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Digital Transformation and Artificial Intelligence in Medical Laboratories, Dentistry, and Biomedical Equipment Technologies

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ABSTRACT: Digital transformation and artificial intelligence are increasingly influencing healthcare delivery by improving data management, diagnostic accuracy, workflow efficiency, and equipment performance. Medical laboratories, dentistry, and biomedical equipment technologies are among the healthcare fields that can benefit significantly from these developments because they depend on large volumes of clinical data, digital images, automated instruments, and technical records. This narrative review discusses the applications of digital transformation and artificial intelligence across these three disciplines. In medical laboratories, artificial intelligence supports specimen management, automated analysis, quality control, result validation, digital pathology, and disease prediction. In dentistry, it contributes to radiographic interpretation, caries detection, periodontal assessment, orthodontic planning, implant placement, prosthetic design, and patient management. In biomedical equipment technologies, artificial intelligence supports predictive maintenance, remote monitoring, lifecycle management, inventory control, and evaluation of intelligent medical devices. Despite these benefits, implementation remains challenged by data quality, interoperability, cybersecurity, algorithmic bias, limited explainability, high implementation costs, and regulatory uncertainty. Artificial intelligence should therefore be applied as a supervised decision-support technology rather than as a substitute for healthcare professionals. Successful

implementation requires strong governance, local validation, workforce training, cybersecurity protection, and continuous performance monitoring.

INTRODUCTION

Digital transformation in healthcare refers to the integration of digital systems, technologies, and data-driven methods into clinical, diagnostic, administrative, and technical services. It extends beyond converting paper records into electronic formats and involves redesigning workflows, communication systems, decision-making processes, and healthcare delivery models.

Modern healthcare transformation includes electronic health records, laboratory information systems, digital imaging platforms, cloud computing, telemedicine, connected medical devices, automated systems, robotics, and artificial intelligence. These technologies allow healthcare institutions to collect, exchange, analyze, and interpret large volumes of clinical and technical data.

Artificial intelligence is one of the most important components of digital transformation. It includes machine learning, deep learning, natural language processing, computer vision, predictive analytics, and generative artificial intelligence. These technologies can identify patterns, classify images, predict outcomes, detect abnormalities, automate repetitive processes, and support professional decisions.

Medical laboratories, dental services, and biomedical equipment departments are particularly suitable for artificial-intelligence applications. Medical laboratories generate large quantities of structured numerical data and diagnostic images. Dentistry relies heavily on radiographic interpretation, visual examination, measurements, and individualized treatment planning. Biomedical equipment technologies depend on operational data, maintenance histories, equipment alarms, performance measurements, and lifecycle records.

The three disciplines are also closely connected. Laboratory instruments and dental imaging devices depend on biomedical engineering support, maintenance, calibration, and digital connectivity. Laboratory and dental data are incorporated into patient records and may be used together to support diagnosis and treatment. Therefore, digital transformation should not be implemented independently within each department but should be based on integrated healthcare systems.

The World Health Organization emphasizes that artificial intelligence in healthcare must be developed and used according to ethical principles that protect human autonomy, safety, transparency, accountability, fairness, and public interest. Accordingly, the implementation of artificial intelligence requires not only advanced software but also high-quality data, clear governance, competent professionals, and continuous monitoring.

This review examines the major applications of digital transformation and artificial intelligence in medical laboratories, dentistry, and biomedical equipment technologies. It also discusses their benefits, limitations, implementation requirements, and future directions.

DIGITAL TRANSFORMATION AND ARTIFICIAL INTELLIGENCE IN HEALTHCARE

Digital transformation depends on the availability of reliable and interoperable information systems. Electronic health records, laboratory information systems, radiology platforms, dental records, and computerized maintenance-management systems must be able to exchange accurate data securely.

Interoperability allows healthcare professionals to access laboratory results, diagnostic images, clinical notes, treatment plans, device alarms, and maintenance records through connected systems. When systems are not interoperable, data may become duplicated, fragmented, delayed, or inaccessible. This limits the value of artificial intelligence because intelligent algorithms depend on complete, standardized, and accurate information.

Healthcare institutions increasingly use cloud-based platforms to store and process data. Cloud computing enables remote access, centralized data analysis, automatic software updates, teleconsultation, and collaboration between different healthcare facilities. It can also support regional laboratory networks and remote dental-image assessment.

However, cloud computing introduces concerns related to confidentiality, data ownership, service continuity, and cybersecurity. Healthcare institutions must clearly define where patient data are stored, who is authorized to access them, how they are encrypted, and how system failures or cyberattacks are managed.

The Internet of Medical Things is another important element of digital transformation. It connects medical devices, analyzers, sensors, imaging systems, and healthcare platforms. Connected devices can transmit clinical and technical data continuously. Laboratory analyzers may send test results and instrument alerts, while dental scanners can transfer three-dimensional models and imaging data. Biomedical devices such as ventilators, infusion pumps, and monitors can transmit performance information.

These connections improve real-time monitoring and operational control, but they also increase cybersecurity risks. A poorly secured device may become a point of unauthorized access to hospital networks. Therefore, cybersecurity must be considered an essential component of patient safety.

Artificial intelligence can be used for descriptive, diagnostic, predictive, and prescriptive purposes. Descriptive systems summarize what has occurred. Diagnostic systems identify abnormalities or possible causes. Predictive models estimate future outcomes or failures. Prescriptive systems recommend possible actions. Generative artificial intelligence can produce text, summaries, images, or simulated content.

Although these tools can support healthcare professionals, they may also generate inaccurate or misleading outputs. Artificial-intelligence results must therefore be reviewed within the clinical or technical context.

APPLICATIONS IN MEDICAL LABORATORIES, DENTISTRY, AND BIOMEDICAL EQUIPMENT TECHNOLOGIES

Medical Laboratories

Medical laboratories are among the most automated areas of healthcare. They use advanced instruments, information systems, digital images, and standardized analytical procedures. Artificial intelligence can enhance laboratory services during the pre-analytical, analytical, and post-analytical phases.

The pre-analytical phase includes test ordering, patient identification, specimen collection, labeling, transportation, preparation, and acceptance. Errors during this phase may affect all subsequent laboratory processes.

Digital systems can reduce these errors by supporting electronic test ordering, barcode identification, specimen tracking, and automated verification of specimen requirements. Artificial-intelligence algorithms may identify duplicate requests, inappropriate tests, incomplete specimens, labeling inconsistencies, or delayed transportation.

Algorithms can also analyze patterns associated with specimen rejection. By comparing the collection site, time, specimen type, collector, transport duration, and rejection reason, laboratories can identify recurring problems and design targeted quality-improvement programs.

During the analytical phase, artificial intelligence can assist with automated measurement, image interpretation, and instrument monitoring. In hematology, computer-vision systems can classify blood cells and detect abnormal morphology. In microbiology, artificial intelligence can assist with colony identification, microscopy, organism recognition, and antimicrobial-resistance prediction.

In clinical chemistry and immunology, machine-learning systems may identify unusual relationships between test results or detect analytical patterns that suggest instrument error. In molecular diagnostics, artificial intelligence can support the analysis of genetic and genomic data.

Digital pathology is another major area of development. Glass slides can be converted into high-resolution digital images that are examined using computer-vision algorithms. Artificial intelligence can identify suspicious regions, count cells, assess biomarkers, and support tumor grading.

These systems may improve consistency and reduce the time required to review large tissue areas. They also support remote consultation and second opinions. However, final pathological diagnosis must remain under the responsibility of a qualified pathologist.

Artificial intelligence can also support laboratory quality control. Traditional quality-control systems use control materials, reference limits, calibration procedures, and statistical rules. Machine-learning models can analyze patient results continuously and detect subtle analytical shifts.

Patient-based quality-control methods may identify changes in moving averages, unusual analyte relationships, calibration drift, or systematic measurement errors. These methods can provide earlier warning than conventional control procedures in some situations.

Autoverification is another important laboratory application. It refers to the automatic release of results that meet predefined rules. Artificial intelligence can make autoverification more advanced by considering previous results, patient demographics, related tests, clinical diagnoses, specimen quality, and instrument status.

This can reduce unnecessary manual review and allow laboratory professionals to focus on complex or high-risk cases. Nevertheless, autoverification rules and artificial-intelligence models must be validated locally before clinical use.

Laboratory data are also increasingly used for disease prediction and clinical decision support. Machine-learning algorithms may combine laboratory values with age, medical history, medications, and vital signs to estimate the risk of sepsis, kidney injury, cardiovascular disease, diabetes, cancer, or clinical deterioration.

These systems may help identify high-risk patients earlier, but predictions should not be interpreted as definitive diagnoses. Clinical assessment, imaging, symptoms, and professional judgment remain essential.

Artificial intelligence can also improve laboratory management by predicting daily workload, staffing needs, reagent consumption, instrument capacity, turnaround-time delays, and equipment failure. This can reduce waste and support better resource allocation.

Despite these advantages, laboratory artificial intelligence faces several limitations. Differences in test names, measurement units, reference intervals, patient populations, analyzers, and reagents may reduce model accuracy. Missing or incorrect data can also lead to unreliable predictions.

Models developed in one laboratory may not perform equally well in another. Local validation and continuous monitoring are therefore necessary. Laboratory professionals must also remain alert to automation bias, in which users may accept an algorithmic recommendation without sufficient critical review.

DENTISTRY

Dentistry is highly dependent on diagnostic images, measurements, visual interpretation, and treatment planning. These characteristics make it suitable for computer vision, predictive analytics, and three-dimensional digital technologies.

Electronic dental records can integrate patient history, clinical examination findings, periodontal measurements, radiographs, intraoral photographs, digital impressions, treatment plans, and follow-up records.

When these records are standardized and complete, they can support artificial-intelligence analysis. However, inconsistent documentation, different tooth-numbering systems, missing imaging data, and free-text notes may limit data quality.

One of the most common applications of artificial intelligence in dentistry is caries detection. Computer-vision systems can analyze bitewing, panoramic, and periapical radiographs to identify possible carious lesions.

Artificial intelligence may help detect early lesions, improve consistency, highlight suspicious areas, and support patient education. However, false-positive findings may lead to unnecessary treatment, while false-negative findings may delay care.

Dentists must therefore interpret artificial-intelligence findings alongside clinical examination, lesion activity, patient risk, and image quality.

Artificial intelligence can also assist in periodontal assessment. It may detect alveolar bone loss, measure bone levels, classify disease severity, and predict disease progression.

Although automated radiographic measurements may improve consistency, periodontal diagnosis cannot rely on imaging alone. Probing depth, bleeding, clinical attachment loss, mobility, smoking history, and systemic conditions remain necessary.

In endodontics, artificial intelligence can help identify periapical lesions, root fractures, missed canals, and anatomical variations. It may also support working-length estimation and assessment of treatment quality.

Orthodontics has undergone major digital transformation through cephalometric analysis, intraoral scanning, three-dimensional models, aligner planning, and remote monitoring. Artificial intelligence can automatically identify cephalometric landmarks, measure facial and dental relationships, segment teeth, and predict tooth movement.

These tools can reduce repetitive measurement time and support treatment planning. However, orthodontic decisions must still consider biological limitations, periodontal health, patient cooperation, and professional judgment.

In implant dentistry, artificial intelligence can assist with bone assessment, identification of anatomical structures, implant-position planning, selection of implant dimensions, and surgical-guide design.

Digital implant workflows can integrate cone-beam computed tomography with intraoral scanning and computer-aided design. Although this may improve precision, errors in image registration or segmentation can be transferred into the surgical procedure. Each stage must therefore be reviewed carefully.

Computer-aided design and manufacturing have also transformed prosthodontics and restorative dentistry. Digital impressions can be used to design crowns, bridges, dentures, inlays, and implant-supported restorations.

Artificial intelligence may assist in identifying preparation margins, designing occlusal surfaces, matching tooth shape, selecting shade, detecting manufacturing defects, and predicting restoration performance.

However, treatment outcomes remain dependent on preparation quality, scanning accuracy, material selection, laboratory procedures, and clinical adjustment.

Artificial intelligence is also being investigated in oral pathology and maxillofacial imaging. It may help screen radiographs, photographs, and histopathological images for cysts, tumors, oral lesions, and potentially malignant changes.

These systems may support early recognition, especially in areas with limited access to specialists. Nevertheless, suspicious lesions still require clinical examination, biopsy when indicated, and histopathological diagnosis.

Digital transformation also affects dental administration. Artificial intelligence can support appointment scheduling, recall systems, insurance documentation, clinical-note generation, patient education, translation, and inventory forecasting.

Generative artificial-intelligence systems can help draft reports and patient instructions, but they may produce inaccurate or fabricated information. All generated content must be reviewed before clinical use.

Biomedical Equipment Technologies

Biomedical equipment professionals are responsible for ensuring that medical devices remain safe, available, calibrated, and clinically effective. Digital transformation changes equipment management from a mainly reactive service into a data-driven and predictive function.

Computerized maintenance-management systems allow healthcare institutions to store detailed information about equipment location, model, manufacturer, purchase date, maintenance schedule, calibration status, repair history, spare parts, downtime, and replacement needs.

When these systems are connected with procurement, clinical departments, and hospital networks, they provide a complete view of equipment performance throughout its lifecycle.

Predictive maintenance is one of the most important artificial-intelligence applications in biomedical equipment management. Traditional preventive maintenance is performed according to fixed schedules. Predictive maintenance uses actual equipment data to estimate when failure is likely to occur.

Algorithms may analyze temperature, vibration, operating hours, battery condition, power consumption, alarm frequency, error codes, calibration drift, and repair history.

This can help biomedical engineers identify deterioration before failure occurs. Predictive maintenance may reduce unexpected downtime, improve spare-parts planning, and increase equipment availability.

However, these models require sufficient historical failure data. Some medical devices rarely fail, making it difficult to develop accurate prediction models. Engineering judgment remains essential.

Remote monitoring allows connected medical devices to transmit performance information to centralized technical platforms. Biomedical teams can identify software problems, battery deterioration, communication failures, or recurring alarms without waiting for a clinical complaint.

Remote monitoring is especially valuable for ventilators, infusion pumps, imaging systems, laboratory analyzers, dialysis machines, and patient monitors.

Nevertheless, remote access creates cybersecurity risks. Maintenance connections must be secured, monitored, and limited to authorized users.

Digital twins represent another emerging technology. A digital twin is a virtual model of a physical device or system that is continuously updated using real-world data.

In biomedical engineering, digital twins may be used to simulate device performance, evaluate maintenance strategies, test software updates, predict component deterioration, optimize equipment placement, and support training.

Although promising, digital twins require accurate models, reliable sensors, and continuous validation.

Artificial intelligence can also improve inventory and lifecycle management. Equipment replacement decisions can be based on age, maintenance cost, failure rate, utilization, downtime, clinical importance, manufacturer support, spare-parts availability, and cybersecurity status.

This provides a more balanced approach than replacing equipment based only on age or retaining it because it remains operational.

Artificial intelligence is increasingly incorporated directly into medical devices. Examples include imaging systems, cardiac monitoring systems, digital pathology platforms, and diagnostic software.

This creates new responsibilities for biomedical engineers and technicians. They must understand software versions, algorithm updates, data requirements, cybersecurity, performance limitations, and post-market monitoring.

Artificial-intelligence-enabled devices may perform differently when patient populations, clinical workflows, input devices, or software versions change. Healthcare institutions should therefore monitor accuracy, false alarms, missed detections, user overrides, complaints, and clinical outcomes.

Biomedical engineering, clinical departments, information-technology teams, manufacturers, and quality-management units must share responsibility for monitoring these systems.

BENEFITS, CHALLENGES, AND GOVERNANCE

Digital transformation and artificial intelligence can improve healthcare quality in several ways. They can support earlier detection of abnormalities, reduce repetitive work, increase consistency, shorten turnaround time, improve equipment availability, and enhance access to specialist services.

They can also support resource management by predicting workload, reagent needs, maintenance requirements, and replacement priorities.

However, the effectiveness of artificial intelligence depends heavily on data quality. Incomplete, inaccurate, poorly labeled, or unrepresentative data can produce unreliable results.

Bias is another major concern. A model trained on a specific population may not perform equally well in another group. Differences in age, sex, ethnicity, disease prevalence, equipment type, and clinical practice can affect performance.

Lack of explainability can also limit trust. Some algorithms provide predictions without clearly identifying the factors that influenced the result.

Automation bias may occur when professionals accept algorithmic recommendations without sufficient review. Artificial intelligence should support professional reasoning rather than replace it.

Privacy and confidentiality are essential concerns because laboratory results, dental images, genomic data, and device records contain sensitive information. Access should be restricted according to professional roles.

Cybersecurity is especially important in connected healthcare environments. Cyberattacks may expose patient information, interrupt services, or affect device performance.

Healthcare organizations must define clear responsibilities for artificial-intelligence governance. This includes procurement, validation, implementation, monitoring, incident reporting, and corrective action.

Human oversight must remain central. A qualified professional should be responsible for final clinical and technical decisions.

Transparency is also necessary. Users should understand when artificial intelligence is being used, what data it analyzes, and what limitations apply.

Systems should be tested across different populations and clinical environments to ensure fairness and equity. Patients should also receive understandable information when artificial intelligence plays an important role in their care.

Implementation, Professional Competencies, and Future Directions

Healthcare organizations should begin artificial-intelligence implementation by identifying a specific clinical or technical problem. Technology should not be adopted simply because it is available.

The next step is to assess data quality, system compatibility, cybersecurity requirements, cost, regulatory status, and evidence of performance.

Artificial-intelligence systems should undergo local validation using the organization's own patient population, devices, workflows, and staff.

Implementation should begin gradually under supervision. Performance should be compared with current practice before large-scale adoption.

Training is essential for all professionals who interact with the system. Users should understand how to operate the technology, interpret results, recognize limitations, report errors, and protect patient information.

Medical laboratory professionals will need skills in laboratory informatics, data interpretation, algorithm validation, quality assurance, and digital pathology.

Dental professionals will require knowledge of digital imaging, intraoral scanning, computer-aided design, artificial-intelligence-assisted diagnosis, and verification of generated documentation.

Biomedical engineers and technicians will need competencies in connected-device management, predictive maintenance, software validation, data analytics, cybersecurity, and lifecycle monitoring.

Performance indicators should include accuracy, sensitivity, specificity, false-positive and false-negative rates, turnaround time, downtime, override rates, user satisfaction, safety incidents, and financial impact.

Artificial-intelligence systems should be reviewed continuously because performance may change over time. Changes in patient populations, devices, software, clinical practices, and disease prevalence can lead to model drift.

Future healthcare systems are expected to use multimodal artificial intelligence. These systems may analyze laboratory values, radiographs, clinical notes, pathology images, genomic information, and device signals together.

In medical laboratories, future systems may integrate specimen-quality assessment, analytical monitoring, clinical interpretation, and risk prediction into a unified platform.

In dentistry, artificial intelligence may connect diagnosis, digital simulation, treatment planning, manufacturing, and follow-up.

In biomedical equipment management, predictive analytics and digital twins may support real-time equipment optimization and automated lifecycle planning.

Although these developments are promising, future progress must remain guided by clinical evidence, ethical standards, regulatory oversight, and patient safety.

DISCUSSION

Digital transformation and artificial intelligence are changing how medical laboratories, dental services, and biomedical equipment departments operate. These disciplines share a strong dependence on accurate data, reliable equipment, standardized procedures, and professional interpretation.

Artificial intelligence can improve diagnostic support and operational efficiency, but high performance in research studies does not automatically guarantee safe performance in routine practice.

Many models are developed using carefully selected datasets that may not represent real clinical environments. Real-world settings include incomplete records, older equipment, diverse patient populations, and workflow interruptions.

The most important transformation is therefore not the replacement of professionals but the development of digitally supported professional practice.

Laboratory professionals may spend less time reviewing routine results and more time managing complex cases. Dentists may use automated measurements while remaining responsible for diagnosis and treatment. Biomedical engineers may shift from reactive repair toward continuous monitoring and predictive management.

A technically accurate system can still cause harm when introduced into a poorly designed workflow. Conversely, a system with moderate performance may provide value when its limitations are understood and safeguards are applied.

Healthcare organizations should therefore avoid purchasing isolated artificial-intelligence systems without a comprehensive digital strategy.

Priority should be given to technologies that address measurable needs, integrate with existing systems, have evidence of safety, and can be monitored after implementation.

Collaboration among healthcare professionals, engineers, information-technology specialists, quality teams, regulators, and patients is essential.

CONCLUSION

Digital transformation and artificial intelligence are redefining medical laboratories, dentistry, and biomedical equipment technologies.

In medical laboratories, they support specimen management, automated analysis, quality control, digital pathology, result validation, and disease prediction.

In dentistry, they contribute to radiographic interpretation, caries detection, periodontal assessment, orthodontic planning, implant placement, prosthetic design, and patient communication.

In biomedical equipment technologies, they support predictive maintenance, remote monitoring, digital twins, inventory management, and lifecycle planning.

These technologies can improve efficiency, consistency, accessibility, and resource utilization. However, they also introduce risks related to data quality, bias, privacy, cybersecurity, explainability, cost, and regulation.

Artificial intelligence should be implemented as a supervised support system rather than as an autonomous substitute for healthcare professionals.

Safe and effective adoption requires high-quality data, local validation, professional training, clear governance, cybersecurity controls, and continuous performance monitoring.

The future of healthcare will depend not only on the sophistication of artificial-intelligence systems but also on the ability of healthcare institutions to integrate them responsibly into clinical and technical practice.

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