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CHALLENGES AND STRATEGIES FOR THE EFFECTIVE ADOPTION OF ADVANCED MEDICAL TECHNOLOGIES IN HEALTHCARE SETTINGS

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ABSTRACT: Integrating advanced medical technologies (AMTs) offers great potential to improve healthcare delivery but presents significant implementation challenges. This study examines barriers to the adoption of AMTs and proposes strategies for successful integration. A comprehensive literature review identifies common issues, including high upfront costs, limited technical expertise, interoperability problems, and resistance to change. Qualitative data gathered through semi-structured interviews with healthcare administrators, clinicians, and IT professionals provides insights into their experiences with AMT implementation. The results show that effective strategies include thorough needs assessments, financial planning, user training, interdisciplinary collaboration, and change management. Strong leadership support, clear communication, and ongoing evaluation are also crucial. This research offers a practical framework for healthcare organisations to overcome implementation barriers and effectively leverage the benefits of AMTs, including improved diagnostic accuracy, better patient outcomes, and increased operational efficiency.
KEYWORDS: Medical technology, implementation challenges, healthcare management, change management, interoperability, user training.

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1. INTRODUCTION

The integration of advanced medical technologies into neurosurgery represents a fundamental transformation of medical practice, offering new perspectives on diagnosis, surgical planning, and therapeutic interventions.

This paper focuses on a specific category of Advanced Medical Technologies: non-AI hardware and software, which are essential for improving process quality in neurosurgical imaging, with particular attention to intellectual property management.

This exploration extends to an understanding of the complex implications of intellectual property protection in the contemporary scientific and technological landscape, particularly in advanced medical fields such as neurosurgery [1].

Such technologies hold significant potential to enhance surgical precision and overall efficiency. Yet, their successful adoption is often hindered by substantial financial implications, the need for specialised training, and the complexities of integrating these innovations into existing healthcare infrastructures [2].

1.1 General Context: Defining the Concept of Advanced Medical Technologies and Their Growing Importance in Modern Medicine

Advanced Medical Technologies, in the context of this paper, refers to hardware instruments and software solutions that do not rely on artificial intelligence but provide significant benefits to neurosurgical practice. These include, but are not limited to, nonconventional radiological technologies [3], neuronavigation systems [4], PACS networks [3], advanced computed tomography and magnetic resonance imaging equipment [3], and 3D surgical visualisation and planning systems [5], [6], [7], [8]. Such technologies are essential for improving diagnostic accuracy, enhancing surgical precision, and ultimately optimising patient outcomes in complex neurosurgical procedures [2].

These AMTs have revolutionised neurosurgery, enabling minimally invasive interventions with enhanced levels of safety and efficiency [3]. The ability to combine preoperative data with intraoperative images enables neurosurgeons to guide instruments with millimetre precision, reducing the risk of damage to healthy anatomical structures and contributing to faster patient recovery [9], [10]. Advanced surgical guidance systems, such as those based on optics or electromagnetics [11], alongside robot-assisted surgery [12], have improved precision and stability in complex neurosurgical procedures [1], [13]. Additionally, advanced visualisation software plays a crucial role in preoperative planning and intraoperative guidance, providing a detailed understanding of anatomical and functional relationships [8], [14], [15]. Furthermore, the integration of PACS networks with neuronavigation systems facilitates interdisciplinary diagnosis by enabling real-time visualisation and manipulation of intricate intracranial structures [3].

1.2 Problem Statement: Presenting the Paradox – Although There Is Enormous Potential, the Failure Rate or Slow Adoption Rate Is High

Despite the enormous potential to transform patient care and optimise surgical outcomes, the efficient integration of AMTs in neurosurgery faces multiple obstacles. A notable paradox is the discrepancy between the substantial theoretical benefits and the often slow or incomplete adoption of these technologies in clinical settings. Among the significant challenges are the high initial costs of acquisition and implementation [2], [16], [17], the need for specialised technical expertise and steep learning curves for medical staff [18], [19], and difficulties related to interoperability with existing systems [20], [21].

Additionally, there are organisational and human barriers, such as resistance to change among medical staff, that require continuous training programs and effective change management to ensure successful integration [22]. Without a coherent implementation strategy, including rigorous financial planning and strong leadership support, the promised benefits of AMTs may remain unrealised [23], [24].

1.3 Research Objectives: Stating the Purpose of the Paper

This scientific paper aims to surpass the descriptive stage of inventorying advanced medical technologies by adopting a practical approach focused on their efficient implementation. To precisely delineate the research objectives, a preliminary SWOT analysis of the current context in healthcare facilities was conducted, thereby identifying essential strategic levers for the optimal adoption of digitalisation and automation in medicine. Thus, the primary purpose of the study is to develop an integrated framework for the evaluation, selection, and efficient integration of non-AI advanced medical technologies in neurosurgery, including considerations of intellectual property and staff training [2], [8]. Additionally, the research aims to identify the most effective practices and formulate recommendations to optimise the adoption process and manage the complexities of intellectual property challenges in medical innovation.

The general objective of the paper is to develop an integrated strategic framework that enables healthcare organisations to navigate the complexities of AMT adoption and maximise clinical and operational benefits. This framework will integrate considerations regarding technical, financial, organisational, and ethical aspects, with particular emphasis on intellectual property management [17].

To achieve this purpose, specific objectives were derived from the following diagnostic analysis matrix:

Table 1. SWOT analysis

STRENGTH(S) (Internal)	CONSOLIDATION proposals (Derived objectives)	WEAKNESSES (W) (Internal)	ELIMINATION Proposals (Derived Objectives)
S1: High potential to improve diagnostic accuracy.	Validation of clinical impact through case studies and qualitative data.	**W1:** High initial acquisition and maintenance costs.	Identification of sustainable financing models and ROI analysis.
S2: The existence of a medical staff dedicated to professional excellence.	Early involvement of clinicians ("early adopters") as opinion leaders.	**W2:** Lack of technical expertise (low digital literacy).	Proposing continuous training programs and dedicated IT support.
S3: The ability to generate large volumes of medical data (Big Data).	Creation of standardized protocols for data valorisation.	**W3:** Interoperability issues between systems.	Analysis of technical solutions for data integration and standardization.
S4: Already existing basic medical infrastructure.	Integrating new technologies as upgrades, not disruptive replacements.	**W4:** Cultural and organizational resistance to change.	Development of change management and internal communication strategies.
OPPORTUNITIES (O) (External)	**FRUITION measures (Derived objectives)**	**THREATS (T) (External)**	**COUNTERMEASURES (Derived objectives)**

STRENGTH(S) (Internal)	CONSOLIDATION proposals (Derived objectives)	WEAKNESSES (W) (Internal)	ELIMINATION Proposals (Derived Objectives)
O1: The rapid evolution of AI solutions and medical robotics.	Monitoring technological trends for future-proof investments.	**T1:** Cybersecurity and privacy risks.	Including security protocols as a central pillar of the strategy.
O2: Better outcomes for patients (Patient Outcomes).	Focusing implementation on patient benefit to increase adoption.	**T2:** Rapid obsolescence of technology.	Scalable and modular investment planning.
O3: The possibility of streamlining operational flows.	Redesign of administrative processes through automation.	**T3:** Rigid or inadequate legislative framework.	Align internal strategies with national and international regulations.
O4: Availability of digitisation funds.	Guiding managers to external funding sources.	**T4:** Discrepancies between patients' expectations and reality.	Managing expectations through transparent communication.

Based on this analysis, the paper is structured around the following three specific objectives:

- Identification and analysis of critical barriers: In-depth evaluation of the financial, technical, and human obstacles that currently hinder the implementation of AMTs, based on specialised literature and interviews with key actors.
- Evaluation of impact and potential benefits: Analysis of how AMTs can concretely improve diagnostic accuracy and operational efficiency, providing solid arguments for the necessity of digital transition.
- Formulation of efficient adoption strategies: Development of a practical framework that includes solutions for financial planning, staff training, interdisciplinary collaboration, and change management, offering hospital managers concrete tools to transform challenges into development opportunities.

1.4 Importance of the Study: Why is this Topic Relevant for Hospital Administrators, Doctors, and Patients

The relevance of this study is multidimensional and addresses a broad range of stakeholders in healthcare.

- For patients, the efficient implementation of AMTs in neurosurgery results in improved clinical outcomes, reduced postoperative complications, faster recovery, and finally, an increase in quality of life [10]. The enhanced precision and minimally invasive interventions enabled by these technologies minimise risks and increase procedural safety [1].
- For neurosurgeons and medical staff, the study offers insights into how to fully leverage the potential of AMTs to increase surgical precision, optimise preoperative planning, and make informed real-time decisions [17]. Understanding the challenges and strategies to overcome them can facilitate adaptation to new technologies and reduce the learning curve [5].
- For hospital administrators and decision-makers, the research provides a framework for better understanding the necessary investments, evaluating their profitability, and developing efficient policies for the acquisition, implementation, and maintenance of AMTs. Addressing challenges related to costs and interoperability can lead to more efficient resource utilisation and workflow optimisation within medical institutions [3].
- For innovators and technology developers, the study emphasises the importance of intellectual property management, providing a context for protecting inventions and stimulating the continuous development of solutions that meet real needs in neurosurgery [25].

Through a systematic approach to these aspects, the present paper aims to contribute to a better understanding and more efficient adoption of non-AI Advanced Medical Technologies, thereby strengthening the foundation for excellence in neurosurgical imaging and ensuring sustainable benefits for the healthcare system.

2. METHODOLOGY

2.1 Study Design: Explanation of the Mixed Approach

This research adopts a mixed-methods approach, combining qualitative and quantitative analyses to provide a comprehensive understanding of the challenges and strategies associated with the adoption of non-AI Advanced Medical Technologies in neurosurgical imaging. This hybrid approach is justified by the complexity of the investigated phenomenon, which necessitates both synthesising existing knowledge and in-depth exploration of the experiences and perceptions of key actors in the clinical environment. The study design is guided by the need to validate and contextualise theoretical findings in practice, thereby facilitating the identification of applicable and relevant solutions. This mixed methodological approach enables a robust examination of both the broader landscape of technological integration and the nuanced perspectives of healthcare professionals, thereby enhancing the validity and applicability of the research findings [26]. This comprehensive strategy enables robust analysis of current practices and informs future innovations, particularly with respect to intellectual property and clinical efficacy [17].

2.2 Literature Review: Data Sources and Criteria for Inclusion and Exclusion of Articles

Data sources

A comprehensive analysis of the specialised literature was conducted to identify common issues, challenges, and documented strategies regarding the adoption of AMTs in medical environments. Bibliographic searches were conducted in major academic databases, including PubMed, Scopus, Web of Science, and Google Scholar, using a combination of key terms relevant to medical technologies, neurosurgical imaging, and intellectual property management.

Inclusion and Exclusion Criteria

Studies published in English, peer-reviewed, that directly address the implementation, adoption, barriers, and strategies related to non-AI AMTs in a medical context, with emphasis on neurosurgery or medical imaging, were included. Recent articles from the past 10 years were prioritised to ensure the information's relevance. Articles focusing exclusively on artificial intelligence-based technologies, preclinical studies, or those without direct relevance to clinical adoption were excluded. Additionally, opinion articles, editorials, or reviews that did not present a transparent methodology for analysing the literature were excluded.

2.3 Qualitative Data Collection: Description of Interview Participants, Interview Guide Structure, and Data Analysis Method

Description of Interview Participants

To obtain a direct and in-depth perspective on the implementation of AMTs, semi-structured interviews were conducted with a diverse sample of key actors. The participants included healthcare administrators, clinicians, and IT professionals responsible for medical infrastructure. This selection ensured coverage of multiple perspectives and experiences relevant to the adoption and management of medical technologies.

Structure of the Interview Guide

To obtain a direct and in-depth perspective on the implementation of AMTs, semi-structured interviews were conducted with a diverse sample of key actors. The participants included healthcare administrators, clinicians, and IT professionals responsible for medical infrastructure. This selection ensured coverage of multiple perspectives and experiences relevant to the adoption and management of medical technologies.

Data Analysis Method

The qualitative data collected from the interviews were analysed using thematic analysis. This method, widely used in qualitative research, involves the complete transcription of interviews, familiarisation with the data, generation of initial codes, identification of themes, review of themes, and final naming of themes [27].

3. BARRIERS IN THE ADOPTION OF ADVANCED MEDICAL TECHNOLOGIES

The adoption of Advanced Medical Technologies in neurosurgical imaging, although vital to medical progress, faces numerous barriers that can hinder or delay their effective integration. These obstacles are complex and manifest across multiple dimensions: financial, technological, organisational, and human, requiring detailed analysis to develop effective strategies for overcoming them. A deep understanding of these impediments is crucial for formulating targeted interventions that facilitate a smooth and beneficial transition toward integrating new technologies into clinical practice. Among the main challenges are high acquisition and maintenance costs, inadequate IT infrastructure, resistance to change among medical staff, and gaps in continuous training, all of which contribute to slow adoption and incomplete realisation of these technologies' potential [19], [28].

3.1 Financial Barriers: Initial Acquisition Costs, Maintenance Costs, Unclear Return On Investment

One of the most significant impediments to the adoption of AMTs in neurosurgery is the considerable financial burden entailed by their acquisition, implementation, and maintenance [29]. The initial acquisition costs are often prohibitive, particularly for stereotactic robotic systems or advanced imaging technologies. Neuronavigational robotic systems can cost hundreds of thousands or even millions of dollars, with research and development expenses reflected in the final product price [30]. For instance, a robotic system such as the Neuromate stereotactic incurred costs exceeding 30 million dollars [30]. Another example is the Renaissance system, with a total cost of approximately $789,000, including the robot, instrument tray, a dedicated workstation, and one year of free technical support [30]. Similarly, extended reality technologies, while offering substantial advantages, are often associated with disproportionate costs relative to their initially perceived value, complicating their widespread integration [31], [32].

In addition to the initial acquisition costs, hospitals and medical institutions face substantial maintenance and operating expenses. These include, but are not limited to, repair costs, consumable replacement, software updates, and ongoing technical support [23], [33]. For a more advanced surgical system, the acquisition cost can range from 1.83 to 1.95 million euros. In contrast, annual operating costs can reach 10% of the selling price, plus 2,000 euros per instrument and other ancillary expenses [34]. Maintenance of advanced medical equipment is essential to ensure optimal functioning and extend service life, but it can impose a continuous financial burden [35]. Factors contributing to operational costs also include human resource expenses, such as the salaries of specialised technical staff required to operate and maintain these systems [36].

Another significant financial challenge is the difficulty of accurately quantifying the return on investment for AMTs.

The benefits of these technologies, such as improving diagnostic precision, reducing complications, shortening patient recovery times, and increasing the safety of medical procedures, are often intangible or difficult to translate directly into short-term financial terms [37], [38]. Although studies have attempted to evaluate the ROI of medical technologies, they usually neglect acquisition and maintenance costs or do not provide conclusive comparisons with alternative technologies [39], [40].

The need for externally validated large-scale studies with robust cost-benefit analyses is pressing to determine the feasibility and financial value of integrating AMTs. Without clear, quantifiable financial justification, healthcare decision-makers face difficulties allocating the resources necessary to adopt these technologies [41], [42].

In addition, global financial disparities mean that the latest technologies are not available everywhere, limiting access to advanced care in resource-limited regions [43].

Thus, financial barriers not only affect medical institutions' capacity to adopt AMTs but also the equity of access to the best medical practices worldwide.

3.2 Technological Barriers: Interoperability, Data Security and Patient Confidentiality

Interoperability

Interoperability of medical IT systems represents a fundamental technical challenge in the adoption of AMTs. In the modern medical environment, data are generated and stored in diverse formats and systems, including imaging equipment, picture archiving and communication systems, radiological information systems, and electronic health records. The absence of smooth, standardised communication between these heterogeneous systems leads to information fragmentation, duplication of effort, and, ultimately, reduced efficiency in clinical workflows [44], [45].

Standards such as DICOM have been developed to facilitate the exchange of images and clinical data in standardised formats [3]. However, full implementation and universal compliance with these standards remain elusive. Many systems are not fully compatible, creating "information silos" that hinder a holistic view of patient data. Integrating new AMTs, such as neuronavigation systems or 3D surgical planning software, often requires complex and costly interfaces to connect to existing IT infrastructure [46]. The lack of interoperability prevents healthcare organisations from utilising a single software provider's product portfolio, as data are stored in provider-specific formats and cannot be easily transferred to other systems [46]. This imposes financial burdens on hospitals and hinders cost reimbursement to healthcare institutions [46]. In addition, many of these technologies cannot be integrated, necessitating manual tasks performed by medical staff at high cost. Increased interaction complexity, along with potentially longer interpretation times, can affect overall productivity. This lack of interoperability can lead to errors, delays in decision-making, and suboptimal utilisation of AMTs' potential [3], [17].

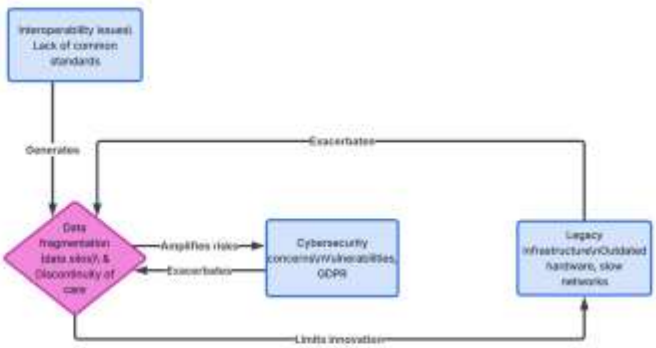

Figure 1. Schematic representation of technological barriers

Data security and patient confidentiality

As the volume of digital medical data grows exponentially with the adoption of AMTs, data security and the protection of patient confidentiality become paramount concerns [47], [48]. Medical images and associated data constitute highly sensitive information, and security breaches can have severe consequences, ranging from substantial legal and financial sanctions to undermining patient trust and damaging the reputation of medical institutions [49], [50], [51].

The challenges in ensuring data security are multifaceted. First and foremost, the need to share data between departments or hospitals for multidisciplinary consultations or research must be balanced against strict confidentiality requirements [52]. Multi-factor authentication and granular access control are crucial [53]. Secondly, cyber threats evolve constantly, and medical systems are often attractive targets for attackers. This necessitates continuous investment in advanced security infrastructure, ongoing monitoring, and regular software updates [54].

A particular aspect of confidentiality is the anonymisation and de-identification of data. These processes, which remove patients' identifiable information, are essential to enable the use of data for research or educational purposes without compromising individual identity [48]. However, the process can be complex and requires sophisticated algorithms to avoid the risk of re-identification [55], [56]. The management of security and confidentiality is not only a technical matter but also an organisational one, requiring clear policies, staff training, and compliance with current regulations [48], [57]. Any gap in this area can undermine trust in AMTs and slow down their adoption [58].

3.3 Organisational and Human Barriers: Lack of Technical Expertise, Medical Staff Resistance to Change, Lack of Adequate Infrastructure

Lack of technical expertise

The integration of AMTs into neurosurgical imaging imposes new and complex requirements on the technical expertise of medical staff. Handling sophisticated equipment, interpreting advanced images, and using specialised software requires a deep understanding not only of medical principles but also of technological ones. The lack of this expertise can lead to suboptimal use of technologies, operational errors, and even rejection of adoption [22], [59]. Traditional medical staff, although excellent in their field, may initially lack the digital and technological competencies required to fully leverage AMTs [60]. This underscores the need for continuous training and education programs that go beyond simple installation training sessions [61]. Developing customised training programs tailored to the specific needs is crucial for ensuring successful integration and safe utilisation of these technologies [62]. A relevant study indicates that physicians are insufficiently prepared for new technologies, which limits their ability to utilise these tools [63] entirely. This lack of technological competencies can lead to medical errors and psychological barriers in adopting modern solutions [63]. In the absence of adequate technical expertise, medical institutions may be compelled to outsource technical support, resulting in additional costs and dependency on external providers.

Medical Staff Resistance to Change

Another significant obstacle to the adoption of AMTs is the resistance to change from medical staff. Changing established workflows, adopting new procedures, and the need to learn new skills can generate discomfort, anxiety, and opposition [64]. This resistance can stem from various factors, including fear of the unknown, perceived increased complexity, uncertainty about the real benefits of new technologies, lack of trust in health systems, or fear of being replaced by machines [19], [61]. A relevant study found that some medical professionals considered that technology would interfere with their ability to make independent diagnoses and with patient relationships [64]. User resistance is a key factor responsible for the failure of digital innovations [65]. Managing resistance to change requires a strategic and empathetic approach. Clear communication of the benefits of AMTs, active involvement of medical staff in the selection and implementation process, ensuring continuous support, and creating an environment that encourages innovation are key elements [64]. Strategies such as co-design with clinicians, mentoring programs, and transparent communication are critical for fostering trust and acceptance [66]. Clinic or hospital leaders play a crucial role in promoting a constructive culture that embraces change as an opportunity for growth and improvement [67]. Visionary and adaptable leaders are essential in establishing constructive cultures and shaping the future of medical care. Failure to address resistance to change can lead to partial or failed implementation of AMTs, even in the presence of indisputable technological benefits [68].

Lack of Adequate Infrastructure

Any AMT, whether hardware- or software-based, depends on robust and adequate IT and physical infrastructure to operate at maximum capacity. The lack of sufficient infrastructure represents a significant barrier to efficient adoption [17], [69]. This includes a series of aspects.

Table 2. Development of the infrastructure elements necessary for implementing Advanced Medical Technologies

Development of the necessary infrastructure		
1	*IT and network infrastructure*	Advanced imaging technologies generate massive volumes of data. An undersized network with insufficient bandwidth or high latency can hinder the fast and efficient transfer of images, which is essential for timely diagnosis and surgical planning. Additionally, data storage capacity must be expanded and secured to manage medical image archives over the long term [70].
2	*Compatible hardware and software*	TMAs often require specialised hardware, compatible operating systems, or other software. Outdated or inadequate infrastructure can lead to incompatibilities, reduced performance, and a frustrating user experience. Often, hospitals in developing countries face substantial limitations, including insufficient access to essential diagnostic tools and outdated surgical equipment [17].
3	*Physical spaces and utilities*	Advanced medical equipment requires dedicated physical spaces with specific requirements for power supply, air conditioning, radiation protection and internet connection. The lack of such facilities, or the difficulties in modernising existing ones, can impede the acquisition and installation of new technologies. Inadequate infrastructure hinders innovation and entrepreneurship in the tech sector [71].

Without adequate infrastructure, the potential benefits of AMTs cannot be fully realised, and investments in these technologies risk underutilisation or inefficiency [17]. Therefore, strategic infrastructure planning is as essential as technology selection.

4. RESULTS: PERSPECTIVES FROM THE FIELD

This section presents a synthesis of qualitative data from semi-structured interviews with healthcare administrators, clinicians, and IT professionals. The thematic analysis of these interviews revealed essential perspectives on the challenges and opportunities associated with the adoption of non-AI Advanced Medical Technologies in neurosurgical imaging, complementing and contextualising the barriers identified in the specialist literature review. These discussions highlighted the complexity of technological adoption, emphasising the interconnected role of organisational, human, and technical factors in the success of implementation [72], [73]. In addition, variability in evaluation and implementation capacity across medical centres was highlighted, directly influencing the pace and effectiveness of technology integration [17].

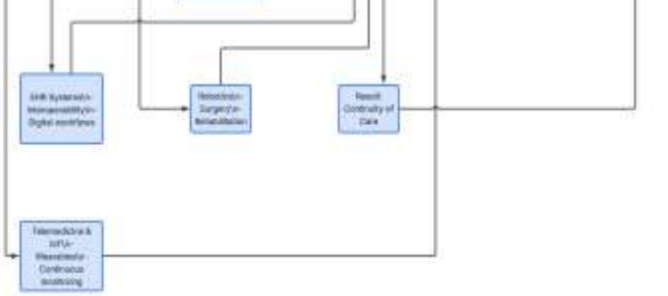

Figure 2. Representative diagram of the use of Advanced Medical Technologies

4.1 Administrators' Experience: Focus on Budgeting, Strategic Decisions, and Efficiency Pressure

Healthcare administrators, including hospital managers and medical directors, highlighted several major concerns regarding the adoption of AMTs, primarily centred on financial and strategic considerations. Budgeting was unanimously recognised as a fundamental challenge. Interviewees emphasised that "initial acquisition costs are often astronomical and represent a major obstacle, especially for public hospitals with limited budgets" [74]. These costs do not refer only to the actual purchase of equipment or software, but also to ancillary expenses for infrastructure, installation, and staff training. A hospital manager mentioned that "often, after the initial budget is allocated for acquisition, long-term costs are underestimated, such as those for maintenance, consumables, and software updates, which can amount to 10% of the system's selling price annually, plus costs for parts and services" [75], [76].

Strategic decisions regarding investments in AMTs are highly complex and involve a delicate balance among the need to provide high-quality medical services, the pressure to remain competitive, and financial constraints. Hospital managers recognised the importance of "keeping up with innovation" to attract patients and elite specialists. Still, they emphasised the difficulty of justifying these investments without a clear and quantifiable Return on Investment. "Benefits, such as improving patient outcomes and increased safety, are intangible in the short term and difficult to translate into financial figures that convince the board of directors or funders" [77], [78], [79]. This lack of clarity regarding ROI creates reluctance to allocate significant resources.

Pressure from operational efficiency was another recurring theme. Hospital managers seek AMTs that not only improve the quality of medical care but also optimise workflows, reduce waiting times, streamline resource utilisation, and ultimately increase the number of patients treated. However, they observed that "often, the integration of new technologies, if not properly planned, can disrupt existing workflows and lead to a temporary decrease in efficiency, generating frustration among staff and additional costs"[22]. The need to ensure compliance with strict medical data regulations adds another level of complexity, requiring investments in security systems and specialised personnel. "Any security breach can have disastrous consequences, both financial and reputational", [54] stated an IT manager with administrative responsibilities. These perspectives underscore the essential role of administrators in navigating the complex landscape of AMT adoption, where financial and strategic decisions have a profound impact on the institution.

4.2 Clinicians' Experience: Impact on the Doctor-Patient Relationship, Learning Curve, Technology-Induced Professional Burnout

The clinicians' perspective, particularly that of neurosurgeons and radiologists, provided insight into the direct and personal impact of AMTs on their daily practice. A central aspect of the discussions was the impact of technology on the doctor-patient relationship. On one hand, clinicians appreciated the "ability of AMTs to provide a more accurate diagnosis and enable safer and less invasive interventions, which translates into increased patient trust and improved clinical outcomes" [80]. The possibility of presenting patients with detailed 3D images of the pathology and surgical plan was considered a significant advantage for communication and trust-building.

On the other hand, there was also concern that "excessive dependence on technology could dilute the human aspect of medical care”, transforming the doctor more into a machine operator. Some neurosurgeons expressed worry that "the time spent with the technological interface could reduce direct interaction time with the patient", affecting empathy and understanding of the human context of the disease [81].

The learning curve associated with new AMTs was a dominant theme. Clinicians acknowledged that "mastering complex neuronavigation systems, surgical robotics, or advanced visualisation software requires considerable effort and extensive practice time" [82]. A radiologist emphasised that "interpreting images generated by new imaging modalities requires specialised expertise not covered by initial training and necessitating continuous courses and training" [63]. The lack of technical expertise manifests directly in this steep learning curve. Some clinicians felt overwhelmed by "the large number of new technologies and the pressure to integrate them rapidly into practice without sufficient time or resources to learn them efficiently" [63].

This constant pressure to adapt to new technologies was associated with professional burnout. "The feeling of being in a perpetual race to learn and adapt to new tools can be exhausting, adding to the already high stress levels in the medical profession," stated a clinician. Resistance to change [64] observed among some colleagues was also a source of tension, with innovative clinicians feeling that "the inertia of the system or more reluctant colleagues slows progress and limits the widespread adoption of beneficial technologies." This aspect confirms the importance of change management and clinical leadership [66].

4.3 IT Professionals' Experience: Technical Integration Challenges and User Support

The interviewed IT professionals provided a crucial perspective on the technical challenges inherent in adopting AMTs, particularly regarding integration and ongoing support. The most frequently cited obstacle was system interoperability. "Hospitals use a multitude of IT systems from different suppliers, and new AMTs must communicate seamlessly with existing PACSs, RISs, EHRs, and other applications, which is extremely difficult" [17], [45]. An IT engineer described the situation as "a complex puzzle, where each piece comes from a different manufacturer and does not fit perfectly with the others" [46]. This lack of interoperability often forces IT departments to develop customised solutions and "bridges" for integration, which are costly, time-consuming, and error-prone. "Standards such as DICOM help, but their implementation varies, and many legacy systems do not fully comply with them, creating isolated data islands" [3].

Data security and patient confidentiality represented another primary concern. IT professionals are responsible for protecting large volumes of sensitive medical data, and the adoption of new AMTs introduces additional vulnerabilities. "Each new system or software integrated expands the potential attack surface," explained a cybersecurity specialist. "We must ensure that data is encrypted in transit and at rest, that access is strictly controlled through multi-factor authentication, and that all systems comply with the regulations in force." The continuously evolving cyber threats require constant monitoring and proactive security updates, which impose enormous pressure on IT teams with often limited resources [54].

User support was identified as a significant operational challenge. IT professionals are the first line of defence when clinicians encounter issues with AMTs. "The steep learning curve for medical staff translates into numerous technical support requests, ranging from connectivity problems to using complex features" [63]. They emphasised the need for extensive and ongoing training programs, not only at installation, to reduce the volume of support requests and enable clinicians to use the technologies efficiently. "The lack of adequate technical expertise among end users leads to sub-optimal system utilisation and frustration" [63], as noted by IT support technicians.

The lack of adequate infrastructure was also frequently reported. Advanced equipment often requires high-speed networks, extensive storage spaces, and powerful servers. "IT infrastructure upgrades are costly and time-consuming, and funding for them is often a battle, even though it is essential for the proper functioning of AMTs" [17], [83]. Despite the revolutionary promise of advanced medical technologies in neurosurgery, their effective implementation hinges substantially on the capacity of IT departments to navigate intricate technical challenges and deliver reliable, proficient support [3], [17], [74].

5. STRATEGIES FOR SUCCESSFUL INTEGRATION

Building on the in-depth analysis of the barriers and on-the-ground perspectives presented in the previous chapters, it is evident that the effective integration of non-AI Advanced Medical Technologies into neurosurgical imaging requires a strategic, proactive, and multidimensional approach. The mere acquisition of state-of-the-art equipment does not guarantee success; a robust practical framework is needed to address the identified financial, technological, organisational, and human challenges. This section proposes a set of interconnected strategies to facilitate the harmonious and sustainable integration of AMTs, translating their potential into tangible benefits for patients, clinicians, and medical institutions.

Synthesis of Literature and Interviews - Proposal of the Practical Framework

The experiences of administrators, clinicians, and IT professionals, corroborated by findings from the specialised literature, emphasise that the adoption of AMTs is a complex process that extends beyond the purely technical sphere. Success depends equally on rigorous financial planning, adequate technical infrastructure, well-developed human expertise, and an organisational culture open to change. Thus, the practical framework proposed here is based on the synergy among these elements and aims to guide healthcare decision-makers. Each strategy detailed in the following subsections is grounded in the need to address specific obstacles and to maximise potential benefits.

5.1 Needs Assessment and Planning: The Importance of the Initial Audit

Any initiative to adopt AMTs must begin with a thorough needs assessment and be accompanied by detailed strategic planning. This is a critical, often underestimated, yet essential stage for aligning technological investments with the institution's clinical and operational objectives [84]. A complex initial audit should include, as seen in Table 3.

Table 3. Assessment of the needs for the implementation of Advanced Medical Technologies

Audit		
1	*Clinical needs analysis*	Accurately identifying clinical problems that can be solved or improved by introducing new technology. In neurosurgery, this can mean improving the accuracy of lesion localisation for surgical indication, reducing intervention time, or increasing surgical safety. The direct involvement of neurosurgeons and radiologists at this stage is fundamental to ensuring the clinical relevance of the proposed solutions.
2	*Assessment of existing infrastructure*	A detailed analysis of the current IT and physical infrastructure is indispensable. This includes network capacity, data storage systems, compatibility with DICOM [3] and PACS [3] standards, and available physical space. Identifying infrastructure gaps before acquisition enables effective planning and budgeting for necessary upgrades, thereby preventing unforeseen costs and delays in implementation.
3	*Human Resources Analysis*	Assessing the current level of technical expertise of medical and IT staff is crucial. This enables the estimation of training needs and the development of targeted training programs to address the identified shortcomings [63].
4	*Assessing the impact on workflows*	Any new technology will influence the way activities are carried out. Planning should include an analysis of how TMA will be integrated into existing workflows, identifying potential bottlenecks and opportunities for optimisation. This may require a redesign of processes or even a restructuring of teams.
5	*Risk analysis*	A proactive assessment of the risks associated with TMA implementation enables the development of adaptation strategies at an early stage [54].

By implementing a comprehensive initial audit, healthcare institutions can substantially mitigate uncertainty, prevent unwarranted financial commitments, and establish a robust foundation for the effective incorporation of AMTs [84].

6. CONCLUSIONS

This paper has explored the challenges and strategies for the efficient adoption of non-AI Advanced Medical Technologies in neurosurgical imaging, providing a comprehensive perspective on the encountered barriers and practical solutions. By integrating specialised literature analysis with the valuable perspectives of hospital managers, clinicians, and IT professionals, the study highlighted the complexity of the implementation process. It emphasised that success does not depend solely on the intrinsic quality of the technology, but also on a holistic strategic framework. In particular, the findings underscore that successful integration depends on an interdisciplinary approach, robust change management, and a deep understanding of interoperability challenges [85]. This underscores the need to develop interoperability strategies to facilitate data exchange, which is essential for improving patient outcomes and operational efficiency in the healthcare system [85]. Without such interoperability, the full potential of AMTs, particularly in precision and safety, remains unrealised [3].

With the rapid technological advances, it is imperative to continuously investigate the long-term impact of AMTs on clinical outcomes, as well as to explore new human-machine interaction paradigms in the context of neurosurgery. In addition, future research should focus on integrating Advanced Medical Technologies with artificial intelligence and augmented reality to improve surgical precision and efficiency, as well as on the long-term evaluation of clinical outcomes [8].

6.1 Summary of the main findings: Technology alone is not sufficient without an implementation strategy

The study confirmed that Advanced Medical Technologies in neurosurgical imaging, although offering extraordinary potential for improving diagnosis, surgical precision, and patient outcomes [43], face significant obstacles that hinder their widespread adoption and integration. These barriers have been classified into three main categories: financial, technological, and organisational/human.

From a financial perspective, we observed that, despite the evident clinical benefits, the initial acquisition costs of AMTs are often prohibitive, and long-term maintenance and operation costs are frequently underestimated. The difficulty of quantifying a clear and immediate Return on Investment, especially for intangible benefits, generates reluctance to allocate the necessary funds [86]. Examples such as robotic neuronavigation systems perfectly illustrate these financial challenges.

The technological barriers are primarily centred on the interoperability of medical IT systems and data security. The absence of smooth and standardised communication between various systems leads to information fragmentation and inefficiency. In addition, the massive volume of sensitive medical data generated by AMTs poses significant security and confidentiality challenges, necessitating ongoing investments in robust infrastructure and strict compliance with applicable regulations [52], [87].

The organisational and human barriers have highlighted that the human factor is as critical as the technology itself. The lack of adequate technical expertise among medical staff and the steep learning curve necessitate continuous, tailored training programs. Finally, resistance to change among medical staff, fueled by fear of the unknown, perceived complexity, or uncertainty about benefits, constitutes a significant impediment. This resistance can lead to sub-optimal use of technologies and professional burnout among clinicians [66].

Our findings underscore a fundamental point: technology alone is insufficient. The success of integrating AMTs is not assured merely by acquiring the latest equipment or software. Without a comprehensive implementation strategy that proactively addresses each of these barriers—financial, technological, organisational, and human—the transformative potential of AMTs remains unrealised. Such a strategy must be multidimensional, encompassing rigorous strategic planning, sustainable financial models, continuous education and training programs, efficient change management, visionary leadership, and an interdisciplinary implementation approach.

6.2 Practical Implications: Final Recommendations for Healthcare Managers

Based on the findings and discussions from the previous chapters, we formulate a series of practical recommendations addressed to healthcare managers, hospital administrators, decision-makers, and clinicians, aimed at facilitating the successful integration of AMTs in neurosurgical imaging:

Table 4. List of recommendations for the adoption of Advanced Medical Technologies efficiently

Recommendation			
1	*Prioritising Needs Assessment and Strategic Planning*	**Conducting a rigorous initial audit**	It must identify specific clinical needs, assess existing infrastructure, analyse staff technical expertise, and anticipate the impact on workflows [74]. This audit must be a collaboration between clinicians, IT and management.
		Development of a detailed implementation plan	It must include clear objectives, measurable milestones, and relevant performance indicators, along with a transparent communication strategy.
2	*Adopting Sustainable Financial Models*	**Conducting an extensive cost-benefit analysis**	It must quantify not only operational savings, but also long-term intangible benefits. Please ensure that you look for externally validated evidence of ROI [78].
		Diversification of funding sources	This can be achieved by exploring grants, public-private partnerships, operational/financial leasing and fundraising campaigns.
		Implementing a lifecycle budget	This must cover not only the purchase but also the maintenance, consumables, upgrades, and, where applicable, decommissioning of equipment.
		Collaborations with multiple authorities	This can ensure adequate reimbursement for procedures performed under the new TMAs.
3	*Investing in Continuing Education and Training*	**Development of customised training programs**	This aspect is necessary for all user categories and extends beyond the initial sessions, encompassing regular workshops, online courses, and simulations.
		Creating a network of overqualified specialists	To promote internal mentorship, facilitate knowledge transfer, and reduce the learning curve [63].
4	*Implementing Effective Change Management and Visionary Leadership*	**Achieving a clear and compelling vision**	To understand the benefits of TMAs and communicate them transparently to all staff [8].
		Active involvement of medical staff	Necessary in selection and implementation processes, reducing resistance to change [66].
		Proactive approach to sources of resistance	Through active listening, offering solutions and building trust. Promoting a culture of innovation and continuous learning.
		Providing psychological support	Necessary for staff in transitional times, recognising that adapting to new technologies can generate stress.
5	*Promoting Interdisciplinary Approach and Collaboration*	**Create a Joint Implementation Team**	Obligatory to include representatives from all relevant departments: clinicians, IT, administrators, quality management experts and intellectual property experts [46].
		Establishing clear roles and responsibilities	Within these teams, it is also necessary to encourage effective communication and consensual decisions.
		Development of standardisation working groups	They need to address interoperability challenges, particularly regarding implementation and compliance with DICOM standards [3].

By consistently applying these strategies, medical institutions can transform the complex challenges associated with AMT adoption into opportunities for growth and innovation, while ensuring the best possible outcomes for patients and an optimised work environment for medical staff.

6.3 Study Limitations and Future Directions: What the Study Did Not Cover and What Should Be Researched in the Future.

Although the present research has provided a valuable perspective on the adoption of AMTs in neurosurgical imaging, it is essential to acknowledge certain limitations and to identify directions for future studies.

Study Limitations

- **Focus on Non-AI Technologies:** The study focused exclusively on non-AI AMTs, deliberately excluding artificial intelligence-based technologies. This represents a limitation, given the exponential growth of AI applications in medicine and neurosurgery, which present their own challenges and opportunities.
- **Specific Geographic and Institutional Context:** Although we aimed to generalise the findings, the qualitative data were collected from a particular sample of participants, predominantly from the

Romanian context. Experiences and challenges may vary across healthcare systems, available resources, and institutional cultures in other regions or countries.

- **Cross-Sectional Nature of the Study:** Being a cross-sectional study, it could not track the evolution of barriers and strategies over the long term or the specific impact of interventions. We could not assess ROI over an extended period or analyse how resistance to change evolves following the implementation of specific strategies.
- **Predominance of Qualitative Data:** Although the methodological approach was mixed, the analysis of results placed a detailed emphasis on qualitative data. Quantitative validation of some findings through statistical analysis of a larger sample could enhance generalizability.
- **Interview Sample:** Although diverse, the relatively small number of interviews may limit the full generalizability of the perspectives.

By addressing these future directions, the academic and practical communities can deepen understanding of the complexities of integrating AMTs into neurosurgical imaging, thereby contributing to the development of more efficient solutions and strategies for a future of medical care grounded in innovation and excellence. These explorations should include the investigation of advanced technologies such as augmented reality, which, alongside AI, promises to revolutionise preoperative planning, intraoperative navigation, and postoperative evaluation, enhancing the precision and safety of neurosurgical interventions [8]. Furthermore, it is crucial to examine how artificial intelligence can improve the management of large volumes of imaging data, facilitating rapid diagnosis and personalised treatments while simultaneously reducing the cognitive burden on medical staff. Standardising protocols and continuous training of medical staff will be essential to ensure consistent results and maximise the benefits of these advanced technologies.

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