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Innovative Applications of Big Data Visualization in Medical Engineering for Hospital Operational Decision-Making

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Abstract: This paper systematically expounds the practical paths of big data visualization in medical engineering within the domains of medical resource optimization, medical quality improvement, patient service enhancement, and financial performance management. By transforming complex medical data into intuitive visual charts and integrating big data analysis technologies with algorithmic models, it achieves the refinement and intelligence of hospital operational management. Studies have shown that big data visualization technology significantly improves hospital operational efficiency, medical service quality, and patient satisfaction, providing core technical support for hospitals' digital transformation and high-quality development, and becoming an indispensable innovative tool in modern medical management.

Keywords: Medical Engineering; Big Data Visualization; Hospital Operations; Decision Support; Innovative Applications.

1. Introduction

In the wave of rapid development of digital economy and medical technology, the healthcare industry is accelerating its transformation towards intelligence. The popularization of technologies such as Electronic Medical Records (EMRs) and medical Internet of Things (IoT) has led to exponential growth in multi-dimensional data, including clinical diagnosis, equipment management, and patient management, which constitute the core of medical engineering big data. However, traditional analysis methods such as tables and text reports struggle to unlock data value, failing to meet the needs of hospital refined management.

Big data visualization technology in medical engineering presents complex data in intuitive forms such as graphics and charts, assisting hospital managers in quickly capturing data patterns. Although this technology has achieved phased results, there is still room for improvement in data integration, analysis accuracy, and scenario expansion. Therefore, exploring its innovative applications in hospital operational decision-making is of great significance for promoting medical digital transformation.

2. Overview of Big Data Visualization in Medical Engineering

2.1. Characteristics of Medical Engineering Big Data

Medical engineering big data is characterized by being multi-source, complex, dynamic, and high-value. Data covers scenarios such as clinical diagnosis, equipment management, hospital operations, and health monitoring, including structured, semi-structured (XML/JSON), and unstructured data. Among them, unstructured data is difficult to process and requires image processing and machine learning technologies for analysis. Additionally, data updates in real-time with disease progression and equipment status, and the value it contains provides key insights for medical optimization.

2.2. Basic Principles and Technologies of Big Data Visualization

Big data visualization realizes intuitive display by mapping data dimensions to graphic attributes which are length, color and shape through technologies like graphics and human-computer interaction. Basic visualization technologies include line charts, bar charts, and heat maps. Line charts present data trends, such as changes in the number of hospitalizations. Bar charts present comparative categorical data, such as departmental revenues. Heat maps display data distributions, such as equipment usage frequencies. Advanced technologies such as 3D visualization and interactive visualization provide three-dimensional presentation and deep data exploration capabilities [1].

2.3. Role of Big Data Visualization in Medical Engineering for Hospital Operational Decision-Making

Big data visualization has four core values in hospital decision-making:

(1) Reduces understanding barriers: Replaces tables with graphics to help non-professionals quickly grasp data cores;

(2) Identifies key patterns: Highlights abnormal trends through graphic changes, such as predicting equipment failure risks;

(3) Supports multi-dimensional analysis: Integrates multi-dimensional data for in-depth mining through interactive operations;

(4) Promotes cross-departmental collaboration: Visualized results are intuitive and universal, facilitating collaborative decision-making among finance, clinical, and other departments.

3. Innovative Application Scenarios of Big Data Visualization in Medical Engineering for Hospital Operational Decision-Making

3.1. Optimization of Medical Resource Allocation

3.1.1. Human Resource Allocation

Human resources in hospitals are core elements for providing medical services, and their rational allocation directly affects service efficiency and quality. Through big data visualization analysis of multi-dimensional data such as medical staff scheduling records, number of consultations, operation duration, and patient satisfaction, the workload of medical staff in different departments and time periods can be clearly presented. Heat maps are used to display the workload distribution of each department at different times of the day during the week—the darker the color, the heavier the workload—enabling managers to quickly identify areas with tight or idle human resources [2].

For example, a tertiary hospital used big data visualization analysis and found that, as shown in Figure 1, the number of patients in the emergency department surged from 7 pm to 9 pm on weekdays, with the peak number of visits reaching 200 people per hour. However, there were only 12 medical staff on duty in the emergency department, the median waiting time was 60 minutes, and the patient satisfaction score was only 6.5. There was an insufficient allocation of medical staff in the emergency department, while some staff in administrative and logistics departments were relatively idle during this period, as shown in Figure 2. Based on the visualization results, the hospital established a flexible scheduling system, deployed 8 medically qualified personnel from administrative and logistics departments, who went on duty after a one-week training to support the emergency department during peak hours, effectively alleviating the pressure on the emergency department. Data shows that the waiting time has been shortened to 42 minutes, a decrease of 30%; the patient satisfaction has increased to 8.2 points, an increase of 26%; and the average patient reception efficiency of medical staff has increased by 25%, from 16 people per hour to 20 people per hour.

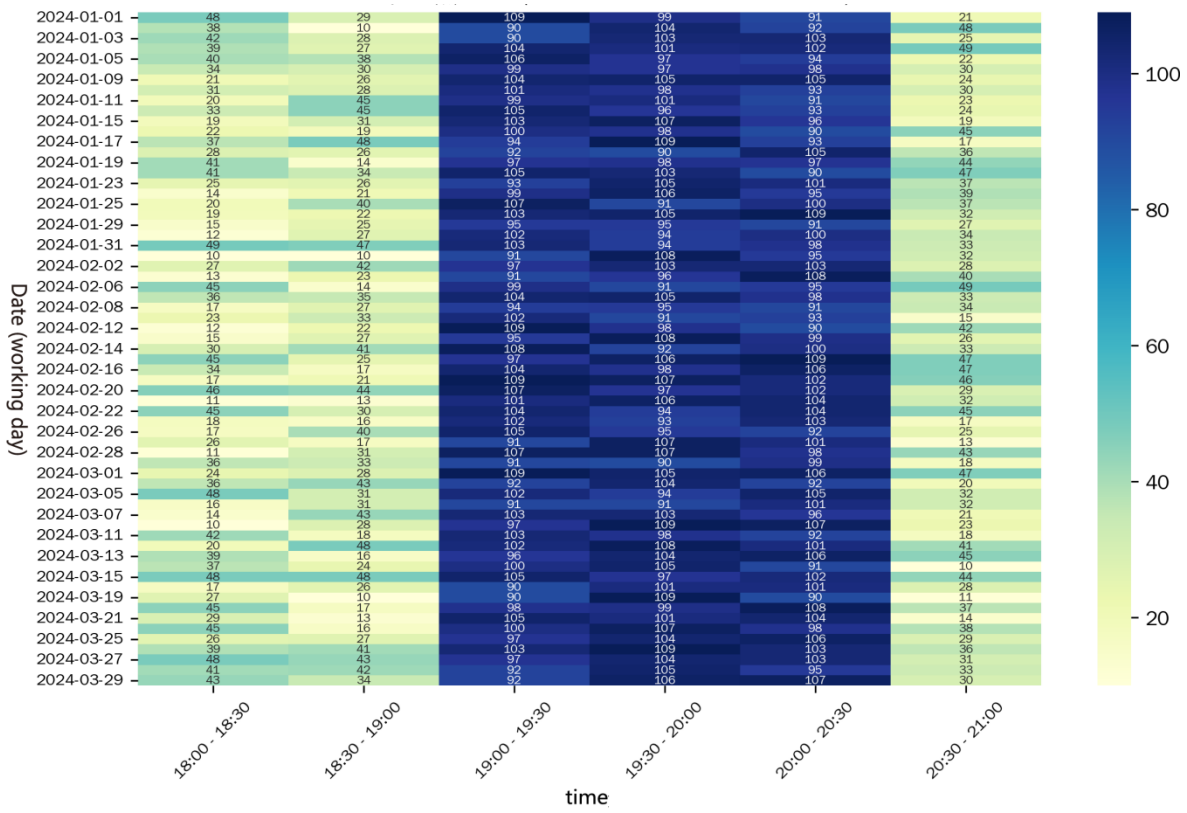

Figure 1. Heatmap of Patient Visits (Statistics Every 30 Minutes from 18:00 to 21:00)

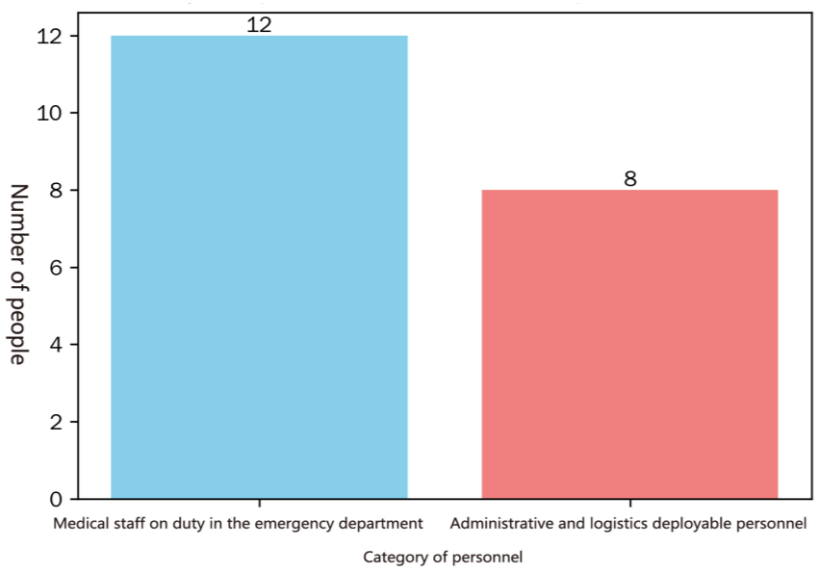

Figure 2. Comparison of the number of emergency medical staff on duty and the number of deployable administrative and logistics personnel

Meanwhile, by analyzing the matching degree between medical staff's professional skills and actual work needs, combined with visual forms such as bar charts, the demand gaps for personnel with different professional skills in each department were clearly presented, providing a scientific basis for personnel recruitment, training, and deployment. Hospitals can carry out targeted professional skills training based on visualization analysis results to improve the overall professional level of medical staff; when recruiting new employees, prioritize talents in short - supply specialties to optimize the human resource structure [3].

3.1.2. Medical Equipment Management

As an important material basis for hospitals to carry out medical services, the management level of medical equipment is related to the normal development of diagnosis and treatment services. Big data visualization technology can realize the data collection and analysis display of the whole process of medical equipment procurement, use, maintenance, and scrapping. In the procurement link, by collecting data such as market evaluations, price trends, and maintenance costs of different brands and models of equipment, Sankey diagrams are used to display the procurement fund flow of medical equipment, clearly presenting the proportion of procurement costs of different types of equipment to help managers reasonably plan equipment procurement budgets. For example, through Sankey diagram analysis, it is found that the procurement cost of a certain type of high - end medical equipment accounts for a large proportion, and the subsequent maintenance cost is high. The hospital can adjust the procurement strategy accordingly, consider equipment with higher cost performance or negotiate with suppliers to reduce the procurement cost [4].

In the equipment use link, dashboards are used to display key indicators such as equipment use frequency, operation duration, and number of failures in real time. When the equipment is abnormal, it is prompted with eye - catching colors or flashing icons. Line charts are used to analyze the change trend of equipment use frequency over time to predict the demand peak of equipment and make advance arrangements for equipment deployment and maintenance. For example, under the big data visualization monitoring of a hospital's CT equipment, data such as the number of scans, operation duration, bearing temperature, and voltage fluctuations over six consecutive months were collected and detected. As can be seen from the line chart in Figure 3, on the 128th day, the bearing temperature exceeded 75°C for three consecutive days, and the number of scans decreased by 15%, predicting wear of core components. It can be seen from the bar chart in Figure 4 that the proportion of maintenance costs of this equipment in the past year has risen to 30%, while the average maintenance level of similar equipment is 20%. By analyzing the changing trend of its operation data, the wear trend of key components was found in advance, maintenance was arranged in a timely manner, and scientific and reasonable intervention measures were formulated. By replacing the bearing in advance at a cost of 50,000 yuan, sudden failures were avoided, with the estimated emergency repair cost being 120,000 yuan. At the same time, the scanning parameters were adjusted to reduce the equipment load. The data shows that the equipment failure rate has decreased by 60%, from 2 times per month to 0.8 times; the maintenance cost has been saved by 70,000 yuan, accounting for 58% of the original estimate; and the service life of the equipment has been extended by 2 years. Calculated at an annual average cost of 200,000 yuan, 400,000 yuan has been saved [5].

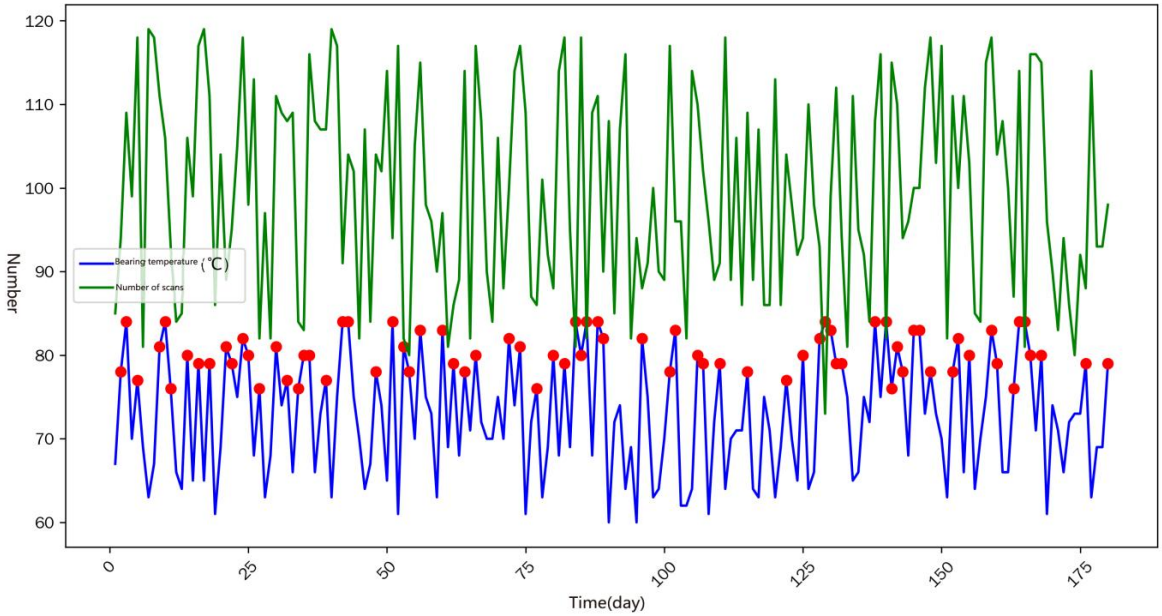

Figure 3. Changes in CT Equipment Bearing Temperature and Number of Scans Over Time

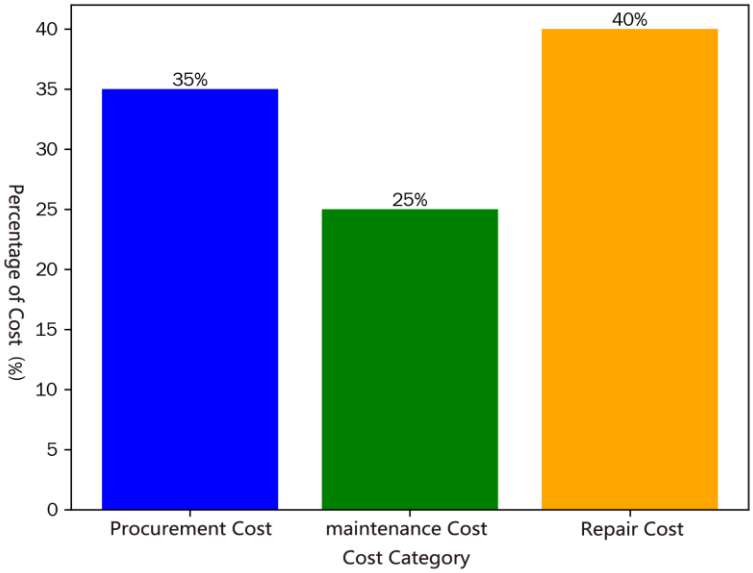

Figure 4. Bar chart of the proportion of various costs of CT equipment

3.1.3. Ward and Bed Management

Through the visualization analysis of big data such as ward and bed occupancy, turnover, and patient length of stay, the dynamic management of wards and beds is realized. The Internet of Things technology is used to collect bed use status data in real time. Combined with patient admission, discharge, transfer and other information, the use status of each ward and bed is displayed in real time with a dynamic map—green for idle, red for occupied, and yellow for reserved. Managers can intuitively understand the distribution and use of beds in the whole hospital through the visualization interface and adjust the bed allocation strategy in time [6].

At the same time, line charts are used to analyze the change trend of patient length of stay, find out the factors affecting the length of stay, optimize the diagnosis and treatment process, and improve the bed turnover rate. For example, after a general hospital uses the big data visualization system, it finds that the bed turnover rate of some surgical departments is low through analysis. Further visual process analysis finds that there are unreasonable aspects in the operation arrangement process, such as too long waiting time for preoperative examination and insufficient postoperative rehabilitation management. The hospital adjusts the operation arrangement process accordingly, optimizes the items and time of preoperative examination, and strengthens postoperative rehabilitation management, so that the bed turnover rate is increased by 25%, and the average waiting time for patients is reduced by 2 days. In addition, through the visualization analysis of patient admission time, discharge time and other data, the bed demand in the future period can be predicted, the bed arrangement can be made in advance, the patient waiting time can be reduced, and the patient satisfaction can be improved [7].

3.2. Medical Quality Monitoring and Management

3.2.1. Clinical Diagnosis and Treatment Quality Evaluation

Clinical diagnosis and treatment quality is the core of hospital medical quality. Using big data visualization technology, various indicators in the clinical diagnosis and treatment process are monitored and evaluated in real time.

By establishing a clinical diagnosis and treatment quality index system, key indicators such as diagnostic accuracy rate, treatment effective rate, rational use rate of antibiotics, and incidence of surgical complications are visually displayed in the form of dashboards, and the data is updated in real time. When the indicators are abnormal, early warnings are issued in time. Line charts are used to analyze the change trend of each indicator over time to evaluate the improvement effect of clinical diagnosis and treatment quality.

For example, comparing the diagnosis and treatment quality indicators of different departments and doctors, and displaying the differences with bar charts to find out the advantages and disadvantages, providing a basis for the performance appraisal and business training of clinical doctors. A hospital found through visualization analysis that the course of antibiotic use by some doctors was too long, exceeding the range recommended by clinical guidelines. Based on this data, the hospital organized experts to formulate standardized diagnostic and treatment paths, and displayed the implementation status of each department in real time through visualization dashboards, which promoted the rational use rate of antibiotics from the original 60% to 84%, and the average hospitalization cost of patients was reduced by 15%. In addition, typical cases can be visually analyzed, and the diagnosis process, treatment plan and treatment effect of cases can be displayed through medical record text visualization, medical image visualization and other ways, so as to promote the exchange and sharing of clinical experience and improve the overall clinical diagnosis and treatment level.

3.2.2. Medical Safety Monitoring

Medical safety is an important guarantee for hospital operations. Through the big data visualization analysis of medical adverse events, drug adverse reactions, nosocomial infections and other data, medical safety hazards are found in time. Heat maps are used to display the distribution of medical adverse events in different departments and time periods, find high-risk areas and time periods, and strengthen monitoring and management. For drug adverse reaction data, scatter plots are used to analyze the relationship between drugs and adverse reactions to evaluate the safety of drugs. A nosocomial infection monitoring visualization system is established to display the occurrence of nosocomial infections in real time, including the number of infected cases, infection sites, infectious pathogens and other information, and line charts are used to analyze the infection trend and take prevention and control measures in time [8].

For example, a hospital found the infection risk in the intensive care unit through the visualization analysis of nosocomial infection data, and timely strengthened the disinfection and isolation measures in this area, increased the frequency of infection monitoring, and effectively reduced the infection rate. In addition, visualization technology can also be used to supervise the implementation of medical safety-related rules and regulations. The implementation of medical operation procedures is displayed through process visualization, and illegal operations are found and corrected in time to ensure the medical safety of patients. For example, through visual monitoring, it is found that some medical staff violate the aseptic operation specifications in the surgical operation process. The hospital carries out rectification in time, strengthens training and supervision, and improves the standardization and safety of medical operations.

3.2.3. Continuous Improvement of Medical Quality Management

Medical quality management is a process of continuous improvement. Through big data visualization technology, the implementation effect of medical quality improvement projects is tracked and evaluated. Gantt charts are used to display the progress arrangement of medical quality improvement projects and monitor the implementation of projects in real time. For the quality index data before and after the improvement, they are displayed in the form of comparative bar charts or line charts to intuitively present the improvement effect. At the same time, the feedback opinions of medical staff and patients are collected, and the key words and hot issues of the feedback content are analyzed through visual methods such as word clouds to find the improvement direction [9].

For example, a hospital carried out a special quality improvement project for the problem of too long waiting time for examination, which was complained by many patients. Through big data visualization analysis, it was found that there were defects in the examination appointment process, resulting in long waiting time for patients. The hospital optimized the examination appointment system, increased self-service appointment equipment, adjusted the examination time arrangement, and continuously tracked the improvement effect through visualization data. After the improvement, the comparative bar chart was used to display the change of patients' waiting time for examination, and it was found that the average waiting time was significantly shortened, and the patients' satisfaction with the examination link was significantly improved. According to the visualization analysis results, the hospital continuously adjusts the improvement strategy, formulates the next improvement plan, and forms a closed loop of continuous improvement of medical quality management.

3.3. Patient Service Optimization

3.3.1. Optimization of the diagnosis and treatment Process

The convenience of the diagnosis and treatment process directly affects the patient's experience of seeing a doctor. Through the big data visualization analysis of the time data of each link of the patient in the hospital, such as registration, waiting for treatment, examination, treatment, payment, etc., the flow chart of the diagnosis and treatment process is drawn, and the time-consuming situation of each link is displayed with different colors and lines to find out the bottleneck link in the process. For example, line charts are used to analyze the change trend of patient waiting time, find the peak period, and shorten the waiting time by increasing the number of sources and optimizing the triage strategy. For the inspection and treatment links, bar charts are used to compare the inspection waiting time and treatment duration of different departments and equipment, and the inspection equipment and treatment resources are reasonably arranged to improve the inspection and treatment efficiency [10].

After introducing big data visualization analysis, a hospital found through analysis that the CT examination appointment process was tedious, resulting in long waiting time for patients. The hospital optimized the appointment system and adopted online appointment, time-sharing examination and other methods, so that the average waiting time for patients to check was shortened from the original 90 minutes to 30 minutes. In addition, visualization technology can also be

used to design a patient self-service system, which guides patients to complete registration, payment, query and other operations through an intuitive interface, simplifies the diagnosis and treatment process, and improves patient satisfaction. For example, patients can view their medical information and examination reports and make online payments through the hospital's mobile APP on the visualization interface without running between various windows in the hospital.

3.3.2. Patient Health Management and Follow - up

With the improvement of people's health awareness, patient health management and follow-up services have been paid more and more attention. Using big data visualization technology, the patient's health records, diagnosis and treatment records, rehabilitation status and other data are integrated and analyzed to provide patients with personalized health management plans. By establishing a patient health status visualization model, the patient's vital signs, disease indicators and other health data are displayed in the form of a dashboard to monitor the patient's health status in real time. When the patient's health indicators are abnormal, an early warning is issued in time, and the corresponding health suggestions are pushed.

For patients with chronic diseases, line charts are used to analyze the trend of their condition changes to provide a basis for doctors to adjust treatment plans. For example, through the visualization analysis of blood glucose monitoring data of diabetic patients, doctors can intuitively understand the fluctuation of patients' blood glucose and adjust the drug dosage and diet plan in time. In terms of patient follow-up, through the visualized follow-up plan management system, the follow-up time arrangement is displayed in the calendar view to remind medical staff to carry out follow-up on time. At the same time, the follow-up data is visually analyzed, and the patient satisfaction with the follow-up service is displayed with a bar chart to find out the existing problems and continuously optimize the follow-up service quality. For example, through analysis, it is found that some patients are not satisfied with the follow-up methods.

4. Conclusion

With its powerful data processing and intuitive presentation capabilities, big data visualization technology in medical engineering has become an important means for hospitals to optimize operational decisions and enhance core competitiveness. It has shown significant advantages in medical resource optimization, medical quality monitoring and management, patient service optimization, and hospital financial and performance management.

With the continuous progress of technology and the deepening of the digital transformation of the medical industry, big data visualization in medical engineering will develop in a more intelligent, integrated, and precise direction. In the future, through the deep integration with cutting-edge technologies such as artificial intelligence and the Internet of Things, big data visualization is expected to further tap the value of medical data, provide more comprehensive and accurate support for hospital operational decision-making, promote the medical industry to move towards higher quality and higher efficiency, and provide patients with more high-quality and convenient medical services.

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