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Human-Machine Interfaces in Health: A Critical Review and Framework of Human-Centered Design Practices

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Abstract. The design of human-machine interfaces (HMIs) in healthcare is a determining factor for the safety, efficiency, and accessibility of medical technologies worldwide. This article presents a structured review of the scientific and regulatory literature published to 2025, with the main objective of identifying the principles, limitations, and best practices applicable to the development of interactive systems in the healthcare sector. This analysis integrates a range of contributions from biomedical engineering, cognitive ergonomics, and user-centered design, highlighting key challenges associated with technological complexity and user diversity. Based on this review, a best practice framework is proposed, consisting of four pillars: visual design, interaction and control, accessibility and inclusion, and continuous evaluation. This framework translates international standards into a series of operational actions that strengthen patient safety and promote a more humanistic and inclusive design focused on the user. The results presented here demonstrate the need to consolidate a set of interdisciplinary methodologies that guarantee usability and equity in technological innovation in health.

Keywords: human-machine interfaces; usability; accessibility; user-centered design; digital health; patient safety

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1 Introduction

Technological advances in the healthcare sector have drastically transformed the existing relationship between human beings and the automated systems used for the diagnosis, monitoring, and treatment of diseases worldwide. In this context, human-machine interfaces (HMIs) constitute an element of central importance for the interaction among healthcare professionals, patients, and technological devices for medical use. The proper design of these interfaces determines not only effectiveness and safety, but also the acceptability of healthcare technologies at all levels. The quality of interaction depends not only on technical components but also on cognitive, perceptual, and ergonomic factors that condition the user experience (Norman, 2013). Janß et al. (2021) highlight in their research the importance of standardizing user interface profiles in surgical environments, with the purpose of ensuring reliable and safe interaction.

The concept of the human-machine interface has been consolidated as a multidisciplinary axis that integrates knowledge from engineering, ergonomics, cognitive psychology, and industrial design. From the healthcare field, these interfaces are created with the purpose of responding to a series of specific conditions, such as the high responsibility associated with clinical decision-making, the diversity of users (physicians, nurses, patients, caregivers), and the need to minimize errors derived from the improper

use of technological devices. According to Johnson et al. (2024), human-computer interaction in medical devices requires the integration of cognitive principles that optimize real-time decision-making. For his part, Nielsen (1993) mentions in his studies that interactive systems should be designed to promote usability, efficiency, and user satisfaction, principles that acquire special relevance when applied in critical clinical environments.

The idea of user-centered design has become established as a fundamental methodology for the development of medical devices and telemedicine systems in many research centers and industry settings. This strategy promotes a deep understanding of users' needs, limitations, and capabilities, which makes it possible to anticipate a set of operational solutions to interaction problems prior to implementation (ISO 9241-210:2019). Shahraki and Nafchi (2023) argue in their research that HMI systems are essential components in the management and control of medical devices, given that they directly influence clinical safety. However, studies have shown that shortcomings persist in the systematic application of these principles, which translates into confusing interfaces that entail cognitive overload and, therefore, potential risks to patient safety (Carayon et al., 2006).

At present, the adoption of technologies such as multiparameter monitors, electronic health record systems, and home care assistance devices requires a critical review of the way in which HMIs are currently conceived. This adoption demands a balance between technological complexity and ease of use Shneiderman & Plaisant (2010), as the diversity of platforms, user heterogeneity, and increasing automation pose significant design challenges. Poor design can lead to interpretation errors, delays in clinical response, or loss of information relevant to healthcare. Singh and Malviya (2023) emphasize in their work that alignment between interface design and patient safety constitutes a central requirement in contemporary medical devices.

The interest in improving interfaces in healthcare is not limited to operational efficiency; it also prioritizes responding to an ethical and humanistic perspective. Accessibility, inclusion, and patient autonomy are essential dimensions in the development of healthcare technologies today. Designing human-machine interfaces that consider users with visual, auditory, or motor disabilities contributes to more equitable and safer care (Kushniruk & Borycki, 2008). This vision aligns with the commitment of biomedical engineering and technological design to promote solutions centered on the dignity and well-being of individuals. Safety in use is a fundamental aspect of this type of technology, in which material selection, interface design, and development processes are of great importance in medical devices (Wiklund et al., 2015). The patient must have the certainty of being able to perform tasks effectively, comfortably, and efficiently, with the assurance that risks are minimal (Cummings, Roff, Cukier, Parakilas, & Bryce, 2018).

In this sense, the present work aims to critically analyze the recent literature on design of human-machine interfaces in the healthcare domain and to propose a framework of best practices that can be used to guide specialists, designers, engineers, and healthcare professionals in the creation of safer, more intuitive, and more accessible technological systems. Based on a structured review, theoretical, regulatory, and technical principles are systematized, allowing for the identification of factors that favor or hinder effective interaction between humans and machines in clinical and domestic environments. Figure 1 shows the conceptual framework for the fundamental objectives of HMIs design in the healthcare setting, which includes aspects such as: *i)* patient safety, *ii)* cognitive efficiency, and *iii)* responsible innovation.

Fig. 1. General objectives of the study on human-machine interfaces in the health field.

Figure 1 synthesizes the general objectives that guide the development of the present work, which reflect the convergence of three fundamental dimensions of medical-technological interface design: patient safety, cognitive efficiency, and responsible technological innovation. The first refers to the need to ensure that every interaction between the user and the system contributes to reducing clinical errors and strengthening the operational reliability of medical devices at any level. The second dimension, which is linked to cognitive ergonomics, highlights the importance of optimizing the mental processes of perception, memory, and decision-making through intuitive, coherent, and visually clear interfaces. Finally, technological innovation is understood not only as the development of new digital tools, but as the ethical and sustainable integration of solutions that respond to the real needs of healthcare professionals and patients. Taken together, these axes constitute the conceptual framework that guides the critical analysis of the literature and the proposal of good practices presented in this study.

2 Theoretical Background and State of the Art

The evolution of human-machine interfaces has been closely linked to the development of technology and interactive computer systems. From their earliest applications at the industrial level to their incorporation into clinical environments, HMIs have evolved from mechanical control instruments to becoming platforms for cognitive interaction that facilitate communication between the user and technology. In the healthcare domain, this transition has made it possible to integrate advanced diagnostic, monitoring, and therapeutic devices into digital networks capable of recording, processing, and representing biomedical information in real time. Leong et al. (2023) highlight in their research that human-machine interaction applied to biomedical manufacturing shares foundations with medical systems, particularly in the integration of sensors and intelligent control. Such progress requires that HMIs design consider both the physiological and cognitive processes of the user, as well as the limitations of the hardware and software systems involved in the process (Norman, 2013).

The theoretical and conceptual framework of HMIs in the healthcare field is grounded in usability, understood as the extent to which a system can be used by specific users to achieve specified goals with effectiveness, efficiency, and satisfaction (Nielsen, 1993). These principles were later incorporated into international standards, such as ISO 9241-210:2019, in which the user-centered design approach is formalized. This standard explicitly establishes that the design process must be based on an explicit understanding of tasks, contexts of use, and user characteristics. In the clinical environment, where precision and speed are decisive, these criteria are essential to reduce errors, improve safety, and increase healthcare professionals' trust in the technology they use daily.

Some studies in biomedical engineering have demonstrated that use errors associated with inadequate interfaces are responsible for critical consequences for patient care. Carayon et al. (2006) emphasize in their work that design failures in medical devices often originate from a lack of alignment between system requirements and the actual capabilities of the end user. The Systems Engineering Initiative for Patient Safety (SEIPS) model proposed by these authors integrates the analysis of working conditions, interaction processes, and health outcomes, offering a holistic view of the hospital sociotechnical system. Applying this model to HMI design makes it possible to anticipate risks, improve operational efficiency, and always strengthen patient safety.

The specialized literature on this topic agrees that cognitive ergonomics plays a crucial role in achieving the effectiveness of human-machine interfaces in medical applications. Shneiderman & Plaisant (2010) state in their manuscript that design should facilitate clear perception of information to enable rapid decision-making, while consistently promoting the reduction of mental workload. Aspects such as control layout, visual hierarchy, color, contrast, and immediate feedback are determining variables in the quality of the user experience. In the hospital environment, as well as in healthcare settings where operators face multiple simultaneous stimuli, an intuitive and predictable interface helps minimize stress and prevent serious operational errors.

In recent years, the expansion of digital health and portable devices has extended the scope of HMIs beyond medical institutions. Teleassistance systems, personal monitors, and mobile health applications require designs capable of adapting (without losing robustness) to non-specialized users, since older adults or individuals with sensory limitations are often the ones who end up handling these technologies. Kushniruk and Borycki (2008) emphasize in their manuscript that the adaptation of visual language, the simplicity of instructions, and accessibility constitute indispensable requirements to ensure the effective adoption of this class of technologies. This trend reinforces the need to develop inclusive design frameworks that consider the cultural and functional diversity of users.

The current state of research and technology shows that, although multiple conceptual and regulatory frameworks exist, the practical application remains fragmented, as gaps persist in the systematic evaluation of the usability of medical devices, especially in-home environments. Likewise, a gap is observed between theoretical recommendations and the reality of industrial design, in which decisions often prioritize economic or market criteria over safety and accessibility. In this sense, the present work seeks to

contribute to closing this gap through a critical review that synthesizes the main contributions of the literature and proposes a framework of best practices aimed at the comprehensive improvement of human-machine interface design in healthcare (Dutta and Dhar, 2025).

3 Methodology

The present work is framed within a structured review, whose purpose is to critically analyze the scientific and technical literature related to the design of human-machine interfaces applied to the healthcare sector. This approach allows the integration of dispersed information across different domains (biomedical engineering, cognitive ergonomics, interaction design, and digital health) to construct a comprehensive view of the advances, limitations, and challenges in the field. Unlike systematic reviews that have already been reported, the narrative method facilitates an interpretive synthesis of the findings, which prioritizes conceptual understanding and the identification of design patterns and best practices that may be useful for professionals and researchers. Unlike systematic reviews, this structured narrative review does not employ a PRISMA protocol; however, the selection process followed explicit inclusion and exclusion criteria applied consistently across sources retrieved from Scopus, Web of Science, and PubMed.

The information gathering for this study was carried out by considering research published to 2025. The main academic, regulatory, and technical sources were included, obtained through indexed databases institutional documents from international organizations such as the World Health Organization (WHO) and the International Organization for Standardization (ISO). In addition, technical manuals, user-centered design standards (ISO 9241-210:2019), and relevant conceptual frameworks were reviewed, such as the SEIPS model, which guides the analysis of sociotechnical systems in hospital environments (Carayon et al., 2006).

To ensure the effectiveness of the research and review, a keyword-based search strategy was proposed using terms such as human-machine interface, usability, healthcare technology, patient safety, medical device design, and user-centered design. The results were limited to publications addressing person-technology interaction in contexts exclusively related to healthcare design and use. In this way, the references were initially identified, from which a sample was selected that met the inclusion and exclusion criteria described below.

Articles and documents that met the following requirements were included:

1. Having been published in peer-reviewed journals or issued by recognized regulatory bodies.
2. Explicitly addressing the design, usability, or accessibility of medical devices or clinical information systems; and
3. Presenting empirical evidence, reviews, or theoretical models applicable to the healthcare context.

It is important to note that studies focused exclusively on industrial automation processes, robotics without human interaction, or technologies unrelated to healthcare delivery were excluded. This action made it possible to refine the selection and retain only those sources relevant to the analysis of user-centered design and patient safety.

At this stage of the investigation, the analysis of sources was conducted in three complementary phases, which are generally described as follows. First, an exploratory reading was carried out to classify the sources according to their approach (theoretical, regulatory, or applied). Second, an analytical reading was conducted, aimed at identifying emerging conceptual categories from each text, such as usability, cognitive ergonomics, accessibility, multimodal feedback, and user evaluation. Finally, an interpretative synthesis was developed, which made it possible to link the results of different authors with current international guidelines associated with design and practical implications for the development of healthcare-oriented HMIs. This process ensured the internal coherence of the review and the traceability of the conclusions.

To ensure the validity of the process, the information was contrasted between primary and secondary sources, verifying the consistency of concepts and the correspondence among the theoretical models reviewed. In addition, conceptual triangulation was applied by comparing the principles derived from the literature with international regulatory frameworks. This procedure made it possible to identify convergences and divergences between design practice and current regulations, thereby strengthening the credibility of the review and the relevance of the proposed framework of best practices.

4 Critical Review of the Literature on Human-Machine Interfaces in Healthcare

The analysis of the literature developed in this work reveals that the design of human-machine interfaces in the healthcare domain has evolved toward an increasingly complex integration of biomedical engineering, ergonomics, and medical informatics. This convergence responds concretely to the need to generate systems capable of processing large volumes of clinical information without sacrificing visual clarity or the ease of interpretation of the information provided by the interface. Norman (2013) notes in his research that the effectiveness of an interface depends on the coherence between its functional architecture and the cognitive expectations of the user. In hospital environments and health-related scenarios, where decisions must be made under pressure and within very short time frames, such coherence can translate into safety and efficiency. A large proportion of the reviewed studies agree that use errors do not originate exclusively from a lack of training, but also from design flaws, which increase mental workload and reduce operational accuracy. Yilmaz et al., (2022) demonstrate that the application of user interface profiles makes it possible to reduce variability in the presentation of clinical information, thereby increasing operator accuracy.

In clinical healthcare settings, the usability of technological devices and human-machine interfaces have historically been associated with the system's ability to support the execution of healthcare professionals' tasks without generating distractions or ambiguities. Shneiderman & Plaisant (2010) highlight in their manuscript that the principles of consistency, immediate feedback, and user control are essential to maintaining trust and preventing errors. Carayon et al. (2006) reinforce this idea in their work through the SEIPS model (Systems Engineering Initiative for Patient Safety), by demonstrating that sociotechnical systems must be evaluated by simultaneously considering human, organizational, and technological factors. The reviewed case studies show that an inadequate arrangement of alarms or controls can lead to critical failures, even when personnel have extensive experience in the use of healthcare-dedicated technology. Hence the importance of incorporating heuristic evaluations and usability testing from the early stages of development. Yilmaz et al. (2025) expand this approach by integrating machine-readable interface requirements in interconnected surgical environments, strengthening interoperability and safety.

Data visualization constitutes another fundamental axis in design of medical HMIs. Current devices integrate multiple physiological variables on a single screen, which can lead to visual saturation and even hinder the rapid interpretation of trends. Nielsen (1993) suggests in his research that an effective interface should prioritize perceptual simplicity and the logical grouping of information. In coherence with this, various authors propose visual hierarchies that clearly distinguish levels of urgency and the type of parameter being monitored. In this context, alarm management is a recurring topic: when alarms are excessive or poorly differentiated, users tend to ignore them, a phenomenon known as alarm fatigue. Improving the visual and auditory prioritization of alerts is a good practice that reduces the likelihood of clinical errors and optimizes patient care.

With the growth and accelerated expansion of both telemedicine and wearable devices, HMIs have crossed the boundaries of the hospital to integrate into diverse environments, including domestic settings. This transition has implied rethinking all conventional design criteria, given that end users often lack adequate technical training and, in many cases, present varying levels of digital literacy. Kushniruk and Borycki (2008) argue that understanding the context of use of this class of technologies is decisive in avoiding adoption failures and even distrust toward them. In the home, an interface must be self-explanatory, error-tolerant, and compatible with the user's daily routines. Iconography design must be clear, with comprehensible text messages and multimodal feedback (visual, auditory, and haptic), which favors therapeutic adherence and patient autonomy. Tase et al. (2024) confirm in their manuscript that the usability perceived by patients in home medical technologies is a determining factor for their acceptance and sustained use.

In this same context, accessibility constitutes an essential component of inclusive design for medical-technological interfaces, since devices and systems must adapt to users with visual, auditory, or motor limitations, ensuring equal access to information and critical functions. According to ISO 9241-210:2019, a truly user-centered design requires consideration of the diversity of capabilities and contexts of use. The reviewed studies show that, although normative recommendations exist, compliance remains partial. Elements such as color contrast, font size, and the availability of auditory or tactile aids are aspects that are frequently underestimated. Promoting a culture of accessibility not only fulfills ethical principles but also increases the reliability and efficiency of HMIs in healthcare. Or, Holden, and Valdez (2022) emphasize that user-centered design and human factors are essential to ensuring effectiveness, efficiency, and satisfaction in mobile health technologies.

The combined analysis and evaluation of the literature show significant advances in both design methodologies and the integration of normative frameworks; however, important gaps persist between theory and practice. On the one hand, many developments continue without formal validation with real users or are limited to laboratory evaluations. On the other hand, both the absence and scarcity of standardized documentation on testing procedures can hinder objective comparisons between devices. In this regard, it can be observed that the adoption of models such as SEIPS and standards such as ISO 9241-210 has been uneven,

especially in low-cost devices, prototypes, or those produced outside the hospital environment. These deficiencies reveal the pressing need to promote interdisciplinary research capable of articulating design, engineering, and behavioral sciences, with the aim of developing continuous evaluation frameworks that guarantee the safety, usability, and sustainability of human-machine interfaces in the healthcare domain. Matias (2025) argues in his work that HMIs represent a point of convergence between technological innovation and organizational complexity, which demands a dual approach combining engineering and design ethics.

There are works that have focused on reviewing how the link between humans and machines is carried out in the healthcare domain, considering that advances in science and technology have drastically changed healthcare systems and the conditions under which experts interact with interfaces (Langote, Saratkar, Kumar, Verma, Puri, Gundewar, & Gourshettiwar, 2024). It is important to recognize that this field is dynamic, since these interfaces have evolved in such a way as to always be both practical and effective. When an interface is well designed, it can improve clinical work, foster communication, and safeguard decision-making, without overlooking the impact that the integration of emerging technologies will have on interface design in the healthcare sector (Amiri, 2024).

5 Framework of Good Practices in Design of Human-Machine Interfaces in Health

The design of HMIs intended for healthcare delivery requires a set of structured principles to guide developers, designers, and engineers in the creation of systems that are safe, understandable, and centered both on the user and on their needs. Based on the review of the literature and international standards on ergonomics and user-centered design (ISO 9241-210:2019), the authors of this document propose a framework of best practices that synthesizes the most relevant criteria for the planning, development, and evaluation of HMIs applied to clinical and domestic environments. It should be emphasized that this framework does not seek to replace existing standards, but rather to make them more operational, so that they become accessible and applicable in real-world projects, promoting convergence among theory, regulation, and medical design practice. As shown in Table 1, the proposed framework differs from existing standards in that it translates normative principles into concrete operational actions, extends applicability to domestic environments, and positions accessibility as a foundational design axis rather than an optional feature.

Table 1. Comparison of the proposed framework with existing reference standards.

Dimension	ISO 9241-210:2019	SEIPS model	Proposed framework
Scope	Interactive systems (general)	Hospital sociotechnical systems	Healthcare HMIs (clinical + domestic)
Validation focus	User-centered process	Work system & outcomes	Iterative heuristic + user testing
Accessibility	Recommended	Not explicit	Core pillar (Axis 3)
Operational guidance	Principles-based	Model-based	Action-based (concrete criteria)
Target audience	Designers/engineers	Researchers/managers	Engineers, clinicians, designers

Dakulagi et al. (2025), for their part, propose a set of techniques and recommended practices for developing intuitive and user-centered HMI, which aligns with the principles of the present framework (figure 2).

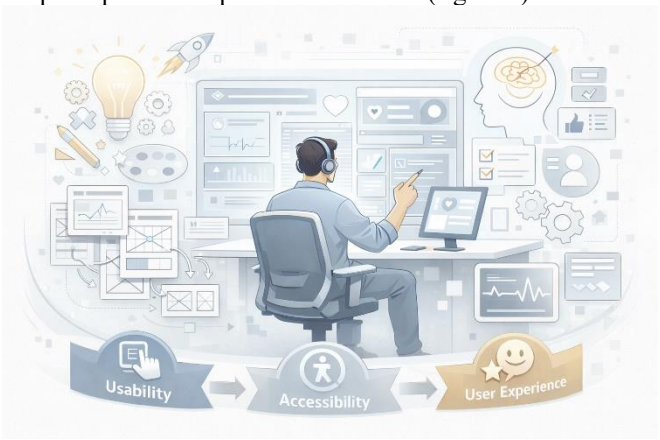

Fig. 2. Graphical representation of the human-machine interface design process (figure created by the authors with the assistance of AI-based image generation tools).

In Figure 2, a Human-Machine Interface designer is shown interacting with a digital interface, which is accompanied by visual elements that symbolize creativity, organization, and feedback. This figure reinforces the approach of the framework proposed in the present work, in which it is emphasized that HMI design for healthcare is a cognitive, technical, and iterative process that integrates usability, accessibility, and user experience.

The first axis of the recommendation framework focuses on the visual design of the interface, understood as the means through which critical information is conveyed to and from the user. It must not be overlooked that a medical HMI should prioritize legibility, adequate contrast, and a clear visual hierarchy to distinguish the levels of urgency of each monitored parameter and variable. Nielsen (1993) establishes in his research that consistency, visibility of system status, and error prevention constitute fundamental principles of usability. Accordingly, it is recommended to use high-contrast typography, avoid color overload, and maintain a spatial layout consistent with the logic of the clinical task. Visual and auditory redundancy (for example, using text and sound for alerts) increases system reliability and reduces the possibility of omitting critical information, especially in environments with high cognitive demand on the user.

The second axis addresses the operational interaction between the user and the machine. According to the research work of Norman (2013), interfaces should facilitate a clear action-evaluation cycle, in which the user understands the consequences of their actions and receives clear and immediate feedback from the system. In the healthcare context, this implies designing easily accessible commands, explicit confirmations for critical operations, and visual or auditory signals that indicate the status of the device and the variables being monitored. Carayon et al. (2006), for their part, highlight that interruptions, context changes, and an excess of alarms can affect the effectiveness of the sociotechnical system. For this reason, it is widely recommended to limit menu depth, simplify navigation paths, and establish priority levels for alarms, so that they enable more efficient management of clinical time and health status monitoring.

The third axis of the proposed framework is oriented toward universal accessibility, which is an indispensable element in the inclusive design of healthcare technologies. The ISO 9241-210:2019 standard emphasizes that the diversity of physical, sensory, and cognitive abilities must be considered from the initial stages of design. Consequently, it is suggested to incorporate interface personalization mechanisms (such as adjustment of font size, brightness, and contrast) and to offer multimodal interaction alternatives (such as voice, touch, or gestures). Kushniruk and Borycki (2008) underscore in their manuscript that accessible design not only expands the potential user base but also improves the overall experience and safety of use in any environment. These actions contribute to reducing technological barriers and promote equity in healthcare, aligning with the humanistic principles of biomedical engineering.

The fourth axis proposes an iterative and continuous evaluation of HMIs across all phases of development. Shneiderman & Plaisant (2010) indicate in their work that the design process should be cyclical: design, test, analyze, and redesign. During the validation stage, both heuristic tests conducted by experts and evaluations with representative users as a statistical sample should be included. Such tests make it possible to identify discrepancies between the designer's intent and the user's interpretation, as they constitute an opportunity to introduce improvements prior to final implementation. In this context, it is recommended to systematically document the results of each iteration, with the aim of generating cumulative evidence and facilitating knowledge transfer among design teams and regulatory bodies.

Complementarily, Table 2 presents an operational synthesis of the proposed framework, organized according to the axes addressed above, as well as the criteria and concrete actions that should be considered in design. The format of this table facilitates the application of the proposal of the present work in diverse contexts (ranging from simulation laboratories to hospital and domestic environments) and may serve as a reference for internal audits, training activities, or certification processes for devices under development. The integration of these guidelines contributes to ensuring that medical HMIs not only comply with technical or regulatory requirements, but also promote safe, intuitive interaction centered on the well-being of the end user.

Table 2. Framework of good practices for design of human-machine interfaces in health.

Axis	Main Criterion	Operational guidelines
1. Visual Design	Clarity and hierarchy of information	Use legible fonts; contrast ≥70%; hierarchy by color or size; avoid visual/auditory redundancy.
2. Interaction and Control	Immediate feedback and error prevention	Simplify menus; confirm critical actions; prioritize alarms; limit interruptions.
3. Accessibility and Inclusion	Adaptability to diverse abilities	Allow font/brightness adjustment; integrate voice or touch control; guarantee chromatic contrast.
4. Iterative and continuous evaluation	Design iteration and documentation	Perform heuristic and user testing; record results and corrective actions.

The application of this framework of good practices fosters an interdisciplinary and systematic approach to the design of medical-technological interfaces, as its adoption promotes interdisciplinary collaboration among engineers, designers, clinical professionals, and end users, thereby generating solutions that are better aligned with real contexts of use. In addition, it strengthens the culture of patient safety by preventing errors derived from interaction failures. The implementation of these guidelines makes it possible to align development projects with international quality standards, thereby optimizing resources and reducing costs associated with late-stage redesigns. Verma et al. (2025) warn in their manuscript that the security and privacy of human-machine interaction in healthcare must be incorporated as integral components of design, thus reinforcing the ethical dimension of the framework. In summary, the proposed framework constitutes a practical tool that translates theory and regulation into operational criteria applicable to responsible innovation in digital health.

Another important aspect that must be considered is the standard ISO 9241-210:2019, which focuses on improving effectiveness and is used to evaluate how effectively well-being, user satisfaction, accessibility, and sustainability are enhanced, while counteracting potential adverse effects of use on health, safety, and performance. In the case of HMI design in accordance with this standard, the following principles are key to a human-centered design approach:

- The design is based on an explicit understanding of users, tasks, and environments.
- Users are involved throughout the entire design and development process.
- The design is driven and refined by user-centered evaluation.
- The process is iterative.
- The design addresses the entire user experience.
- The design team includes multidisciplinary skills and perspectives.

There are four Human-Centered Design (HCD) activities that must be carried out during the design of an HMI in an interactive system, as shown in Figure 3. These include:

- Understanding and specifying the context of use.
- Specifying user requirements.
- Producing design solutions.
- Evaluating the design.

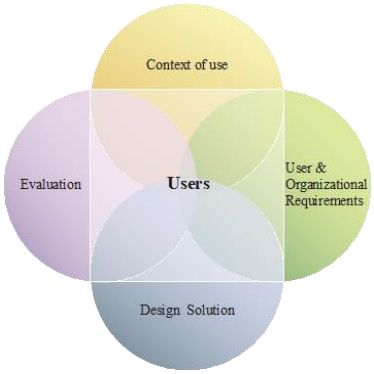

Fig. 3. Principles of the Human-Centered Approach.

The evaluation of HMI design should be conducted through multiple quantitative and qualitative user-centered evaluation methods. User-based testing and the use of standards and guidelines as inspection methods can be applied without the need for end users. Some of the human-centered research and design tools include, for example: heuristic evaluations and expert reviews, interviews with stakeholders and users, storyboarding, and surveys. Below, in Figure 4, an image of a medical HMI is presented, in which several clear advantages can be identified as a human-machine interface, aligned with principles of usability, cognitive ergonomics, and patient safety.

The human-machine interface illustrated in Figure 4 constitutes a representative example of how the principles established in the proposed best-practices framework can be materialized in a functional and safe medical HMI. Its analysis makes it possible to demonstrate the direct correspondence between the axes of the framework and the design decisions observed in the interface.

Visual design and information hierarchy: In accordance with the first axis of the framework, the interface presents a clear visual hierarchy that prioritizes critical clinical information. The numerical values associated with vital signs (heart rate, oxygen saturation, blood pressure, and respiratory rate) are displayed using large, high-contrast typography against a dark background. This strategy facilitates rapid reading and reduces cognitive overload in high-demand environments, aligning with the principles of clarity and visibility of system status.

Interaction and system control: The second axis of the framework is reflected in the functional arrangement of the interactive elements. Controls associated with critical actions, such as system configuration and alarm management, are clearly differentiated from informational elements, thereby reducing the likelihood of accidental activations. Likewise, the continuous visual feedback provided by biomedical signals (ECG and respiratory waveforms) reinforces the user's action-evaluation cycle, supporting conscious control and informed decision-making.

Accessibility and inclusion: From the perspective of the third axis, the interface incorporates features that promote accessibility, such as the use of universal iconography, appropriate color contrast, and a coherent spatial distribution of information. These design decisions enable use by users with varying levels of experience and perceptual capabilities, establishing a solid basis for adaptation to specific accessibility requirements in accordance with the principles of universal design.

Evaluation and continuous improvement: Finally, the fourth axis of the framework relates to the modular and structured nature of the interface, which facilitates heuristic evaluation and usability testing with real users. Organization into functional blocks allows interaction points and information flows to be clearly identified, supporting the introduction of iterative improvements aimed at increasing safety, efficiency, and user satisfaction throughout the system life cycle.

Fig. 4. Example of a medical human-machine interface that illustrates the practical application of the proposed best practice framework, integrating visual hierarchy, immediate feedback, accessibility, and patient safety-oriented assessment (figure created by the authors with the assistance of AI-based image generation tools).

Overall, the analyzed interface exemplifies how the systematic application of the proposed best practice framework can translate into technological solutions that integrate usability, patient safety, and a humanistic approach. This alignment reinforces the framework's validity as an operational tool to guide the design and evaluation of human-machine interfaces in the healthcare sector.

6 Discussion and Conclusions

The analysis of the literature made it possible to verify that the design of human-machine interfaces (HMIs) in the healthcare domain has evolved from approaches focused on technical efficiency toward comprehensive models that incorporate cognitive, social, and ethical dimensions. The usability principles defined by Nielsen (1993) and the concepts of natural interaction described by Norman (2013) are finding increasing application in biomedical engineering, where interfaces not only mediate access to clinical information but also directly influence safety and the quality of care. This convergence among disciplines has driven the creation of standards such as ISO 9241-210:2019, which consolidates the user-centered design paradigm as a transversal axis in healthcare technological innovation.

Despite normative and conceptual advances, the practice of HMIs design in healthcare continues to exhibit substantive gaps between theory and application. The reviewed studies indicate that many organizations partially adopt international guidelines, prioritizing functionality and cost over usability evaluation. This omission results in interaction failures that may lead to clinical errors, loss of information, or decreased user trust. The evidence suggests that design often focuses on system capabilities rather than on the real limitations of operators or patients, generating a disconnect between technological potential and its effective use.

One of the most relevant findings is the importance of the context of use as a determining variable in interface effectiveness. Carayon et al. (2006) and Kushniruk and Borycki (2008) agree that interaction with medical devices is conditioned by the physical environment, working conditions, and user characteristics. Therefore, design must consider the variability of scenarios (from intensive care units to homes) to ensure functional consistency and accessibility. Contextual adaptation also implies recognizing cultural and linguistic diversity, which becomes especially relevant in regions with technological inequality or limited digital literacy. This humanistic perspective reinforces the need for design processes to include the participation of end users, ensuring more intuitive and equitable solutions.

The evaluation process of HMIs should be conceived as a continuous activity that feeds back into the design cycle. Shneiderman & Plaisant (2010) propose that iteration and validation with users are essential to identify friction points and opportunities for improvement. However, the review indicates that many healthcare institutions lack systematic protocols to evaluate usability after implementation. This gap limits organizational learning and the ability of institutions to prevent recurring errors. Integrating participatory evaluation methodologies and interaction audits would contribute to consolidating a culture of continuous improvement. This aligns with the principles of patient safety and operational efficiency.

Inclusive design of HMIs represents not only a technical issue but also an ethical one. Accessibility, as defined by ISO 9241-210:2019, is a right that guarantees the participation of all people in the use of healthcare technologies. However, the reviewed literature shows that accessibility mechanisms are often implemented marginally or as aesthetic add-ons, rather than being integrated from the conceptual design phase. Incorporating accessibility as a guiding principle implies anticipating users' sensory, cognitive, or motor limitations and offering equitable alternatives for interaction. This vision aligns with Norman's (2013) postulates on the moral responsibility of design, which should be oriented toward human well-being beyond commercial or productive ends.

The framework of good practices proposed in this work translates the reviewed theoretical and normative principles into operational actions for the development of medical HMIs. Its structure into four axes (visual design, interaction and control, accessibility and inclusion, and continuous evaluation) makes it possible to comprehensively address the different levels of interaction among user, technology, and environment. This synthesis helps bridge the gap between scientific knowledge and professional practice, offering designers and engineers a concrete tool to guide their innovation processes. Moreover, the framework fosters interdisciplinary communication by providing a common language between technical specialists and clinical professionals, thereby strengthening knowledge transfer.

Although the review offers a broad overview of the evolution and challenges of HMI design in healthcare, limitations inherent to the narrative approach are acknowledged. The absence of quantitative analysis prevents statistical comparisons among studies, and the uneven availability of sources in different languages may have restricted the diversity of perspectives. Nevertheless, these limitations do not invalidate the results; rather, they point to opportunities for future research aimed at empirically validating the proposed framework of good practices. Field studies in hospitals and homes with different user profiles are recommended to test the model's effectiveness and generate measurable indicators of usability, accessibility, and satisfaction.

In conclusion, the design of human-machine interfaces in healthcare should be conceived as an interdisciplinary process, centered on the user and committed to safety, accessibility, and quality of care. The conducted review confirms that the integration of ergonomic, normative, and humanistic principles constitutes the basis for developing sustainable and ethically responsible healthcare technologies. Adoption of the proposed framework of good practices will allow institutions and developers to move toward a more reflective, inclusive design culture aligned with users' real needs. Ultimately, improving interaction between humans and technology not only optimizes system efficiency but also reaffirms the humanistic purpose of engineering applied to healthcare.

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