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Review Article

Artificial Intelligence and Closed Loop Systems

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ABSTRACT

Artificial Intelligence (AI) Artificial Intelligence (AI) in healthcare involves diverse approaches like machine learning and deep learning applied to speed up the drug development process, enhance therapeutic treatment regimens, and improve patient outcomes. In the context of technologies mentioned above, a closed-loop system means a tool measuring the physiological parameters of a patient (electrical brain activity) or the concentration of a drug in the bloodstream of a patient to adjust the drug delivery to a therapeutic window automatically. In the modern world, this type of system has become very popular to overcome limitations associated with the conventional dosing methods, such as Body Surface Area (BSA)- and weight-based dosing. As an example, one should mention BSA-based dosing, which is one of the most common ways of drug administration. It does not take into consideration critical pharmacokinetics (PK) differences in patients due to genetic polymorphisms, circadian rhythms, and sex differences. Thus, PK intra-individual and inter-individual variability is not reflected in such calculations; as a result, order-of-magnitude variations in the systemic level of the administered chemotherapy occur. Consequently, overdosage and underdosage of patients are inevitable, which results in increased toxicity and poor drug efficacy. Patients with cancer experiencing chemotherapy-induced toxicities tend to switch to another therapy, postpone their treatments or even quit. Moreover, since underdosage goes unnoticed by medical practitioners, the consequences for a patient are very serious; underdosing can cause cancer metastasis and tumor growth. In order to eliminate such problems, it is necessary to develop an intervention to maintain the appropriate plasma drug concentration. As a rule, this causes poor drug administration that can be characterized as underdosage and overdose leading to inefficiency and toxicity. In turn, underdosing can cause tumor growth and metastasis. The goal of this article is to explore the use of artificial intelligence and closed-loop systems for enhancing pharmacy workflows (mobile-based drug management),

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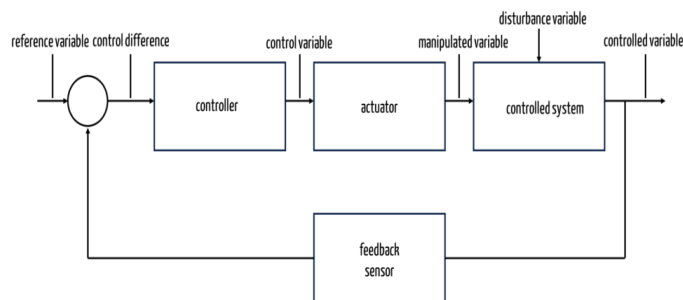


drug delivery systems, and their particular applications (personalized chemotherapy, neuromodulation, and glucose-responsive insulin).

INTRODUCTION

These "closed-loop" The particularity of a closed control loop with medical devices is the measurement of some physiological parameter and subsequent adjustment of the flow of energy or materials to the physiological parameter (through an actuator) such that the physiological parameter itself would be controlled and kept at some target value. A "closed-loop system in relation to a medical device" should "be understood to mean a system which allows the device to detect, analyse and treat a medical condition without any human intervention." It is quite obvious that the "closed-loop system" should not simply recognize and treat any disease. On the contrary, the whole process must start from detecting it. The "real" closed loop implies several repetitions of the chain measure -

regulate - measure. The closed-loop system calculates the concentration of the drug in the blood and adjusts the infusion rate to maintain the concentration of the drug in the therapeutic range of the drug. Closed-loop drug delivery systems are currently being used in the clinics for the treatment of other diseases. For instance, the artificial pancreas for type II diabetes mellitus is a well-known example. The controlled variable (actual variable; e.g., in our example, actual room temperature) is used to estimate its deviation from the reference variable. The controller tries to reduce this deviation by affecting the control device (also referred to as the actuator) using the control variable. In our heating process, the controller directs a message to the valve. It then controls the opening of the valve (control variable), hence changing the volume of hot water flowing into the radiator inlet.



Diagrammatic representation of closed loop working system

Applications of Closed Loop System

1] Technology, ecology, economy

The following are some cases of closed loop systems, which can be observed from the realms of technology, ecology, and economics. Cruise control system in automobiles

Automatic irrigation system for flower boxes
Population of wild animals controlled by hunting and nurturing
Interest rate manipulated to control inflation.

The difficulties encountered by the controller as a result of major disturbance variables become evident in the latter case especially where the disturbance variables are influenced by the control variables.

2] Medicine

The human body is an extremely complicated control system which regulates various physiological variables such as body temperature, heartbeat, respiration rate, blood glucose concentration, pH, or eye dilation. Unlike the simplistic example of heating process, there are numerous control variables in the human body. All these variables depend on each other and have constantly varying reference variables. For instance, when the body gets sick, then the reference variable concerning temperature (fever) increases, or when people exercise their body requires higher values for respiration rate and heartbeat.

c) Medical technology

In the medical field, various closed loop applications exist including the following:
Automatic anesthetic application systems
Blood pressure stabilizers
Neurostimulators
Infusion of muscle relaxants
Pacemakers

Types of Closed loop systems

Control loops for internal control
The distinctive feature of this type is that there is no control variable visible from outside. The control loop controls a ventilator to maintain the temperature inside the device below a certain maximum value.

External control loops for technological characteristics

In this case, the control loop regulates some external parameter of the device, usually acting on its applied component. The rotational speed of a bone drill or the current of an HF surgical system (controlled according to the impedance of the patient's tissue) may serve as an example. External control loops for physiological parameters
Physiological parameters can be controlled using control loops. Some examples

include:

Dose of anesthetic based on depth of anesthesia
Ultrafiltration rate in a dialysis machine based on volume of blood
Insulin dose in an (implantable) insulin pump based on blood glucose level

Mechanisms for Closed-Loop Drug Delivery

The working principle of a closed-loop drug delivery system operates by continuously repeating a three-part process: first, monitoring the physiological state of the patient; second, evaluating the information collected using an algorithm; and third, actuation of the necessary changes in therapy. The difference between the two is that whereas open-loop drug delivery systems administer set doses regardless of the patient's condition, closed-loop systems make necessary adjustments in relation to the patient's current physiological state.

Real-Time Monitoring Sensors: High Performance Liquid Chromatography Mass Spectrometry (HPLC-MS), an advanced technology used in CLAUDIA (Closed-Loop Automated Drug Infusion regulator), provides precise measurements of drug amounts in the body. HPLC-MS is deemed to be the state-of-the-art device in pharmacokinetics because it can reliably isolate individual drugs in complex biological samples. This requires the system to carry out fast sample preparation, isolating the drug from the biological matrix (e.g., blood), in a matter of minutes instead of hours. Other sensors employed in closed-loop drug delivery systems are glucose responsive hydrogels that rely on proteins, such as Concanavalin A, for their functionality or magnetic composite films in microfluidic chips that rely on resistance to measure fluid flow rate.

Pharmacy Workflow & Dispensing Optimization



Manual review and paper-based dispensing lists, typical of traditional inpatient pharmacy workflows, are inefficient and prone to mistakes. Conventional practices provide limited amounts of information on drugs on a small piece of the A4 list. This results in many dispensing mistakes due to a phenomenon known as "similar drugs," when look-alike medicines are confused. Moreover, manual order review takes a lot of time for pharmacists, limiting their ability to track drug logistics outside of the pharmacy premises. The introduction of closed-loop management systems with the use of mobile devices, tablets, and mobile nursing trolleys optimizes all processes involved.

Higher Inpatient Efficiency: Digitization of the drug list with mobile tablets allows creating dynamic lists, containing visual information about drugs, like package pictures and voiceprints. These lists calculate the most efficient dispensing route, thus, facilitating the process of dispensing all medications for a certain ward in a one-way trip without turning back. In one study, time savings on preparing dispensing lists were estimated to be from 7 up to 44 minutes across various wards. Moreover, the digital transformation increases work efficiency since the automatic data verification helps reduce dispensing mistakes from 5 to 1 per month. Integration with the Hospital Information System also allows fast pre-prescription reviews by pharmacists, usually taking less than 40 seconds to complete.

Lower Paper Consumption: The adoption of a paperless operation significantly reduces the environmental impact of the process. Previously, big hospitals used to spend over 500 sheets of paper per day only on dispensing lists in various wards. After the introduction of a new system with the help of mobile tablets, the annual amount of paper saved by one inpatient pharmacy equals around 180,000 pieces of A4 paper. Such

transition contributes to achieving a "green working mode" in line with the development of sustainable hospitals and low-carbon health care.

Better Traceability and Safety: Closed-loop systems allow tracking each step, starting from drug placement and checking until their distribution and receiving by a nurse. Two-dimensional code on sealed logistics boxes makes it unnecessary for nurses to open packages and check the contents to be able to register and sign for them with the help of tablets. Should any inconsistencies happen, pharmacies can consult surveillance video as part of the digital workflow. Integrated technologies of PDAs and mobile trolleys improve the protection of the "five rights" of medicine management and significantly increase the probability of accurate patient identification. Closed-loop electronic medication management systems include CPOE, barcode medication management, and eMAR to monitor the entire medication process in real-time. They eliminate the risks of medication errors through automated checks of prescriptions and administrations of medication throughout the entire process. Prevention Mechanisms in Dispensing Implementation of EMMS into pharmacy practice takes care of mistakes arising from limitations in the current paper-based process of dispensing as follows:

Automated Filtering and Checking: The doctor sends orders directly through the Hospital Information System, and this system filters out allergy-related drugs and overdose cases, while pharmacists screen irrational prescriptions filtered by the computerized system before issuing the medicines to wards.

Visual and Digital Identification: The paper list is replaced by mobile tablets that enable pharmacists to make use of package images and



vocalization of medicine names as a way of avoiding errors related to "similar drugs."

Traceable Handover: Medicines are packed in logistic boxes with 2-D barcodes. Logistics personnel and nurses use these barcodes for identification during handover of the medicines to ensure their correct distribution to the wards without item-to-item check. Safe Medication Administration at the Point of Care The nurses act as the last line of defense for the safe administration of medications, and EMMS offers them tools that ensure the protection of the five rights of medication administration:

Dual Barcode Scanning: Before administering any medication, the nurse must scan both the medication's barcode and the barcode on the patient's wristband. In this process, the computer performs an instant check against the EMR. If there are any discrepancies (wrong patient or wrong medication), the computer will automatically sound a warning alarm to prevent the execution of the order.

Dose and Execution Sequence Check: For high alert drugs or IV drugs, the system may require two nurses to verify the order before executing it by performing a second barcode scan. The computer also logs the information of all the

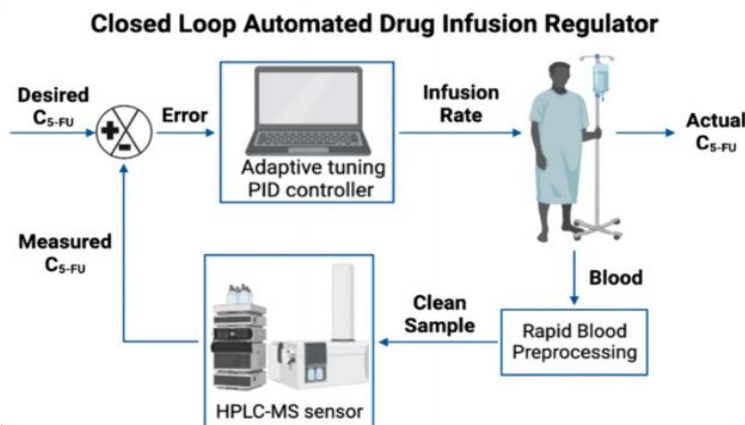
medications executed and will prevent duplicate administrations and will verify the correct dosage from the digital data log.

Preventing Omissions: The computer system will remind nurses of any orders that have not been executed. This feature eliminates the likelihood of omitting medications. Effect on the Rate of Errors and Safety Indicators Research into the adoption of such closed-loop systems demonstrates substantial long-term gains in clinical safety:

Rate of Errors Decreased: For example, one study conducted at a tertiary hospital revealed a substantial decrease in the frequency of medication errors during the short and mid-term period. The average rate of error dropped from 0.57 to 0.07 per month in the long term.

Patient Identification: The adoption of barcoding technology with the help of PDA devices improved the accuracy of patient identification to 100% in long-term investigations.

Timeliness and Efficiency: Apart from the benefits in terms of safety, digitalization also resulted in the reduction of dispensing time (from 7 to 44 minutes) and enhanced the rate of implementation of fresh drug distribution.



Drug Discovery & Formulation The advent of artificial intelligence (AI) has had profound implications for the pharmaceutical industry by moving the focus of drug discovery from traditional approaches to a more modern, more data-driven approach.

Accelerated Drug Discovery: The use of AI-powered algorithms helps analyze large biological and chemical databases to uncover complex patterns, facilitating the discovery of new treatment targets and predicting drug candidates. One example includes the AI-based virtual screening which can help quickly filter compounds with potential to become drug candidates out of a chemical library. AI tools including DeepMind's AlphaFold can help solve the problem of predicting protein structure thus offering critical insights into protein-ligand interactions to accelerate the process of identifying lead compounds.

Predicting Synthetic Routes: Through the use of AI-retrosynthesis tools, such as "RXN for Chemistry" created by IBM, AI can predict synthetic routes to complex compounds using deep learning technology. After the optimal route is predicted, AI-enabled robots, such as the "Chemputer" developed at the University of Glasgow, can then automate the whole process of synthesizing the compound, thus accelerating the process of discovering drugs.

Optimization of Formulations (3D-Printed Drugs & Nanomedicines)

3D-Printed Drugs: With the help of algorithms powered by AI, the design and formulation of customized drugs, taking into account patient-specific parameters, including age, body weight, and medical history. Using simulation, the drug release profiles, drug strength, and drug geometry can be optimized, while issues related to the

printing process itself can be addressed by optimizing the printing process.

Nanomedicines: Predicting interactions between nanocarrier particles and the environment enables accelerated optimization and production of targeted nanocarriers such as liposomes and nanoparticles. In particular, nanocarrier designs maximizing tumor targeting while minimizing off-target effects can be predicted based on experimental results. Additionally, microfluidic chip design for manufacturing nanomaterials can be further optimized based on predicted fluid dynamics. Application of AI and Closed-Loop Systems for Specific Medical Conditions The development of AI and closed-loop systems has facilitated numerous breakthroughs for customized medicine across different medical fields. The advantage of these systems is that they adapt according to individual patients' requirements without a delay.

Cancer/Oncology

Adapting the dosage of chemotherapy agents represents another important use of closed-loop systems, especially in relation to the 5-fluorouracil (5-FU) drug, which is currently the third most popular chemotherapeutic agent worldwide. The typical practice involves administering drugs in proportion to the Body Surface Area (BSA), which is ineffective due to significant differences in pharmacokinetics caused by polymorphisms, gender-specific characteristics, and circadian rhythm. CLAUDIA (Closed-Loop AUtomated Drug Infusion regulAtor): This system personalizes the dosage of 5-FU by constantly monitoring the drug -MS. The dosage algorithm uses an adaptive PID controller to calculate the error value of the concentration and change the rate of infusion in order to maintain the optimal range of drug concentrations in the bloodstream. In preclinical trials, CLAUDIA managed to



maintain drug concentrations in the range in 45% cases against only 13% for BSA-controlled administration and successfully addressed interindividual differences in pharmacokinetics.

Magnetically Actuated Microfluidic Chip: To administer chemotherapy agents locally, one may use untethered 3D printed microfluidic chips known as SMAMs. They can be directed to a particular spot with the help of external magnets and activated to start releasing medicine in cancer tissues. Neuromonitoring and Neurology
The introduction of closed-loop neurostimulation systems is set to change how neurological diseases such as Epilepsy and Parkinson's Disease are treated, by shifting focus away from continuous, cyclic electrical stimulation to "responsive" treatment. Neuromorphic Neuromodulation: Implants are designed to mimic the architecture of the brain and employ neuromorphic architectures, with continuous monitoring of intracranial EEG and LFP signals, looking for any aberrations that might indicate seizure.

AI-Based Prediction: Instead of streaming all the data to a distant cloud to detect any anomaly, the on-device Spiking Neural Network will do the job and identify whether seizures occurred. It will then stimulate the brain only when there is evidence of a problem, which results in less frequent stimulation, increased battery life, and better treatment accuracy. In adaptive implementations of this algorithm, it will even be possible to train the network in-situ without having an expert present to monitor seizures. Human brain has tremendous computational capabilities, between 10^{13} and 10^{16} operations per second, and consumes roughly 20W of power. On the other hand, the computer performing the same classification tasks needs about 250W. The human brain consists of roughly billions of neurons ($\sim 9 \times 10^9$) connected via trillions of synapses ($\sim 3 \times$

10^{14}), providing information processing at 6×10^{16} bits/second. Modern scientific studies aim to investigate whether the capability of neuromorphic chip technology can be used to design implanted body-machine systems where it is possible to take advantage of properties such as co-localization of memory and logic, connectivity, and parallel computation. The field of neuromorphic computing has advanced immensely, with examples being IBM TrueNorth and Intel Loihi chip technologies as well as systems developed in Human Brain Project in Europe such as BrainScales, SpiNNaker, NeuroGrid, IFAT, and DYNAPs. They can be employed in domains such as object detection and medical imaging. Endocrinology & Diabetes
Closed-loop insulin systems are meant to act like an artificial pancreas to ensure strict regulation of insulin levels with little variation among patients.

Stimuli-Responsive Hydrogels: Scientists have invented injectable and thermosensitive hydrogels with Concanavalin A (ConA), a lectin protein that acts as a glucose binding agent. The "intelligent" hydrogels change phase from liquid to gel form at 37°C , creating a depot for drugs.

Automated Insulin Delivery: The mechanism works on detecting high levels of blood glucose, which then bind with the ConA contained in the hydrogel, leading to the spontaneous delivery of fast-acting insulin in a dose-responsive fashion. This approach allows one to avoid regular insulin shots and the invasive surgery to install an insulin pump. Advantages of AI and Closed Loop Systems AI technology along with the application of closed loop systems presents immense benefits in terms of clinical efficacy, cost-effectiveness, and hospital logistics. Precision & Efficacy

Patient Specific Treatment: By continuously monitoring and changing the rate of infusion to achieve a precise level of drugs within the



therapeutic window, closed loop systems offer highly personalized drug delivery.

Higher Drug Concentration: According to preliminary investigations, the CLAUDIA closed-loop drug infusion system was able to maintain an ideal level of drug concentrations during 45% of the treatment period compared to only 13% using body surface area dosing methods.

Lower Toxicity: Such systems are highly effective in avoiding drug toxicity because they prevent drug concentrations from going beyond safety limits.

Better Patient Outcomes: With accurate dose adjustments, there is no risk of underdose, which is the primary reason for tumor formation in oncology treatments. Moreover, responsive stimulation treatment in neurology only delivers treatment when an abnormality is noted, thus increasing precision and longevity of batteries.

Cost-Effectiveness

Economic Feasibility: Studies have found that devices such as CLAUDIA demonstrate economic viability, with their cost-effectiveness ratios (ICER) being \$92,500 for each quality-adjusted life year (QALY) provided.

Cost Efficiency in Comparison With TDM: As TDM procedures tend to be time-consuming for health workers, a closed-loop system might become cost-efficient in the long run by saving medical personnel's time.

Cost Savings: Through eliminating the risk of adverse drug interactions and other adverse effects, these technologies help alleviate excessive medical costs resulting from hospitalization.

Optimization of Resource Distribution: AI-based algorithms used for predictive analytics can

improve manufacturing operations and logistics management and help allocate resources efficiently, possibly leading to cheaper drugs in the future. Workflow Enhancements

Reduced Workload: The move from paper-based dispensing to digital technology leads to substantial reduction in workloads for pharmacists and nurses due to automated order checks and lists management.

Quickened Dispensing Times: Digitalization of workflows leads to faster dispensing as preparation time of drugs within hospital wards has been decreased from about 7 to 44 minutes.

Prevention of Errors: Closed loop EMMS system that includes barcode scanning and verification has helped achieve 100% accurate patient identification and reduce medication errors significantly.

Improved Supply Chain Management: AI algorithms help in managing the drug supply chain through trend analysis and improved forecasting of demand based on performance data. Challenges of AI and Closed-Loop Delivery Systems Despite promising clinical applications, there are several crucial limitations related to hardware, human-system interaction, and algorithmic aspects of implementing closed-loop technology and artificial intelligence. Limitations of System and Hardware

Power Consumption and Telemetry: The current generation of responsive neurostimulation devices typically requires transmitting information from an external source. Continuous data telemetry increases energy consumption rapidly, which is one of the main limitations of bioelectronic medicine technology since reducing power consumption is crucial for prolonging the lifetime of devices.



Portability of Sensors: Although advanced methods of monitoring drug levels (such as HPLC-MS) provide high accuracy, they are not portable. Consequently, current versions of these sensors make devices such as CLAUDIA only usable in hospitals and clinics, which hinders their implementation in outpatient settings until portable mass spectrometry becomes possible.

Human-System Interactions

Alert Fatigue: Alert fatigue is a constant danger to health care professionals who interact with automated devices. In particular, nurses working with closed-loop systems face the risk of overlooking certain alerts or ignoring them due to being overloaded by too many system alerts, which might affect the process of drug administration.

Work Flow Interruption: professionals to develop undesirable practices, such as scanning patient identification bands in batches. For example, nursing professionals might decide to do so to reduce the frequency of interruptions caused by automatic alerts reminding about the necessity to follow the "five rights." Unfortunately, scanning patient ID bands does not guarantee verifying the right patients, thereby causing potential complications that the system was supposed to avoid.

Algorithmic and Data Challenges

Interpretable AI Models: Many machine learning models currently used in the practice are black boxes, meaning that it is impossible to derive insights concerning their functionality from their outcomes. Hence, the lack of transparency and interpretability of algorithms is among the most important barriers to the adoption of AI in clinical practice.

Data Quality: One of the most significant challenges associated with AI is related to ensuring sufficient data quality for training

models. It is necessary to have high-quality training data to prevent inaccurate predictions caused by various types of concept or data set drift. Additionally, using biased samples poses similar risks.

Ethics and Security
Incorporating AI and autonomous closed-loop systems in clinical settings presents several ethical issues and security threats that should be adequately addressed to minimize any risk to patients' health and to preserve public trust.

Data Privacy and Cybersecurity Issues

Protection of Patient Data: One of the main issues associated with training AI based on massive biomedical datasets relates to privacy concerns. According to HIPAA regulations in the United States, the HIPAA Privacy Rule sets standards for protecting "protected health information," including medical records and other health-related data that are handled by healthcare providers and clearinghouses. Ensuring that these systems operate HIPAA-compliant is one of the most important barriers to the adoption of AI-based treatment approaches.

"Brainjacking" Threats: Another issue with using wireless IMDS is related to cybersecurity. An attacker who gains unauthorized access ("brainjacks" the system) might change the parameters of therapeutic stimulation, thus posing a physical threat to the patient. Moreover, any disruption to the feedback loop will inevitably interfere with the treatment itself. However, high-level security solutions should take into account some technical limitations, such as limited battery life, to avoid malicious software consuming energy.

Regulatory Challenges

Validation of AI Results: A crucial obstacle to using AI in clinical practice lies in the absence of appropriate frameworks for validation of AI results due to the complexity of the process. Since many AI algorithms act as "black boxes" in this



case, regulators should be able to ensure transparency.

Autonomous System Guidelines: There is a critical need to develop FDA/EMA recommendations to ensure that autonomous closed-loop systems are safe for patients. Fortunately, regulatory agencies start addressing the problem: for example, in May 2024, the European Council adopted the necessary AI regulations ensuring that AI is secure and reliable and respects fundamental rights. Also, actions such as FDA Digital Health Innovation Action Plan play an increasingly important role in developing regulations for innovative AI solutions.

Clinical Endpoints Framework: To bring systems like CLAUDIA to the clinics, researchers should define specific clinical endpoints that highlight the advantages of such technology in terms of safety and efficacy over the current standard. Such frameworks should allow rapid progress in AI despite all innovation requirements.

AI Applications: Future Scope of AI and Closed-Loop Systems A more advanced future for pharmaceutical care and bioelectronic medicine will be marked by evolution from clunky and non-mobile to highly mobile devices that can automatically adapt to the physiological needs of a patient. Untethered, Wearable Devices

Miniaturization of Sensing Hardware:

Advanced sensing hardware such as the HPLC-MS currently provides the state-of-the-art standard for performing pharmacokinetic analysis but remains too bulky for practical implementation in closed-loop systems outside the clinical setting. Miniature mass spectrometry development is expected to make devices like CLAUDIA portable or even wearable so that patients could receive a

strict dose control of chemotherapy at home rather than in a hospital.

3D-Printed Self-Sensing Microfluidic Chips: A recent development of the self-sensing magnetically actuated microfluidic (SMAM) chip shows promising potential for autonomous delivery systems. This technology uses 3D-printing technology to combine complicated network microchannels with an innovative functional module that does not require external pumps. **Integrate On-Demand Release Capabilities:** Using piezoresistive composite films, these chips can track their pumping and analyte concentration in real-time, allowing for an internal closed-loop system and facilitating on-demand delivery of drugs. Proof-of-concept studies demonstrate the possibility of such magnetically actuated devices to release drugs within physiological models. **On-Device Continuous Learning Shift to Neuromorphic Chips:** New generations of medical implants aim at using neuromorphic (bio-mimicking) hardware that collocates memory and logical units similarly to how it happens in the brain. Such neuromorphic processors as Intel's Loihi and IBM's TrueNorth can perform biological signal analyses using extremely low power (microwatts).

On-Chip Active Learning: In contrast to conventional AI, neuromorphic architecture supports "on-device" learning that helps an implant adaptively learn from its own data. As far as treatment personalization requires adjusting the algorithms depending on changing physiological signals of the patient (seizure pattern changes in epilepsy), this is extremely important.

Elimination of Cloud Dependency: Achieving computational self-sufficiency allows eliminating data transfer from the implant to the external cloud. As a result, these devices save their batteries by eliminating energy-consuming data exchange,



thus significantly extending battery lifespan while increasing data privacy.

CONCLUSION

Shifting from one-size-fits-all dosing to AI-powered closed-loop technology is a major turning point in the field of clinical medicine. BSA formula used in traditional clinical practices has several limitations, the main of which include its inability to consider important factors affecting the pharmacokinetics of drugs in different patients. Namely, individual genetic polymorphism and circadian cycles are not taken into account. As such, implementing CLAUDIA and other similar autonomous systems allows for achieving much higher therapeutic accuracy compared to CRIs due to the longer period during which the medication level remains at an optimal level. However, these innovations can also be instrumental for reducing medication errors made during clinical practice. Specifically, the use of closed-loop EMMS, involving barcoding, and real-time verification has managed to lower the monthly error rate from 0.57 to 0.07, with the rate of correct patient identification rising up to 100%. In turn, the transition to digital inpatient pharmacy management with the help of mobile devices leads to a drop in dispensing error rate by as much as 80%, alongside improved efficiency, with no need to use millions of papers. Ultimately, these improvements are set to change the direction of clinical pharmacy development. Indeed, while at present most advanced sensors tend to remain stationary, the miniaturization of equipment and creation of 3D self-sensing microfluidics allow for creating wearable autonomous drug delivery devices. Moreover, bio-inspired neuromorphic architectures make implantable systems capable of self-training using continuous learning processes without any interaction with cloud networks.

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