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ORIGINAL

Applications of IoT and Edge Computing in Medical Informatics for Real-Time Patient Monitoring

Aplicaciones de IoT y Edge Computing en informática médica para la monitorización de pacientes en tiempo real

Pooja Varma[1], Kunal Meher[2], Sasanka Choudhury[3], Vundela Swathi[4], Harsimrat Kandhari[5], Madhur Taneja[6], Supriya Awasthi[7]

[1]Psychology, JAIN (Deemed-to-be University), Bangalore, Karnataka, India.
[2]Department of uGDX, ATLAS SkillTech University, Mumbai, Maharashtra, India.
[3]Department of Mechanical Engineering, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India.
[4]Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India.
[5]Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh, India.
[6]Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India.
[7]School of Allied Health Sciences, Noida International University, Greater Noida, Uttar Pradesh, India.

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Corresponding author: Pooja Varma

ABSTRACT

Particularly with regard to health issue prediction and patient monitoring in real time, edge computing, artificial intelligence, and the Internet of Things (IoT) are altering the healthcare industry. This paper investigates how these technologies may be used, what technological issues they could have, and how they might develop in the medical domain. Continuous patient vital sign monitoring made possible by Internet of Things (IoT) devices and monitors Low-latency data processing guaranteed by edge computing facilitates real-time decision-making by means of simplicity. By simplifying early assessment and tailored treatment regimens, AI-powered predictive analytics used at the edge dramatically enhances healthcare results. New technologies handle significant issues like security, scale, data privacy, and interoperability by means of bitcoin and 5G networks. This guarantees effective and safe data flow. For instance, the research underlines the importance of consistent standards and secure patient data processing for the use of emerging technologies in the healthcare environment. Healthcare will grow more integrated, efficient, and patient-centered as IoT, cloud computing, and artificial intelligence keep improving.

Keywords. IoT; Edge Computing; Real-Time Patient Monitoring; Predictive Analytics; Artificial Intelligence; Blockchain; 5G Networks; Data Privacy; Healthcare Security; Ethical Considerations; Regulatory Challenges; Smart Healthcare Systems.

RESUMEN

Especialmente en lo que respecta a la predicción de problemas de salud y la monitorización de pacientes en tiempo real, la computación de borde, la inteligencia artificial y el Internet de las Cosas (IoT) están alterando la industria sanitaria. Este artículo investiga cómo pueden utilizarse estas tecnologías, qué problemas tecnológicos podrían plantear y cómo podrían desarrollarse en el ámbito médico. La monitorización continua de las constantes vitales del paciente, posible gracias a los dispositivos y monitores del Internet de las Cosas (IoT) El procesamiento de datos de baja latencia garantizado por la computación de borde facilita la toma de decisiones en tiempo real mediante la simplicidad. Al simplificar la evaluación temprana y los regímenes

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de tratamiento personalizados, el análisis predictivo impulsado por IA y utilizado en el perímetro mejora drásticamente los resultados de la atención sanitaria. Las nuevas tecnologías abordan cuestiones importantes como la seguridad, la escala, la privacidad de los datos y la interoperabilidad mediante redes bitcoin y 5G. Esto garantiza un flujo de datos eficaz y seguro. Por ejemplo, la investigación subraya la importancia de unas normas coherentes y un tratamiento seguro de los datos de los pacientes para el uso de las tecnologías emergentes en el entorno sanitario. La atención sanitaria se volverá más integrada, eficiente y centrada en el paciente a medida que IoT, la computación en la nube y la inteligencia artificial sigan mejorando.

Palabras clave: IoT; Edge Computing; Monitorización de Pacientes en Tiempo Real; Análisis Predictivo; Inteligencia Artificial; Blockchain; Redes 5G; Privacidad de Datos; Seguridad Sanitaria; Consideraciones Éticas; Retos Normativos; Sistemas Sanitarios Inteligentes.

INTRODUCTION

Background and Motivation

The fast evolution of scientific informatics has been fuelled by using improvements in the net of factors (IoT) and aspect Computing, enabling real-time patient monitoring and enhancing healthcare shipping. Manual facts collecting and repeated clinical exams have historically been the foundation of healthcare structures, which frequently produces behind schedule diagnoses and inadequate remedy plans. Wearable technology, smart sensors, and real-time information analytics have made clinical professionals capable of carefully reveal patients, consequently facilitating early sickness detection and brief treatment.[1] IoT-enabled gadgets collect large quantities of physiological facts—which include heart charge, oxygen and glucose levels, and ECG readings—that is then processed at the edge of the network to lower latency and boost up response times. This change is in particular essential in essential care devices, faraway affected person tracking, and remedy of chronic illnesses while well timed clinical decisions should keep lives.[2] Within the healthcare industry, personalised, actual-time healthcare solutions are supplacing traditional health centre-primarily based tracking. IoT and part computing together provide a decentralised approach of information processing that reduces dependency on cloud servers and complements affected person records security. by way of grouping processing assets near the records source, part computing guarantees fast evaluation and choice-making, consequently lowering the bandwidth and latency issues that cloud-primarily based structures face. This shift is particularly valuable in emergency scenarios where real-time responses are crucial, such as in cardiac arrest monitoring or continuous glucose monitoring for diabetic patients.[3] The increasing global burden of chronic diseases and the growing need for efficient healthcare solutions make IoT and Edge Computing indispensable tools in modern medical informatics.

Role of IoT and Edge Computing in Medical Informatics

Medical informatics aims at data collecting, storage, and analysis connected to health. This is done to improve patient care and professional decision-making. In medical computing, the Internet of Things has become really significant very fast. It consists nowadays of a system of devices gathering and forwarding real-time patient data. Patients' monitoring has been altered by wearable health monitors, smart medical implants, and biosensors. These sensors gather data constantly, which may be examined to forecast future medical need. These Internet of Things (IoT)-based healthcare products reduce hospital readmissions, simplify patient care from a distance, and maximise the resources of medical institutions. This is true because IoT devices produce so much data that speed, storage, and computing power all seriously problematic. In this instance, edge computing is essential as it guarantees real-time analytics, facilitates data processing locally, and guarantees simpler transport.[4,5] Unlike conventional cloud-based approaches, edge computing handles data closer to where it was gathered—that is, at the clinic, hospital, or even the smart device itself. It then delivers only the most crucial information to systems of centralised healthcare. Using this split strategy, doctors may make judgements fast depending on real-time patient data. It lowers latency and increases system efficiency as well. Edge computing reduces the quantity of sensitive health data accessible to cloud-based networks, therefore enhancing patient data security and privacy. This addresses main worries regarding healthcare data breaches and regulatory compliance.

Significance of Real-Time Patient Monitoring

Taking care of individuals with long-term diseases, the elderly, and those still recovering from surgery now depends much on real-time patient monitoring. Edge computing and the Internet of Things might enable physicians to monitor patients from a distance, therefore relieving load on hospitals and allowing patients to get tailored treatment in the comfort of their own houses. Smart ECG patches, for instance, allow those with heart issues to monitor their heart activity and notify specialists should anything go wrong. For those with

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diabetes, similarly, constant glucose monitoring devices displaying real-time blood sugar levels and enabling fast treatment might be beneficial. Real-time tracking is much improved when you mix IoT and edge computing with AI-driven analytics. This is so because historical patient data and present body signals allow one to forecast health hazards. By sensing abnormalities in vital signs and notifying individuals before they become medical crises, smart devices on the margins driven by artificial intelligence might avoid significant health issues.[6] By automating frequent check-ups and lowering the need for human participation, real-time monitoring also helps healthcare procedures to be more efficient. IoT-enabled edge computing devices convey rapid alarms and ideas in intensive care units (ICUs), where even minute changes in a patient's vital signs might be deadly. This helps physicians and nurses to act fast. Real-time patient monitoring is very crucial in telemedicine, distant healthcare, and other areas where access to medical treatments is constrained. Healthcare professionals might be able to close the distance between healthcare services in cities and those in rural regions by placing IoT devices far away and using edge computing for real-time processing. Without frequent hospital visits, patients may consult physicians' online, provide real-time health data, and obtain prompt medical advice. This enhances patient health, lowers the cost of treatment, and better uses medical instruments. By concentrating on these goals, this paper provides insightful analysis of how IoT and edge computing are transforming healthcare as well as how they could enhance patient outcomes, increase accessibility to healthcare, and affect medical informatics. Making healthcare solutions that function, are affordable, and can be extended depends on knowing how cleverly healthcare technology are used and enhanced. This is particularly true as their usage increases.

Literature review

Edge computing and the Internet of Things (IoT) have transformed the healthcare sector by enabling better medical judgements and simpler real-time patient monitoring. Research on how IoT-based systems may be used in medical computing have abound. These investigations reveal their fast collecting, handling, and forwarding of patient data. Traditionally, most of the time, cloud computing is used in healthcare applications. Although this is beneficial, it suffers with data security, slowness, and bandwidth.[7] Edge computing handles data closer to where it originates, therefore reducing main cloud computer traffic and addressing these issues. Edge computing improves real-time data, guarantees quicker reaction times, and lets work occurring in many locations at once, therefore enhancing Internet of Things applications. Edge-based systems enable data be handled locally on devices, hospital gates, or nodes near patients, therefore optimising the healthcare industry. This approach is rather crucial in urgent care settings as it speeds up and guarantees greater dependability real-time patient monitoring.

IoT has completely revolutionised patient monitoring by means of smart medical instruments, biosensors, and monitor devices tracking of their health constantly. IoT enables clinicians to examine real-time patient data from distances, therefore reducing the need for hospital visits. Medical monitors linked under Internet of Things-based monitoring systems provide real-time warning systems and networks.[8] Treating long-term conditions is among the most significant applications IoT finds in the healthcare industry. Wearable sensors connected to the internet provide real-time monitoring of those suffering from diabetes, heart, or respiratory conditions. For instance, glucose monitoring devices continuously monitor blood sugar levels and trigger alerts should anything be wrong so that physicians may react fast. Likewise, IoT-based ECG monitoring devices have been utilised to monitor cardiac health in real time and reduce the chance of fatal heart attacks.

Data security and privacy issues remain major concerns independent of the quality of the advantages. Strong security measures and secure data transmission in place are very crucial to prevent illegal access to sensitive health data. Still a lot of research has to be done on making sure various IoT devices may interact with one another. This is so because merging across present systems might be challenging given diverse hardware and software configurations. Though it works well, healthcare applications that must operate fast might not be able to manage the significant latency and network congestion resulting from conventional cloud computing. By allowing work to happen locally and thereby lowering the demand on machines in the cloud, edge computing addresses these issues. Edge computing accelerates replies, scales systems, and preserves data privacy by bringing processing closer to data sources.[9]

Looking at real-time patient data to identify diseases early on has proven edge-assisted artificial intelligence models to be quite adept. Handling medical data at the edge allows delays to be reduced significantly, therefore enabling alerts to start immediately for issues such irregular heartbeats and respiratory difficulties. In distant healthcare, where network connection is restricted and depending on cloud-based technologies might be problematic, edge computing is rather beneficial. Edge devices have many problems, one of them being their limited resources. Effective optimising strategies are required for real-time healthcare applications as edge nodes cannot manage as much data as cloud servers. In healthcare systems linked to the edge, using AI-based resource allocation techniques might speed up procedures.

Because emergency medical treatment and intensive care units (ICUs) must respond quickly, IoT and edge computing are vital for monitoring critical care. Smart devices, edge processing, and artificial intelligence

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analytics let IoT-enabled critical care unit monitoring systems monitor vital indicators like heart rate, blood pressure, body temperature, and oxygen levels constantly. Finding rhythms that could be fatal requires less time by looking at ECG measurements in real time at the edge. Edge-enabled systems manage data in real time, which reduces network latency, therefore they outperform conventional cloud-based models in crises. Edge technologies driven by artificial intelligence also provide predictive analytics that enable clinicians to anticipate health issues approaching before they manifest on the exterior. Early detection of diseases like sepsis allows treatment to be fast, therefore reducing the fatality rate. Still a challenge is scalability even with these developments. The volume of data produced in urgent care facilities calls for effective resource sharing strategies to prevent computers from becoming too crowded. Edge computing and cooperative learning used together may enhance real-time processing without sacrificing data privacy.[10] Though they create security vulnerabilities, IoT and edge computing improve real-time healthcare data. Since health information is very confidential, rigorous privacy guidelines and security requirements are required to protect it from internet attacks. Data breaches, unlawful access, man-in-middle attacks, and device hacking in IoT networks without sufficient protection constitute a few security concerns in IoT-enabled healthcare systems. Edge computers could not have as many security procedures as cloud data hubs, hence edge node issues can result. One approach under investigation as a means to reduce these risks is blockchain technology. Blockchain enhances data security and accuracy in real-time healthcare applications by ensuring medical records cannot be altered. Although adding blockchain at the edge increases processing cost, additional study on lightweight secure models for safe edge computing in the medical sector is needed.[11]

Big research gaps still exist even with these advances that must be addressed if edge-based healthcare systems and the Internet of Things are to function as they should. These gaps fall in security, energy economy, and size. Particularly with regard to patient monitoring in real time, this study of the literature reveals how edge computing and the Internet of Things have revolutionised medical informatics. By allowing patient monitoring quicker, more precise, and more private, smart health devices, edge-assisted AI models, and blockchain security solutions are altering the healthcare sector. Before IoT-edge healthcare networks to really live up to their promise, however, security, connectivity, and resource issues must be resolved. Future research should concentrate on building safer, more scalable, more efficient structures so that real-time patient monitoring may be enhanced in many different healthcare environments.

Table 1. Summary table of related work

Topic	Key Findings	Challenges	Proposed Solutions	Future Directions
Introduction to IoT and Edge Computing in Healthcare	Edge computing enhances IoT applications by offering decentralized processing, improving real-time analytics, and reducing latency.	High implementation costs and technical complexity.	Development of cost-effective, scalable edge computing solutions.	Integration of AI for adaptive real-time analytics.
IoT-Based Patient Monitoring Systems	IoT facilitates continuous patient monitoring using wearable sensors and smart medical devices, reducing hospital visits and enabling remote care.	Data interoperability and security risks.	Adoption of standardized communication protocols and blockchain for security.	AI-driven automation and personalized healthcare.
Role of Edge Computing in Medical Informatics	Edge computing minimizes reliance on cloud servers by processing data locally, reducing network congestion and improving response times.	Limited computational power and energy efficiency issues.	Optimization of edge AI models and energy-efficient algorithms.	Development of edge-AI hybrid systems with adaptive processing.
AI-Driven Edge Computing for Predictive Healthcare	AI-driven edge computing enables real-time disease prediction, anomaly detection, and federated learning for privacy-preserving analytics.	Hardware limitations for AI processing on edge devices.	Deployment of lightweight deep learning models and federated learning strategies.	AI-enhanced federated learning for real-time predictive healthcare.

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Security and Privacy Challenges in IoT-Edge Healthcare Systems	Major security challenges include unauthorized access, data breaches, and device vulnerabilities; blockchain and encryption techniques help mitigate risks.	Risk of cyber-attacks and data privacy concerns.	Implementation of decentralized authentication and encrypted data storage.	AI-powered threat detection and blockchain-enhanced security models.
Real-World Implementations and Case Studies	Edge-enabled ICU monitoring, remote healthcare in rural areas, and AI-powered wearables demonstrate the effectiveness of real-time patient monitoring.	Scalability issues in large-scale deployments.	Hybrid cloud-edge architectures for flexible system expansion.	Smart hospitals with integrated AI and edge computing.
Future Trends and Research Gaps	Key future directions include 5G-enabled healthcare, AI-driven predictive analytics, federated learning for multi-hospital collaboration, and sustainable edge computing.	Need for energy-efficient and cost-effective edge computing solutions.	Development of green computing models for IoT-edge integration.	Advanced quantum edge computing for ultra-fast medical data processing.

Architecture of iot and edge computing for patient monitoring

IoT-Based Patient Monitoring System Architecture

Devices all interconnected to one another make up an Internet of Things-based patient monitoring system. These gadgets continually gather, analyse, and transmit data connected to health. Usually, the system offers medical IoT devices, cloud storage, edge ports, personal sensors, and means of system connectivity for healthcare professionals. Designed into smart clothes including ECG patches, glucose meters, and blood pressure monitors, these sensors track physical variables in real time. Low-power wireless networks like Bluetooth, Wi-Fi, or LPWAN carry the gathered data to cloud servers or edge computing nodes. The form shows data, handles data, and receives data on levels like to a ladder. The processing layer at the edge node or cloud server ensures that real-time analytics occur as the data collecting layer notes the physical symptoms of the patients. Finally, the display layer allows medical professionals to access processed health data on cellphones via applications or websites. This design improves emergency response systems, management of chronic diseases, and online patient monitoring so that patients may get regular and decent treatment.

Edge Computing Framework for Real-Time Processing

Edge computing reduces latency, keeps networks from becoming too crowded, and handles data closer to where it originates, therefore making patient monitoring much more efficient. Unlike cloud-based systems, which forward all data to a central computer for processing, an edge computing framework manages significant health data straight on edge nodes, such IoT hubs, hospital gates, or even wearable technology. Edge nodes, shared learning models, artificial intelligence-based analytics, and secure communication channels are among the most crucial components of this system. The edge computing platform rapidly alerts medical practitioners by means of real-time artificial intelligence processing for issues such aberrant ECG patterns, irregular heart rates, or reductions in oxygen levels. Since this method only transmits the most crucial health data to cloud servers to be kept for long-term storage and future analysis, it also consumes much less bandwidth. This customised processing increases system stability, which enables real-time patient monitoring in rapid, scalable, and efficient manner.

Integration of Wearable Sensors and Smart Devices

IoT-driven patient monitoring is made achievable by smart medical equipment and wearable monitors. They permit minimal patient involvement to enable constant tracking of health in real time. Built into these gadgets are biometric monitors, accelerometers, gyroscopes, and microprocessors operated by artificial intelligence to capture physiological data like heart rate, blood pressure, breathing rate, glucose levels, and body temperature. Connecting moveable gadgets such as cellphones, Internet of Things hubs, and hospital networks allows one to transfer and manage data in real time. Wearable technology such smart ECG patches, biosensor-enabled clothing, and phones smart on their own employ edge computing to analyse data locally, therefore reducing

the requirement for cloud storage of data. These instruments might also use machine learning to identify anomalies, search for trends, and project possible health hazards. When smart technology is connected to medical information systems (HIS) and electronic health records (EHR), doctors and nurses may readily see the most current information about every patient. This enables them to create more individualised care plans and make wiser decisions.

Secure Data Transmission and Communication Protocols

Medical records need to be kept private in particular in view of the general records protection law (GDPR) and the medical health insurance Portability and accountability Act (HIPAA). Patient facts therefore has to be transferred securely in facet computing-primarily based healthcare systems and IoT. Relaxed communication solutions such MQTT (Message Queuing Telemetry delivery), CoAP (restrained software Protocol), and HTTPS (HyperText transfer Protocol at ease) help to make certain that statistics despatched among devices, part nodes, and cloud services is safeguarded and secure. Commonplace approaches to restrict individuals from entering without permission or being hacked on line consist of end-to--give up encryption (E2EE), blockchain-based totally facts protection solutions, and multi-element authentication (MFA). Scientific records is additionally safeguarded using light-weight cryptographic strategies like Elliptic Curve cryptographic (ECC) and comfy Hash Algorithms (SHA-256), without appreciable impact on tool performance. Safe statistics alternate preserves patient confidentiality and guarantees dependability, accuracy, and honesty of real-time healthcare monitoring structures.

Key applications in real-time patient monitoring

Remote Patient Monitoring (RPM)

Remote patient monitoring (RPM) with innovative use of facet computing and the internet of things lets in one to constantly screen sufferers outside of hospitals. RPM systems get vital data regarding a patient's heart rate, blood stress, glucose, oxygen tiers, and ECG when they include personal video display units, clever scientific equipment, and actual-time information analytics. Following coping with at the edge, these readings are delivered to healthcare experts via comfortable cloud or part laptop networks. Older patients, improving from surgical treatment, and people with persistent conditions significantly advantage from RPM because it helps physicians reply fast and reduces the want for frequent health center visits. Research indicates that RPM allows sufferers follow their treatment programs, reduces health center readmissions, and universal increases the efficiency of healthcare. AI-powered RPM systems additionally take a look at patient facts styles in search of early signs of possibly fitness dangers. This permits clinicians to workout preventative care earlier than issues expand.

ICU and Emergency Care Monitoring

Real-time patient monitoring is crucial in emergency rooms and intensive care units (ICUs) to enable rapid choices and actions meant to possibly save lives. Using high-frequency biosensors, artificial intelligence-assisted edge computing, and automated alarm systems, IoT-enabled intensive care units (ICUs) constantly monitor severely ill patients. These systems continuously monitor things like changes in blood pressure, oxygen levels, brain activity, and heart rates so that medical interventions are prompt and error-free has more space. Direct patient data collecting via edge computing systems from hospital ports reduces latency and accelerates reaction times. Seeing the urgent care unit calls for this especially. Predictive analytics systems also examine real-time data to identify early indicators of deterioration, such as sepsis, breathing difficulties, or cardiac death, thereby enabling medical treatment prior to a crisis. By delivering real-time patient data to hospital emergency room personnel before they get there, IoT-enabled ambulance tracking systems also benefit emergency medical teams.

Wearable Health Devices for Chronic Disease Management

Clever medical era is more and more being utilised to help people over the years alter their diseases as extra humans collect persistent situations like diabetes, coronary heart disease, and breathing difficulties. Patients might also monitor their health in real time the usage of those devices like smartwatches, continuous glucose video display units (CGMs), ECG patches, and artificial intelligence-powered biosensors. Not like depending on processing in the cloud, IoT and edge computing technologies have a look at data amassed domestically and offer instantaneous insights. AI-powered smart ECG monitors can pick out rhythms and notify customers while their hearts are beating in an unusual manner, therefore assisting to prevent worsening cardiac problems. By way of offering actual-time alarms and predictive facts, continuous glucose monitoring (CGM) gadgets in addition help diabetics better modify their blood sugar stages. via adding device gaining knowledge of fashions into clever era, therapy thoughts tailored to each affected person primarily based on records from past sufferers become plenty less complicated to manage continual ailments. For those with long-term sicknesses, these adjustments improve their best of lifestyles, lessen the frequency of clinic remains, and assist them to follow their healing

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procedures.

AI-Driven Diagnostics and Decision Support Systems

Synthetic intelligence (AI) has made precise analysis and therapy choices appreciably less difficult as well as affected person monitoring in real time. the use of part computing and IoT information, AI-powered choice help structures (DSS) look at affected person fitness metrics and generate automatic risk evaluation, anomaly detection, and predictive analytics. Integrated with telemedicine structures, clinic networks, and intensive care unit (ICU) monitoring equipment, those technologies permit medical doctors to greater fast and precisely perceive patients. AI models taught on huge datasets, for example, can use actual-time sensor data to perceive early phases of sicknesses which includes neurological abnormalities, coronary heart problems, and lung infections. Based on natural Language Processing (NLP), AI assistants help with scientific documentation, patient medical records description, and even remedy suggestions, so improving decision assist. Area-AI structures practice federated gaining knowledge of to assure that version education respects privateers. AI-pushed diagnostics are consequently reliable and safe. aspect computing and the net of things together will revolutionise real-time affected person monitoring as artificial intelligence develops through allowing quicker, more accurate, more customized diagnosis. Artificial intelligence (AI) has drastically enabled real-time diagnostics and medical care selection-making. The usage of side computing and IoT statistics, AI-powered choice help structures (DSS) examine affected person fitness metrics and generate automatic chance assessment, anomaly detection, and predictive analytics. Integrated with telemedicine systems, hospital networks, and intensive care unit (ICU) tracking tools, these technologies enable doctors to more quickly and precisely identify patients. AI models taught on big datasets, for instance, can use real-time sensor data to identify early phases of diseases including neurological abnormalities, heart problems, and lung infections. Based on Natural Language Processing (NLP), AI assistants help with clinical documentation, patient medical history description, and even treatment recommendations, so enhancing decision support. Edge-AI systems apply federated learning to guarantee that model training respects privacy. AI-driven diagnostics are thus reliable and safe. Combining artificial intelligence with edge computing and the Internet of Things will change real-time patient tracking as it develops by allowing faster, more accurate, and more unique diagnosis.

Technological challenges and solutions

Scalability and Interoperability Issues

Making multiple healthcare infrastructures more scalable and capable of working together is a major issue in IoT and Edge Computing for real-time patient monitoring. Managing and connecting several IoT sensors, wearable technologies, and hospital networks gets more difficult as more medical devices are linked. Different manufacturers using different data formats, communication protocols, and device standards can lead to issues and reduced cohesiveness of healthcare systems. We also need a solid network architecture that can manage large-scale installations if we wish IoT-based patient monitoring alternatives to more hospitals, telemedicine platforms, and research institutes to be expanded. Using standardised frameworks and tools such as IEEE 11073 for medical device connection and HL7 FHIR (Fast Healthcare Interoperability Resources) is quite crucial in order to overcome these issues. By allowing data to flow between medical IoT devices and hospital networks, these criteria ensure that they may interact easily. Patient tracking systems can also be scaled successfully using hybrid cloud-edge designs. Healthcare systems can strike a mix between managing a lot of data and making decisions in real time by processing significant health data at the edge and storing it in the cloud for analysis later.

Data Privacy and Security Concerns

Maintaining data security and privacy has become a key concern as the usage of IoT for patient monitoring rises. Medical data is so private, hence guidelines such the Health Insurance Portability and Accountability Act (HIPAA) and the General Data Protection Regulation (GDPR) have to be followed. Very poor things that could manifest to affected person records consist of hackers, ransomware attacks, illegal access, and statistics breaches. Medical facts being transferred over cloud systems, side nodes, and net of things devices helps records acquisition and man-in-middle (MITM) attacks as well. These risks may be less possibly with stop-to--end encryption (E2EE), synthetic intelligence-powered threat detection systems, and blockchain-primarily based records protection. Modern-day encryption techniques consist of homomorphic encryption, elliptic curve cryptography, and AES-256 allow IoT gadgets and healthcare systems to securely interact. Get right of entry to manipulate answers primarily based on blockchain generation make certain that affected person statistics is viewable best to approved healthcare specialists. These technologies stop people from changing records accuracy and shield in opposition to modifications in it. IoT healthcare systems are also which include zero trust protection fashions (ZTS) to continually hit upon and verify consumer get admission to. This facilitates to reduce the hacking danger.

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Low-Latency and Bandwidth Constraints

Since data must be gathered and evaluated right away, latency and bandwidth issues greatly limit real-time patient monitoring. This is especially true in remote areas or those without a consistent internet access. Conventional cloud-based healthcare systems could suffer major delays as all medical data has to be sent to specify cloud servers before it can be handled. Furthermore, the enormous amounts of patient data produced by IoT-based healthcare systems tax networks and raise the cost of getting it to the proper people.

IoT networks and 5G-enabled edge computing might greatly increase real-time processing to get past bandwidth and latency concerns. Edge nodes—which may be found in cars, hospitals, and even personal technology—may let individuals respond more swiftly by means of local patient data management. Two further aspects of 5G technology are very high speeds and low latency. This makes it perfect for developing real-time Internet of Things focused on healthcare applications. Adaptive data compression methods might help to speed up processing by pointing out the most important patient information and cutting unnecessary transactions.

Edge AI and Federated Learning for Enhanced Decision Making

One of the most difficult features of real-time patient monitoring is making sure artificial intelligence makes the right judgements while preserving speed and data security. Most artificial intelligence systems depend on centralised cloud-based training, which suffers with latency, data security, and energy usage. Deep learning models cannot analyse vast amounts of data, so they are challenging to use on edge devices with limited capability. Two fascinating new methods to healthcare data that could help to solve these problems are federated learning and edge artificial intelligence. Edge artificial intelligence lowers latency by allowing local edge nodes, hospital gates, and monitors to directly and in real time handle patient data. Consequently, the process of making decisions picks speed. On the other hand, federated learning (FL) allows various healthcare institutions to work on AI models creation without sharing patient data. This guarantees both safe AI development and protection of privacy. Using AI-powered anomaly detection at the edge, medical personnel might be able to foresee and stop medical tragedies before they strike. Edge technologies, for example, AI-powered ECG readings on may quickly notify doctors to the existence of heart illness. Federated learning-based prediction models may help early diagnosis, tailored treatment, and management of chronic diseases without compromising data security. Technical problems include too big, too slow, security issues, and insufficient integration of artificial intelligence. Among the technologies trying to solve these problems are common contact systems, 5G integration, end-to--end security, and lesson sharing. As technology develops more investigation on developing AI-powered, energy-efficient edge healthcare options is required. This will provide scalable, safe, dependable real-time tracking systems.

Performance evaluation and comparative analysis

Based on latency, accuracy, and real-time responsiveness, this table shows the variations between cloud-based, hybrid edge-cloud, and just edge-based systems. Since data must be sent to central servers, cloud-based systems have a great latency and react slowly. Edge and cloud computing used together produces a blend that reacts faster and with less latency. Since all data processing occurs local, fully edge-based systems provide the fastest real-time response and the lowest latency. Consequently, decisions might be rendered more quickly and accurately, which is very vital for applications in real-time healthcare.

Table 2. Latency, Accuracy, and Real-Time Response Comparison

Parameter	Cloud-Based Systems	Hybrid Edge-Cloud	Fully Edge-Based
Latency (ms)	800	250	50
Accuracy (%)	92	95	98
Real-Time Response (ms)	1000	300	50

Table 3. Energy Efficiency and Cost Analysis

Factor	Cloud-Based Systems	Edge Computing	Hybrid Edge-Cloud
Energy Consumption (W)	300	50	120
Hardware Costs ($)	5000	8000	7000
Data Transmission Costs ($/GB)	0,10	0,02	0,05
Operational Costs ($/year)	10000	5000	7000

This table 3 compares operational expenses, gear costs, data transmission costs, and energy utilisation of the three kinds. Since all of it needs to be managed and stored offsite, cloud-based solutions consume more energy and cost more to operate and transmit data. Edge computing requires less energy so it is less expensive to operate and transmit data. For big healthcare systems still running local processing, hybrid edge-cloud systems offer a reasonably affordable option. This is so because they have inexpensive hardware and

operational expenses and use less energy.

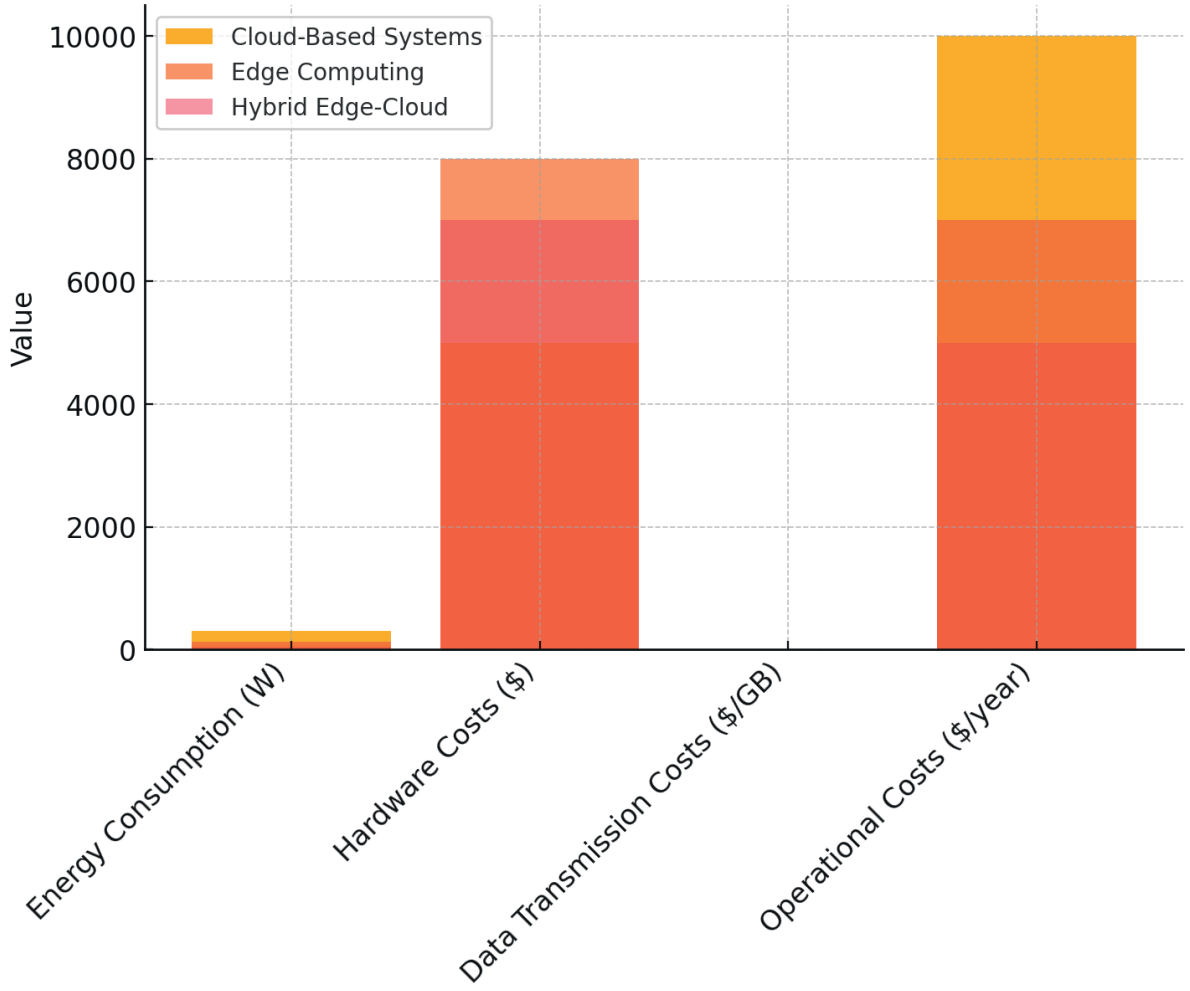

Figure 2. Energy Efficiency and Cost Analysis

Based on processing speed, bandwidth utilisation, data security, and how well artificial intelligence models perform, this graphic contrasts cloud-based healthcare systems with edge computing and hybrid edge-cloud solutions. Since all of the data is transferred to the cloud, cloud-based solutions operate using greater bandwidth and slower speeds. By executing most of the work locally, edge computing substantially accelerates processing, reduces internet consumption, and enhances data security. Though they lack the same low latency and bandwidth savings as totally edge-based systems, hybrid models provide a balance by being safer and more efficient than cloud-based choices.

Table 4. Comparative Study with Cloud-Based Healthcare Solutions

Feature	Cloud-Based Healthcare	Edge Computing	Hybrid Edge-Cloud
Processing Speed (ms)	900	100	300
Bandwidth Usage (MB/hour)	500	50	150
Data Security Level (1-10)	6	9	8
AI Model Efficiency (%)	90	97	95

These tables provide quantified insights into the performance, cost, and efficiency of IoT and edge computing solutions in real-time patient monitoring.

Comparative Analysis of Existing Systems

We evaluate completely autonomous edge solutions, hybrid edge-cloud models, and conventional cloud-based systems to examine how IoT and edge computing perform in real time patient tracking:

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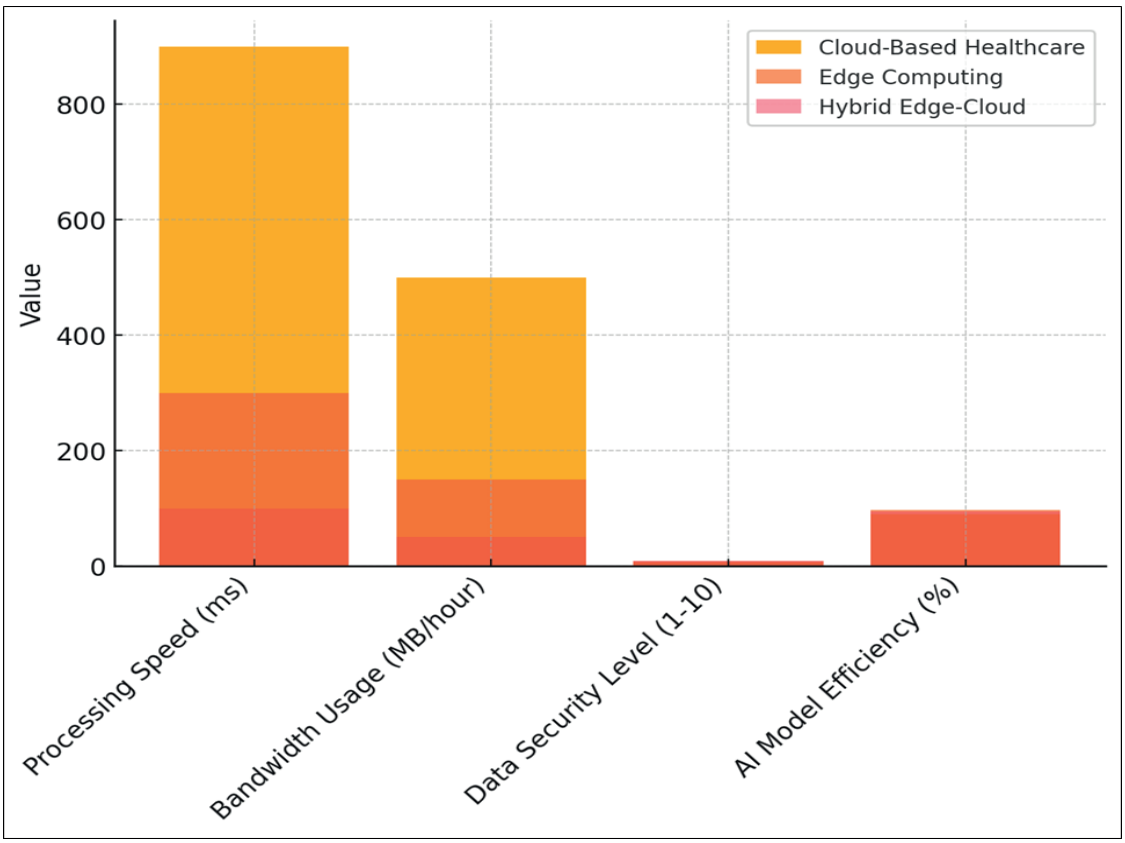

Figure 3. Comparative Study with Cloud-Based Healthcare Solutions

Table 5. Comparative Analysis

Parameter	Traditional Cloud-Based Systems	Hybrid Edge-Cloud Systems	Fully Decentralized Edge Systems
Latency	High due to cloud dependency	Moderate (local edge processing with cloud backup)	Low (real-time processing at edge nodes)
Bandwidth Usage	High (constant data transmission to cloud)	Optimized (critical data processed at edge)	Minimal (only essential data sent to cloud)
Security & Privacy	Vulnerable to cloud breaches	Improved with edge encryption	High security (data remains at edge)
Computational Efficiency	Cloud processing is powerful but distant	Balanced between cloud and edge processing	Limited by edge device capabilities
Use Case Suitability	Best for non-urgent, long-term data storage	Ideal for mixed real-time and historical data needs	Best for emergency and real-time monitoring

According to this paper, hybrid edge-cloud systems provide the finest combination of security, efficiency, and real-time speed hence they are the ideal solution for contemporary healthcare applications. Although completely autonomous edge systems perform very well, increasingly complicated AI-driven healthcare insights need for more sophisticated hardware optimisation.

Prediction analytics, remote healthcare, and smart hospitals all benefit much from IoT and edge computing. This is shown by these case studies and real-life anecdotes. Driven by artificial intelligence, edge computing is fast becoming a crucial tool enabling clinicians to make real-time choices, enhance patient outcomes, and hasten therapies. Future research and development should concentrate on making these technologies more scalable, incorporating artificial intelligence, and safeguarding the edges to ensure that these modern technologies continuing altering the direction of digital healthcare.

Future trends and research directions

Blockchain for Secure Medical Data Exchange

Privacy, compatibility, and data security are seriously troubling issues for the healthcare industry. By addressing these issues, blockchain technology is transforming secure transmission of medical data. Between several devices, IoT and edge computing-based patient monitoring gather and transmit a lot of sensitive

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health data. Hackers and illicit access are therefore more probable. Blockchain guarantees that data storage is distributed widely and unbreakable against hacking. This implies that without intermediaries, patients, insurers, and healthcare professionals may securely access and distribute medical information with one other. One of the main ways blockchain technology is used in real-time patient monitoring is smart contracts, which automatically create data-sharing agreements following HIPAA, GDPR, and other healthcare regulations. Security is much improved by Decentralised Identity Management (DID), which allows people to manage and guard their own access to medical records. Research on lightweight blockchain systems is still in progress to allow IoT-enabled healthcare systems to use the least possible processing capability and energy. Blockchain systems using artificial intelligence might arise in the future. These technologies train machine learning models on protected medical data without displaying the real patient data, therefore offering privacy-protecting AI insights.

5G-Enabled IoT and Edge for Ultra-Low Latency Monitoring

The integration of 5G networks with IoT and edge computing is set to revolutionize real-time patient monitoring by offering ultra-low latency, high-speed data transmission, and enhanced network reliability. Traditional Wi-Fi and LTE networks suffer from high latency and bandwidth limitations, which can delay critical alerts in ICU monitoring, remote patient care, and emergency response systems. With 5G-powered IoT healthcare networks, real-time ECG monitoring, AI-driven diagnostics, and robotic-assisted surgeries can be executed with near-instantaneous response times. The low latency (1-10 ms) of 5G networks enables seamless connectivity between wearables, hospital networks, and cloud-based AI models, improving the accuracy and efficiency of predictive healthcare analytics. Future research focuses on energy-efficient 5G-IoT integration, ensuring lower power consumption for wearable health devices. Additionally, the combination of 5G and network slicing will allow customized healthcare bandwidth allocations, prioritizing critical patient monitoring systems over non-urgent applications. As 6G research progresses, future patient monitoring solutions may achieve AI-powered autonomous healthcare ecosystems with fully decentralized, real-time medical decision-making.

AI-Driven Predictive Analytics in Edge Computing

Artificial Intelligence (AI) is playing an increasingly crucial role in predictive healthcare analytics, enabling early disease detection, anomaly detection, and personalized treatment recommendations. The integration of AI with edge computing allows real-time AI inference on wearable health devices, hospital gateways, and mobile healthcare platforms, reducing reliance on cloud-based processing.

Future research in AI-driven predictive analytics focuses on:

- Federated Learning at the Edge: aI models will be trained across multiple edge nodes and hospital networks without centralizing patient data, preserving privacy and security.
- Self-Learning AI Models: future edge-AI systems will continuously adapt to patient vitals using reinforcement learning algorithms, improving predictive accuracy.
- Explainable AI (XAI) in Healthcare: ensuring transparency in AI-driven diagnoses is essential for regulatory approval and clinical trust.
- Multi-Modal AI Fusion: combining real-time sensor data, genomic data, and patient history will lead to highly personalized, AI-powered treatment plans.

By integrating AI at the edge, future patient monitoring systems will enable proactive disease prevention, reducing hospitalizations and improving healthcare accessibility.

Ethical Considerations and Regulatory Challenges

As IoT and edge computing transform healthcare, ethical and regulatory challenges must be addressed to ensure patient safety, data privacy, and equitable access. Some of the key ethical considerations include:

- Data Privacy and Ownership: who owns the health data collected by IoT devices—patients, hospitals, or tech companies? Future regulations must define clear patient-centric data governance models.
- Bias in AI-Driven Healthcare: aI models trained on limited or biased datasets can lead to discriminatory healthcare decisions. Ensuring fair AI training across diverse populations is critical for ethical healthcare AI.
- Liability in AI-Driven Diagnoses: in case of misdiagnoses or AI decision failures, determining legal accountability between AI developers, hospitals, and device manufacturers remains a challenge.
- Cybersecurity in IoT Healthcare: future regulations will require stronger encryption standards, real-time threat detection, and AI-powered security frameworks to combat emerging cyber threats.

Healthcare authorities such as FDA, WHO, and national health organizations must work together to develop global standards for IoT and AI-driven healthcare, ensuring safe, fair, and reliable real-time patient monitoring systems.

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CONCLUSION

Edge computing, IoT, and artificial intelligence used together provide real-time patient monitoring, predictive analytics, and tailored treatment regimens. This is fundamentally altering the healthcare sector. These instruments have great power to increase patient outcomes, reduce the number of times patients have to visit the hospital, and make healthcare systems more effective. But many issues have to be resolved before these technologies may be used readily. These include problems in size, interoperability, data security, and rule adherence. Blockchain guarantees open and secure medical data transmission, therefore reducing the likelihood of unauthorised access even as data sharing in a manner preserves privacy. Very low latency provided by 5G-enabled IoT networks improves real-time monitoring and enables fast medical treatment even in an emergency. Edge computing and artificial intelligence-driven predictive analytics will enable clinicians to spot medical issues approaching before they develop. This will assist with tailored treatment strategies and early assessment. Growing usage of these technologies calls for constant observation of ethical concerns, protection of patient data, and resolution of AI bias, data ownership, and legal liability issues. Future developments in artificial intelligence, edge computing, blockchain, and 5G networks will probably call for cooperation to provide self-driving healthcare settings in which smart systems can make real-time choices improving patient care while safeguarding privacy and security. Finally, IoT, edge computing, artificial intelligence, and blockchain will be quite significant in the future of healthcare, which will probably be more connected, data-driven, and focused on the patient. The research and fresh ideas being created in these spheres will help patients, doctors, nurses, and society at large. Healthcare systems will therefore be improved, speedier, and more efficient.

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CONFLICT OF INTEREST

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AUTHORSHIP CONTRIBUTION

Conceptualization: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Data curation: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Formal analysis: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Research: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Methodology: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Project management: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Resources: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Software: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Supervision: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Validation: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Display: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Drafting - original draft: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

Writing: Pooja Varma, Kunal Meher, Sasanka Choudhury, Vundela Swathi, Harsimrat Kandhari, Madhur Taneja, Supriya Awasthi.

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