.11 Software for simulation

Simulation-based education in anesthesiology has gained wide integration over time (Higham and Baxendale, 2017). However, development of anesthesia software simulators has been limited and scarce evidence of their implementation is available in the current literature. We believe that the potential of software simulation is under-exploited. Unfriendly operability, outdated graphics, limited scenarios and expensive subscriptions for individuals can negatively affect their widespread adoption (Edwards and Lampotang, 2020).

The system treasury can fund and sustain a continuously updated high fidelity software simulator.

Next-generation game engines (such as Unreal Engine 5[24]) can deliver photorealistic point-of-view simulation environments (El-Wajeh et al., 2022). Furthermore, virtual and augmented reality technologies may be adopted over time if their generated immersive experiences prove to be superior in cost/effectiveness terms over screen-based simulation (Alam and Matava, 2022).

To provide evidence-based scenarios, simulations can be fed by global data generated by real cases. Intraoperative physiology and biochemistry can be simulated by integrating big data from anesthesia records enhanced by machine learning technology.

Anesthesiologists can learn and train with a high-fidelity software simulation platform and test their proficiency through automatic system examinations which generate blockchain certifications. Pushing this idea further, official examinations can be enhanced by compensating users with system retributions (such as credits or storage capacity), for the simulated time according to payment rates consistent with actual anesthesia cases, therefore mitigating the obstacle of prolonged times required to perform truthful scenarios. This would reduce the bias of “short latency times” generating a realistic length simulation in which subjects do not tend to become hypervigilant while aware of being in a simulation, expecting critical events to be triggered imminently in the first minutes.

The wearable transponder can be used to validate users performing simulations by matching their acceleration patterns with movements in the virtual environment.

10.12 Academic content production

A decentralized educational platform can be created by funding high quality multimedia content creators through community voting (Leible et al., 2019; Rahardja et al., 2021). Educational content may include lectures, tutorials, anesthesiological metrics, case reports, measurements on specific procedures, near-misses and accident reconstructions.

System governance can democratically fund research and scientific publishing in accordance with the ecosystem academic objectives (Mackey et al., 2019).

10.13 Limitations

Although this proof-of-concept advocates decentralization, it is important to note that a governance layer is necessary in order to ensure scientific rigor. This implies that a self-governed community should be able to determine which professionals are admitted or rejected, based on accreditation of professional certifications, compliance with patient safety and adherence to quality standards for data generation. It should be noted that decentralized governance may introduce potential drawbacks to the system that will require its definitive implementation to be a meticulous process (Buterin, 2021).

A decentralized autonomous organization (DAO) can potentially be assembled on top of the system (Ziolkowski et al., 2020; Liu et al., 2021); however, since there is no precedent for similar implementations in anesthesiology, we believe that full decentralization should be achieved gradually if possible (Buterin, 2022d; Henrik et al., 2022).

Whereas different blockchains may be implemented (Tasca and Tessone, 2019), it would be opportune to materialize their functionalities through projects founded on peer-reviewed research (such as Cardano)[25] and developed through evidence-based methods consistent with our system’s inherent philosophy.

We anticipate adoption resistance as a primary limitation to scalability. Unfamiliarity about novel technologies and the need to use additional hardware may restrain acceptance by professionals (Lustenberger et al., 2021). However, we foresee that as the global community gradually assimilate the benefits of decentralization and data immutability, the proposed system architecture may become a new paradigm in the way data is recorded in operating rooms (Pandya et al., 2021). In the long run, global adoption is expected to be driven by patient demand for modern safety technologies.

10.14 Closing thoughts

Keeping control of patients’ parameters in all scenarios is a central goal of anesthesiologists. We believe that health professionals who work with control systems should stream and record immutable data as proof

24 https://www.unrealengine.com/

25 https://cardano.org/

of transparency and respect for human life. Great progress in the field can be driven by generating accurate records and making measurements openly available to science.

The proposed architecture seeks to provide a transformative path for anesthesiology, assuming as a guiding principle that "better information makes for better decisions". In summary, this is how we believe technology should be implemented to scientifically improve patient safety, outcomes, and quality.

> "Whereas science elicits changes in order to know, technology knows in order to elicit changes."
>
> \- Mario Bunge

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author. Authors declare the following official manuscript blockchain address: bc1qrf5da0wqvexjl36axn2llzxndrn0xvx7x884rr

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Authors declare that they hold patent applications for the proposed system and are the co-founders of "Euclidean: Time Series for Science ™"; a technology development project based on the exposed ideas, and of which this document should be considered its theoretical paper.

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