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OS-FMEA AND AI IN OCCUPATIONAL HEALTH: NEW STRATEGIES FOR RISK ASSESSMENT AND MITIGATION IN VACCINATION ROOM

OS-FMEA E IA NA SAÚDE OCUPACIONAL: NOVAS ESTRATÉGIAS PARA AVALIAÇÃO E MITIGAÇÃO DE RISCOS EM SALAS DE VACINAÇÃO

OS-FMEA E IA EN SALUD OCUPACIONAL: NUEVAS ESTRATEGIAS PARA LA EVALUACIÓN Y MITIGACIÓN DE RIESGOS EN LAS SALAS DE VACUNACIÓN

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ABSTRACT

Occupational accidents involving sharp objects and exposure to biological agents are frequent among healthcare professionals in Brazil, and the constant reporting of these events reflects an insufficient application of biosafety standards. This work is based on feeding an AI with a theoretical/technical framework and, after prior training, having it evaluate an image/photograph of a function/task of a sector or worker, returning with a complete analysis by generating an ETA (Ergonomic Task Analysis) and an OS-FMEA (Occupational Safety FMEA). To apply this methodology, the function of a vaccine agent in a UBS was taken. As preliminary results, the AI was able to analyze the image, score the related occupational risks, and propose corrective actions, generating an ETA. In addition, the AI was able to generate an analysis of the function through the OS-FMEA and, after applying the corrective actions suggested by it in a hypothetical situation, obtain a reduction in RPNs (risk priority numbers). In this work, a table of Occurrence x Severity x Detection (OxSxD) concepts specific to healthcare workers was also obtained. updated with publicly available data up to 2022.

RESUMO

Acidentes de trabalho envolvendo objetos perfurocortantes e exposição a agentes biológicos são frequentes entre profissionais de saúde no Brasil, e a constante notificação desses eventos reflete uma aplicação insuficiente das normas de biossegurança. Este trabalho se baseia em alimentar uma IA com um arcabouço teórico/técnico e, após treinamento prévio, fazê-la avaliar uma imagem/fotografia de uma função/tarefa de um setor ou trabalhador, retornando com uma análise completa gerando uma ETA (Análise Ergonômica de Tarefas) e uma OS-FMEA (FMEA de Segurança Ocupacional). Para aplicar esta metodologia, foi tomada a função de um agente vacinal em uma UBS. De acordo com os resultados preliminares, a IA foi capaz de analisar a imagem, pontuar os riscos ocupacionais relacionados e propor ações corretivas, gerando um ETA. Além disso, a IA foi capaz de gerar uma análise da função por meio do OS-FMEA e, após aplicar as ações corretivas sugeridas por ela em uma situação hipotética, obter uma redução nos RPNs (números de prioridade de risco). Neste trabalho, também foi obtida uma tabela de conceitos de Ocorrência x Gravidade x Detecção (OxSxD) específicos para profissionais de saúde. atualizado com dados disponíveis publicamente até 2022.

RESUMEN

Los accidentes de trabajo con objetos cortantes y exposición a agentes biológicos son frecuentes entre los profesionales de la salud en Brasil, y el constante reporte de estos eventos refleja una aplicación insuficiente de las normas de bioseguridad. Este trabajo se basa en alimentar a una IA con un marco teórico/técnico y, tras un entrenamiento previo, hacer que evalúe una imagen/fotografía de una función/tarea de un sector o trabajador, regresando con un análisis completo generando un ETA (Análisis Ergonómico de Tareas) y un OS-FMEA (FMEA de Seguridad Laboral). Para aplicar esta metodología se tomó la función de un agente vacunal en una UBS. Como resultados preliminares, la IA fue capaz de analizar la imagen, puntuar los riesgos laborales relacionados y proponer acciones correctivas, generando una ETA. Además, la IA fue capaz de generar un análisis de la función a través del OS-FMEA y, tras aplicar las acciones correctivas sugeridas por éste en una situación hipotética, obtener una reducción de los RPN (números de prioridad de riesgo). En este trabajo también se obtuvo una tabla de conceptos de Ocurrencia x Severidad x Detección (OxSxD) específicos para trabajadores de la salud. actualizado con datos disponibles públicamente hasta 2022.

INTRODUCTION

1 Occupational accidents are adverse events that occur during the performance of professional activities, resulting in physical injuries or functional impairment (Bertelli et al., 2020). The consequences of these accidents can range from temporary disability to fatality (BRASIL, 2014). Work accidents involving sharp objects and exposure to biological agents are frequent among health professionals in Brazil, and the constant reporting of these events reflects insufficient application of biosafety standards (Dos Anjos et al., 2023), when lack of training and resistance to the use of PPE aggravate this scenario (Silva et al., 2019). In addition to accidents, occupational diseases caused by accidental exposure to biological materials also represent a serious public health problem (Bertelli et al., 2021).

2 These accidents, known as Biological Material Exposure Accidents (BMEA), involve contact with bodily fluids - such as blood - increasing the risk of contamination by infectious diseases and cause a significant impact on the health and quality of life of workers (Kos et al., 2023). The use of needles, sharp objects, and exposure of skin and mucous membranes are the main routes of contamination in these cases (Miranda et al., 2017; BRAZIL, 2019). For example, in Minas Gerais state, between 2012 and 2021, blood was the main fluid related to these accidents, highlighting the persistence of unsafe behaviors over the years (Ornelas et al., 2024).

3 Studies indicate that factors such as gender and level of education influence the occurrence of these accidents. Women, brown people, and professionals with complete high school education are the most affected (Carvalho et al., 2023; Miranda et al., 2017; Santos & Cavalcante, 2021). A study with 111 records of BMEA in the state of Minas Gerais revealed that 54% of the accidents occurred between 2020 and 2021, during the COVID-19 pandemic, and most cases involved women (Ornelas et al., 2024). In São Luís-MA, 986 cases of BMEA were reported between 2021 and 2022, being predominant among women (77.9%), brown people (59.8%), and nursing technicians (53.1%) (De Sousa et al., 2024).

4 In this scenario, Regulatory Standard 32 (NR-32) is a milestone in Brazilian legislation for protecting the health of healthcare professionals. Established in 2005, the standard regulates aspects such as biosafety and the use of personal protective equipment (PPE) (Marziale et al., 2012). Although Regulatory Standard 32 (NR-32) requires mandatory reporting of accidents involving sharp objects, many professionals do not report these events, which reflects the lack of importance attributed to biological risks, especially in places with difficult access to occupational health sectors (Dos Santos et al., 2021).

5 This standard is based on the continuing education of professionals, the development of occupational risk management programs, and the implementation of prophylactic measures (BRASIL, 2012 apud Marziale et al., 2012). The NR-32 guidelines cover biological, chemical, and physical risks, as well as the proper use of personal protective equipment (PPE), such as aprons, gloves, masks, goggles, and caps (Marziale et al., 2012). Although adherence to the use of PPE is satisfactory in a general analysis, there are gaps especially in the use of masks

and aprons, which points to the need for more effective policies to increase awareness and adherence among health professionals (Silva et al., 2019; Novo & Nunes-Nogueira, 2023).

6 The overload of health services generated during the COVID-19 pandemic is an example of a scenario that promotes increased occupational risks for health workers. In this sense, the literature on the subject shows that workers subjected to high levels of stress are more prone to accidents (Gomes et al., 2021; Bakke & Araújo, 2010). In addition, psychosocial factors, such as high work demands and low control over working conditions, also contribute to the increased risk of BMEA (Souza et al., 2016; Messias et al., 2024). The exposure of these workers can lead to other health events, requiring measures to adapt the number of professionals, improve organization and working conditions, provide personal protective equipment in adequate quantity and quality, and implement measures that promote the strengthening of teams (Silva et al., 2020). These data reinforce the importance of interventions that address both biosafety and psychological factors in the work environment (Seben & Moretto, 2022).

7 The COVID-19 pandemic has accelerated the adoption of emerging digital technologies in healthcare, especially in the context of digital healthcare services and telemedicine (Araújo & Pimentel, 2024). This advancement is aligned with Industry 4.0, which integrates technologies such as data analysis and artificial intelligence, enabling improvements in occupational safety, resource management, and service efficiency (Saraswat et al., 2022). As highlighted by Queiroz (2021), the application of lean management principles has proven effective in modernizing healthcare systems, enabling more efficient coordination of financial, human, and logistical resources and contributing to the provision of safe and quality services.

8 The term Smart Healthcare describes a reality that incorporates digital technologies to analyze health information and then effectively deal with and react to the demands of the healthcare environment in an intelligent way (Muhammad et al., 2021). Digital systems such as cloud computing, machine learning (ML), and artificial intelligence (AI), along with emerging biotechnologies, are the cornerstones of smart healthcare (Muhammad et al., 2021; Mbunge et al., 2021). However, organizational and cultural challenges, technological barriers, and lack of regulation are identified as potential barriers to the successful implementation of Health 5.0. The healthcare sector is at the beginning of a paradigm shift to achieve a new era of intelligent disease control and detection, smart health management, and decision-making (Mbunge et al., 2021).

9 The difficulty in implementing appropriate risk analysis and management practices is not exclusive to the healthcare sector. As in sectors such as mining, construction, and energy, effective occupational risk management faces significant challenges, such as subjectivity in analysis and the complexity of operations (Mutlu et al., 2024). In the healthcare sector, these difficulties are aggravated by the multifaceted nature of risks, involving everything from exposure to biological agents to psychosocial factors (Marziale et al., 2013; Scozzafave et al; 2019; Messias et al., 2024; Martinez & Fischer, 2019).

10 In this context, multifactorial occupational risk analysis tools, such as Occupational Safety Failure Mode and Effect Analysis (OS-FMEA), become essential to identify, prioritize, and mitigate risks in healthcare services. The application of OS-FMEA allows a systematic and quantitative analysis of failure modes, analyzing their multicausality. In this way, it provides a well-founded direction for corrective actions, focused on the health and safety of the worker (Cavaignac et al., 2020).

Occupational Safety FMEA (OS-FMEA)

Failure Mode and Effect Analysis (FMEA) has been widely used to identify and assess risks in a variety of sectors, from the military to industry. In recent years, its application has expanded into the field of occupational safety, leading to the development of Occupational Safety FMEA (OS-FMEA). This adaptation aims to more accurately assess risks associated with the health and safety of workers in different industries, recently including worker and patient health (Chalak et al., 2021; Doss et al., 2023), as well as focusing on healthcare process safety (ALMashaqbeh & ALKhamisi, 2023).

OS-FMEA uses three main criteria for risk assessment: occurrence (O), which assesses the frequency with which a failure can occur; severity (S), which measures the potential impact of a failure; and detection (D), which measures the ability to identify failures before they affect the system. The combination of these three factors generates the Risk Priority Number (RPN), a metric used to prioritize risks and determine which ones should be addressed most urgently (Cavaignac & Uchoa, 2018). Studies show that OS-FMEA is particularly effective when dealing with work environments that present a high risk of accidents, such as the healthcare sector, where professionals are exposed to biological agents and sharp materials (Mutlu & Altuntas, 2019).

The integration of auxiliary methodologies into FMEA has increased its effectiveness. The combination with Fuzzy Cognitive Mapping (FCM) and Multi-objective Optimization on the Basis of Ratio Analysis (MOORA) improves risk prioritization by allowing the consideration of causal relationships between risk criteria and overcoming limitations of the traditional Risk Priority Number (RPN) (Dabbagh & Yousefi, 2019). In addition, the integration of FMEA with the Fuzzy Probability Estimation Algorithm (BIFPET) and Fault Tree Analysis (FTA) also increases the accuracy and reliability of risk assessments, being widely applied in high-risk sectors, such as the textile industry (Mutlu & Altuntas, 2019).

Another relevant approach is the use of hybrid techniques, such as the Fuzzy Inference System (FIS) and Fuzzy Data Envelopment Analysis (DEA), which improve the reliability of results in occupational risk management. These methodologies circumvent the limitations of traditional FMEA, such as the lack of consideration for uncertainties and different weights of risk factors, resulting in a more detailed and accurate analysis (Rezaee et al., 2019). The use of these hybrid approaches allows organizations to prioritize critical risks and implement corrective actions more effectively.

In addition to hybrid approaches, new adaptations of FMEA have been developed for specific sectors. The customization of occurrence, severity, and detection indices for the construction sector, for example, facilitates the practical application of this tool, improving the accuracy of risk analysis in this field (Cavaignac & Uchoa, 2018). Similarly, the use of FMEA in conjunction with the enhanced AHP Model for the management of occupational diseases in the mining sector demonstrates the feasibility of integrated methods for preventing work-related diseases (Bao et al., 2017). These innovations underscore the flexibility of FMEA and its ability to adapt to the specific needs of different industries.

For the healthcare sector, semi-quantitative methods can be used as a tool for assessing occupational health risks as a key element of risk management, based on semi-structured interviews and using the fuzzy analytical hierarchy process (FAHP) (Chalak et al., 2021). However, for healthcare workers, there are no quantitative indices in the literature obtained through official data, along the lines of those available for the construction industry (Cavaignac & Uchoa, 2018).

METHODOLOGY

This study was developed with the objective of evaluating the occupational and ergonomic risks associated with the function of administering vaccines in a Basic Health Unit (UBS) in the city of Imperatriz, Maranhão, using an integrated approach of ergonomic task analysis and advanced risk management tools, such as FMEA (Failure Mode and Effects Analysis), combined with the application of artificial intelligence (AI). The methodology was organized in stages to ensure the identification and mitigation of risks in the work environment.

Stages of using artificial intelligence

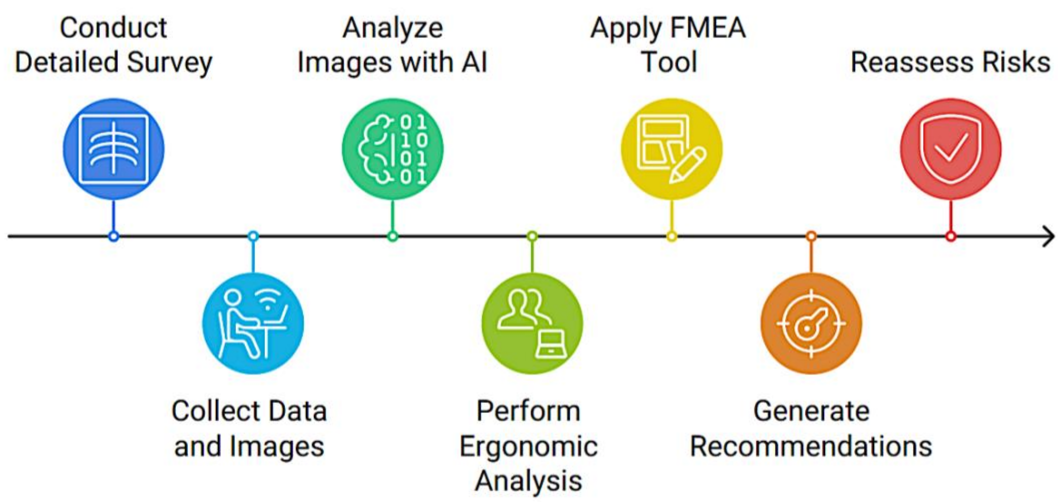
Initially, a detailed survey of working conditions in critical areas of the UBS was conducted, focusing on the vaccination room. Data was collected, including photographic records of the environment and the activities performed by workers. These records aimed to capture non-compliances with Regulatory Standard NR 32, which establishes guidelines for occupational health and safety in health services. The images obtained were analyzed by an artificial intelligence system, using a free license from ChatGPT, an OpenAI language model, after prior training. The AI was responsible for autonomously identifying non-compliances in the images, highlighting aspects such as inadequate ergonomics, the use of Personal Protective Equipment (PPE) and the organization of the work environment.

Next, a detailed ergonomic task analysis (ETA) was carried out to verify the impacts of working conditions on the health of professionals, considering factors such as repetitive movements, prolonged static postures, and the ergonomics of equipment handling. This analysis was conducted automatically by AI, which assessed ergonomic aspects and compared the identified risks with compliance standards, such as NR 32, NR 6 (PPE), NR 17 (Ergonomics), NR 24 (Sanitary and Comfort Conditions) and NR 15 (Unhealthy Activities).

After identifying the risks, the FMEA tool was applied by AI to quantify and classify the failure modes and their effects. The calculation of the Numerical Priority Risk (NPR) was performed based on occurrence, severity and detection criteria, allowing a systematic approach in prioritizing corrective actions. Based on the analyzed data, AI generated recommendations for corrective measures, such as reorganization of the workspace, ergonomic adjustments at vaccination stations and improvements in the use of PPE by workers.

Finally, the AI was responsible for carrying out a risk reassessment after the hypothetical implementation of corrective actions, recalculating the RPN to verify the effectiveness of the suggested measures. This comparative reanalysis between the initial and post-correction situations provided a clear overview of the risk reduction and improvement of working conditions (Figure 1).

Figure 1. Methodology use for AI-driven risk assessment

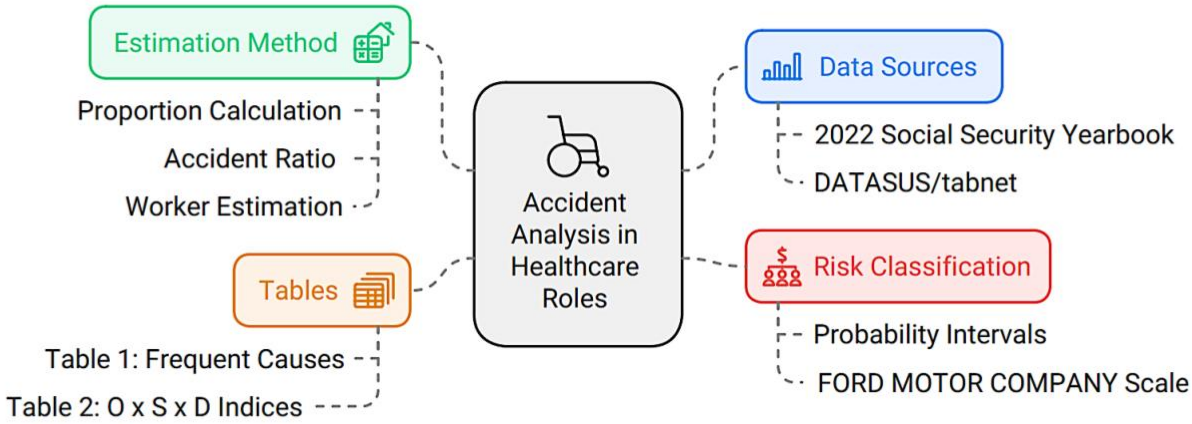


Source: Authors, 2024.

Obtaining the O S D incidences

The data used for this analysis were obtained from the 2022 Social Security Yearbook and the DATASUS/TABNET system of the Ministry of Health. The number of workers registered in the three functions (nurse, nursing technician, and nursing assistant) was estimated based on the number of typical accidents registered in DATASUS/TABNET, for the three functions, in 2022, totaling 15,163 cases. To determine this estimate, the proportion between the total number of workers in the Health and Social Assistance area (3,811,524) and the number of typical accidents (62,556) correlated to the three functions, obtained from the 2022 Social Security Yearbook, was used, resulting in approximately 60.9 workers per accident. Applying this ratio to the 15,163 typical accidents in the three functions, we arrive at an estimated total of 921,440 registered workers. From then on, it is possible to calculate the probability of a worker in each role having an accident in each type of occurrence, assigning numerical indices from 1 to 10, related to the probability intervals (Ford Motor Company, 2011). Figure 2 summarizes how the O, S and O indices were obtained.

Figure 2. Summary of how the O, S and O indices were obtained



Source: Authors, 2024.

The last table presents the risk classification for the different types of accidents, with the probabilities of occurrence and the corresponding risk categorization, which varies from low to moderate. The classifications were assigned based on probability intervals, using the 2011 FORD MOTOR COMPANY qualitative scale, reflecting the probability of accidents in the roles analyzed. Table 1 presents the 10 most frequent causes of accidents related to the roles of nurses, nursing technicians and assistants, obtained from DATASUS/TABNET, for the period of 2022. Table 2 shows a compilation of Severity and Detection indices, proposed by Cavaignac & Uchoa, (2018), and occurrence, obtained in the manner previously explained.

Table 1. Occurrence indices obtained from social security

Accident Type	Probability (%)	Risk	Assigned Concept
Same-level fall, slip, trip, misstep	0.078	5	Moderate
Contact with sharp, penetrating object, intent undetermined	0.050	4	Low
Impact caused by projected or falling object	0.043	4	Low
Impact of active or passive chemical agent caused by other objects	0.038	4	Low
Aggression by bodily force	0.035	4	Low
Exposure to other specific factors	0.033	4	Low
Crushing, collision, compression, entrapment within objects	0.025	4	Low
Fall on or from stairs or steps	0.023	4	Low
Circumstances related to lifestyle conditions	0.018	4	Low
Excessive exercise, vigorous or repetitive movements	0.016	4	Low
Blow, bite, or similar inflicted by a patient	0.018	4	Low

Source: Data from DATASUS/Tabnet, 2022 Social Security Yearbook and Ford Motor Company, 2011. Adapted.

Table 2. Severity (S), Occurrence (O), and Detection (D) Index Reference

Severity (S)	Index	Occurrence (O)	Assigned Concept (O)	Detection (D)	Index
No real impact	1	Excessive exercise, vigorous or repetitive movements	4	Direct visual detection (Very easy)	1
Irrelevant trauma	2	Circumstances related to lifestyle conditions	4	Detection by manual/tactile inspection (Easy)	2
Trauma requiring first aid	3	Blow, bite, or similar inflicted by a patient	4	Detection by basic checklist (Moderate)	3
Temporary incapacity without leaves	4	Crushing, collision, compression, entrapment within objects	4	Detection by structured checklist (Moderate)	4

Temporary incapacity with short leave	5	Contact with sharp, penetrating object	4	Detectable with routine inspection (Moderately difficult)	5
Temporary incapacity with long leave	6	Same-level fall, slip, trip, misstep	5	Detectable with monitoring instruments (Difficult)	6
Partial permanent incapacity	7	Impact caused by projected or thrown object	4	Detectable with auditing methods (Very difficult)	7
Total permanent incapacity	8	Impact of active or passive chemical agent	4	Detectable only by intense audit	8
Death of directly involved workers	9	Bodily force aggression	4	Difficult to detect without instrumental methods	9
Death of non-directly involved workers	10	Exposure to other specific factors	4	Virtually impossible to detect	10

Source: data from authors and Cavaignac & Uchoa, 2018. Adapted.

For the applicability of the OS-FMEA, the model recommended by Uchoa et al. (2019) was used, which was adapted for better performance from the reference table indicated by Cavaignac and Uchoa, (2018) and adapted in this work. Table 3 shows the model used for the application of the OS-FMEA in this work, and Table 4 shows the model used for the application of the OS-FMEA in a hypothetical situation, after the corrective actions suggested by the IA.

Table 3. Template table for FMEA implementation in occupational risk analysis

Failure Type	Potential Failure Mode	Occurrence Nature	O	Potential Effects of Failure	S	Detection Measure	D	RPN

Source: Uchoa et al. (2019). Adapted.

Table 4. Template table for FMEA application in occupational risk analysis post corrective actions

Implemented Corrective Action	Potential Failure Mode	Occurrence Nature	O	Potential Effects of Failure	S	Detection Measure	D	RPN

Source: Uchoa et al. (2019). Adapted.

RESULTS AND DISCUSSION

The photographic records obtained by the authors during the approach to the on-site process allowed the AI, after previous training, to identify a group of non-conformities, highlighting the irregularities regarding non-compliance with regulatory standards and other manuals of institutional procedures. As a database on occupational health and safety, documents such as the text of regulatory standards NR-32, NR-1, NR-15, NR-17, NR-24, the biosafety manual of the Center of Disease Control and the procedure manual of the National Immunization Program (Centers for Disease Control and Prevention [CDC], 2020; Ministry of Health of Brazil, 2014), in addition to the international standard ISO 45001, which is a standard of the International Organization for Standardization for occupational health and safety management systems (Associação Brasileira de Normas Técnicas [ABNT], 2018). As literature about the application of risk management tools, the documents that were used as a reference in this work were made available.

Based on the analysis of Figures 3, 4 and 5, which record the vaccine application function as well as the vaccination room environment, the AI identified a set of nonconformities and performed the ETA and OS-FMEA. In turn, the results of the ETA and OS-FMEA analyses were evaluated and suggestions for improvements were fed back to the AI, until a satisfactory final analysis was prepared. The results obtained in the ergonomic task analysis and in the Occupational Safety Failures Analysis performed by the AI are in Tables 6 and 7, followed by their respective detailed discussions. To preserve the privacy of the individuals, present in the images, concealment stripes were applied over the faces and identifiable elements.

Figure 3. Non-conformities found in the vaccination situation: (a) stooped posture of the health professional, (b) inadequate posture of the companion, (c) lack of restraint devices for the baby and (d) environment with ceramic floors, potentially slippery

Source: Authors, 2024.

Figure 4: Non-conformities found in the washing area: (a) presence of a cardboard box near the sink, (b) inadequate disposal of medical waste with an open lid, (c) absence of clear signage about the waste, (d) lack of visible PPE for handling waste

Source: Authors, 2024.

Figure 5. Non-conformities at the workstation: (a) damaged chairs compromising ergonomics, (b) helmet and personal belongings out of the proper place, (c) lack of organization of documents and work materials

Source: Authors, 2024.

The images show a typical scenario of a vaccination room, where both the health professional and the companion actively participate in the process of administering the vaccine to a baby. However, several ergonomic factors were identified, suggesting the need for adjustments both in the environment and in the postures adopted during the procedure. The professional administers the vaccine standing up, leaning over the baby, which can cause discomfort over time. This inclined posture increases the risk of muscle injuries, especially in the lower back and shoulders, due to the repetition of the activity. The proposed solution is to use chairs with adjustable height so that the vaccination can be performed in a neutral position, with the professional seated, which would reduce the strain on the upper limbs and spine.

The companion, who is holding the baby, also adopts an inadequate posture. Sitting in a chair without adequate support for the back and feet, the father is forced to lean forward, which can cause back pain and fatigue, especially if the waiting time or restraint of the baby is prolonged. The use of adjustable ergonomic chairs with back and footrests could reduce this discomfort and ensure a healthier position.

Another point of concern is the lack of adequate restraint devices for the baby, who is being manually restrained by the father. This can result in sudden movements and even accidents during the administration of the vaccine, in addition to being a source of discomfort for both. Restraint cushions or pillows designed for babies could be introduced to facilitate positioning and ensure the safety and stability of the procedure. The physical environment also presents risks. The ceramic floor, if wet, can become slippery, increasing the risk of falls. In addition, the available chairs seem inadequate for long waiting periods, especially in the case of companions with agitated babies. The implementation of non-slip mats and ergonomically appropriate chairs would contribute to safety and comfort.

The ergonomic risks identified can be mitigated by introducing simple measures, such as adjusting working postures, using appropriate chairs and supports for the baby. Improving these conditions would benefit both healthcare professionals and caregivers, minimizing the risk of discomfort, musculoskeletal injuries, and accidents. The corrective measures suggested for the nonconformities found are contained in Table 5, which shows the ETA performed based on observations of the photographic records.

Table 5. ETA of the Vaccination Room Vaccine Application Function (Based on the Three Photos)

Identified Non-compliance	Related NR Items	Suggested Corrective Actions
Absence of appropriate containers for disposal of sharps and biological waste	NR-32 (32.3.7, 32.5.3) - NR-06 (PPE - Hazardous waste collection)	Install rigid and appropriate containers for sharps disposal and adequately mark waste disposal areas in accordance with biosafety standards.
Presence of cardboard box in the work area designated for handling biological materials	NR-32 (32.2.4) - NR-24 (Comfort and safety conditions)	Remove the cardboard box and add specific containers for contaminated waste. Implement organization practices and segregation of biological waste.
Improper use of PPE, such as gloves and gowns	NR-32 (32.2.4.6) - NR-06 (Personal Protective Equipment)	Implement regular training on PPE use and adopt daily checklists to ensure proper equipment usage.
Lack of clear and visible signage for hazardous waste disposal	NR-32 (32.3.7.1.3)	Implement appropriate signage following NR-32 and NR-06 guidelines to ensure all workers follow correct disposal protocols.
Inadequate trash bins for contaminated waste (without lids and pedal operation)	NR-32 (32.6.3) - Biosafety CDC (Biological material disposal practices)	Replace regular trash bins with pedal-operated, puncture-resistant lidded bins and ensure proper waste segregation.
Lack of adequate lockers for personal items (motorcycle helmet stored improperly)	NR-24 (Workplace comfort conditions)	Install appropriate lockers in locker rooms or rest areas to ensure proper storage of personal items like helmets and clothing.
Inadequate furniture (chairs and furniture not following ergonomic guidelines)	NR-17 (Ergonomics) - NR-24 (Workplace comfort conditions)	Replace furniture with adjustable ergonomic chairs and ensure the work environment meets ergonomic and comfort standards.
Excessive people in the vaccination room, leading to crowding	NR-24 (Sanitary and comfort conditions at work)	Limit the number of people in the vaccination room and control access to ensure safe distancing and security in the area.

Source: Authors, 2024.

The ergonomic task analysis (ETA) in the three images provided reveals significant nonconformities in the vaccination room work environment. These nonconformities compromise both the safety of workers and good hygiene and biosafety practices, which are essential in healthcare environments. To ensure a safe work environment in compliance with regulatory standards, several corrective actions were proposed based on the guidelines of standards NR-32, NR-24, NR-17, and NR-06, in addition to international recommendations, such as the biosafety guidelines of the CDC (2020), the PNI, (2014) and the ISO 45001 standard (ABNT, 2018). One of the main problems observed was the lack of suitable containers for the disposal of sharp and biological waste, which violates NR-32 and NR 06.

The correct segregation and disposal of contaminated materials is essential in healthcare areas, especially in places where potentially hazardous biological materials, such as syringes and needles, are handled. The lack of suitable containers for the disposal of these materials increases the risk of accidents, such as punctures and cross-contamination. The proposed solution is the installation of rigid containers, adequately marked, to ensure the safety of workers and compliance with the biosafety practices recommended by the CDC (2020). The PNI Vaccination Procedures Manual reinforces that disposal containers must be appropriate, with a lid and identified to avoid risks.

Furthermore, the presence of cardboard boxes in the work area intended for handling biological materials is a failure that violates the waste organization guidelines of NR-32 (item 32.2.4) and the comfort and safety conditions of NR-24. Cardboard boxes are inadequate for storing contaminated biological materials, since they are not puncture-resistant and can easily break, creating risks of contamination in the work environment. NR-32 clearly requires the correct segregation and packaging of waste, and it is recommended that these boxes be replaced with appropriate, properly marked containers.

The lack of clear and visible signage regarding the disposal of hazardous waste represents a significant risk to the healthcare work environment, since it makes it difficult to correctly identify and handle these materials. According to NR-32 (item 32.3.7.1.3), it is mandatory that hazardous waste disposal areas be properly marked to ensure that all workers can identify and follow the established disposal protocols. This requirement aims to reduce exposure to potentially contaminant biological and chemical materials, preventing accidents and ensuring the safety of professionals involved in the process. The implementation of appropriate signage, as also guided by NR-06 on safety procedures with PPE, contributes to compliance with biosafety standards and protects the health of workers.

In addition, the inadequacy of waste bins for contaminated waste, which do not have a pedal-operated lid, exposes workers to the risk of direct contact with hazardous waste. NR-32 (item 32.6.3) and CDC guidelines (2020) indicate that waste bins in healthcare environments must be puncture-resistant and have pedal-operated lids to prevent manual contact with waste. Installing appropriate waste bins will help significantly reduce the risks of biological contamination and improve biosafety in the workplace.

Another non-compliance found was the lack of adequate cabinets for personal items, such as the motorcycle helmet, which was stored in an inappropriate place inside the vaccination room. NR-24 (Comfort Conditions) establishes that work environments must be equipped with appropriate lockers so that workers can store their belongings in a safe and organized manner. The absence of adequate lockers for personal items compromises the organization of the workspace and increases the risk of cross-contamination in vaccination areas. ISO 45001, the implementation guide for health and safety at work, also emphasizes the importance of adequate storage areas to ensure hygiene and safety in the work environment. The suggested corrective action is the installation of individual lockers in changing rooms or designated areas, allowing for the correct storage of personal belongings, such as helmets and clothing.

Inadequate furniture, such as chairs and tables that do not follow the ergonomic criteria established by NR-17, was another critical point identified. Inadequate ergonomics can cause musculoskeletal injuries in workers who spend long periods in the same position, as is common when administering vaccines. According to NR-17, furniture must be adjustable and provide comfort to prevent muscle fatigue and repetitive strain injuries. The literature reinforces that inadequate ergonomic working conditions are directly linked to the increase in absences due to occupational diseases, such as work-related musculoskeletal disorders. The recommended solution is to replace furniture with adjustable chairs and tables, which allow workers to adjust their posture.

The lack of control over the number of people presents in the vaccination room, leading to crowding, was another problem identified. NR-24 also requires that work environments be adequately sized, avoiding overcrowding and ensuring adequate distancing between workers. In healthcare settings, such as vaccination rooms, controlling the flow of people is essential to prevent the spread of infectious agents and maintain the safety of both workers and patients. The recommendation is to implement stricter access control to the vaccination room, ensuring that only the necessary personnel are present and that the number of people in the environment is adequate.

The nonconformities identified in the three images analyzed indicate the urgent need for improvements in working conditions in the vaccination room. Implementing the suggested corrective actions, such as replacing furniture, using PPE appropriately, organizing the space with cabinets, and controlling access, will bring significant improvements in both the safety and comfort of workers. To study the impacts of the nonconformities found in situ and the effectiveness of the proposed corrective actions, an OS-FMEA was performed based on the data collected. The results of applying the OS-FMEA in the real situation and after the hypothetical application of the corrective actions are explained in Tables 6 and 7.

Table 6. OS-FMEA of the Vaccination Room Vaccine Application Function (Actual situation)

Non-compliance	Failure Mode	Occurrence Nature	O (Occurrence)	Potential Effects of Failure	S (Severity)	Detection Methods	D (Detection)	RPN
Lack of proper waste disposal signage	Improper disposal of hazardous materials	Contact with sharp, penetrating object	4	Death of directly involved workers	9	Difficult to detect without instrumental methods	9	324
Inadequate furniture causing poor ergonomics	Physical discomfort and incorrect posture	Crushing, compression, entrapment within objects	4	Temporary incapacity with short leave	5	Detectable with basic checklist	3	60
Lack of adequate PPE	Exposure to biological agents	Contact with sharp, penetrating object	4	Temporary incapacity with long leave	6	Detectable with monitoring instruments	6	144
Inadequate storage of personal items	Disorganization and clutter in workspace	Circumstances relative to life conditions	4	Irrelevant trauma	2	Immediate visual detection	1	8
Absence of proper containers for sharps and biological waste	Accidental puncture or cuts from sharp objects	Contact with sharp, penetrating object	4	Partial permanent incapacity	7	Detectable with routine inspection	5	140

Source: Authors, 2024.

Table 7. OS-FMEA of the Vaccination Room Vaccine Application Function (after corrective actions)

Corrective Actions Implemented	Failure Mode	Occurrence Nature	O (Occurrence)	Potential Effects of Failure	S (Severity)	Detection Methods	D (Detection)	RPN
Installation of appropriate signage for hazardous waste disposal	Improper disposal of hazardous materials	Contact with sharp, penetrating object	4	Requires first aid trauma	3	Detectable with routine checklist	3	36
Replacement of inadequate furniture with ergonomic alternatives	Physical discomfort and poor posture	Crushing, compression, entrapment within objects	4	Requires first aid trauma	3	Detectable with structured checklist	4	48
Provision and correct use of Personal Protective Equipment (PPE)	Exposure to biological agents	Contact with sharp, penetrating object	4	Irrelevant trauma	2	Immediate visual detection	1	8
Installation of lockers for secure storage of personal items	Disorganization causing tripping or clutter	Circumstances relative to life conditions	4	No real impact	1	Immediate visual detection	1	4
Placement of rigid, labeled containers for sharps and biological waste	Accidental puncture or cut from sharps	Contact with sharp, penetrating object	4	Requires first aid trauma	3	Detectable with basic checklist	3	36

Source: Authors, 2024.

The comparative analysis between the real situation and the hypothetical situation after the implementation of corrective actions reveals substantial changes in the Occurrence (O), Severity (S) and Detection (D) indices, resulting in a significant decrease in the Risk Priority Number (RPN) in several failure modes. Each index was adjusted according to the intervention performed, enabling risk mitigation to meet the regulatory requirements of biosafety and ergonomics, as specified in standards NR-32 and NR-06.

In the initial situation, the lack of signage for the proper disposal of biological waste increased the risk of cross-contamination, justifying a severity index of S = 9, since exposure to infectious agents could, in extreme cases, lead to the death of the workers directly involved. With the implementation of appropriate signage, the severity was reduced to S = 3, indicating that the risk was mitigated to a level in which potential damage would be limited to minor trauma requiring only first aid. This change reflects the importance of corrective actions in reducing severe consequences, as recommended by studies that highlight the role of adequate infrastructure in health care settings (Marziale et al., 2012).

Regarding detection, the initial situation presented an index of D = 9, since the lack of signage made it difficult to identify the risk without inspection methods, such as specific assessment protocols. With the signage and use of checklists, the detection rate was improved to D = 3, making the identification of problems in existing signage accessible through routine inspections, as recommended by ISO 45001 (2018). The occurrence rate, however, was maintained at O = 4 in both situations, because, although corrective measures help in guiding disposal, they do not eliminate the risk associated with the human factor.

Inadequate furniture in the real situation caused physical discomfort and incorrect postures, resulting in a severity index of S = 5, which corresponds to a "temporary disability with short absence" due to potential musculoskeletal damage. With the change to ergonomically appropriate furniture, the severity was reduced to S = 3, reflecting a decrease in the consequences for "traumas requiring first aid", due to the promotion of a safer and more comfortable work environment.

The occurrence index was maintained at O = 4 in both situations because, despite the improvement in furniture, the possibility of physical discomfort persists in environments where workers remain for long periods. In the detection, the initial situation allowed identification only by a basic checklist (D = 3), while the situation after the intervention required a structured checklist (D = 4) to ensure compliance with ergonomic standards. The literature suggest that furniture adaptation is essential for preventing occupational injuries, but that continuous compliance assessment is necessary (ABNT NBR ISO 45001, 2018).

The lack of adequate PPE in the initial situation exposed workers to biological agents, justifying a severity index of S = 6, which reflects the risk of temporary incapacity with long absence due to severe contamination. With the implementation of appropriate PPE, the severity was reduced to S = 2, corresponding to "irrelevant trauma", since adequate protection prevents direct exposure, minimizing the severity of potential consequences.

The occurrence index remained at O = 4, since the risk of contact with biological agents still depends on the correct use of PPE, which can vary according to individual behavior. Detection, however, improved substantially, going from D = 6 (dependent on instrumental monitoring) to D = 1 (direct visual detection), which facilitates the verification of the presence and use of PPE. These changes corroborate the recommendations of Marziale et al. (2012) on the importance of PPE in preventing contamination and the role of simple verification routines to ensure correct use.

The absence of specific lockers for storing personal items led to an initial severity index of S = 2 (irrelevant trauma), since disorganization could cause minor accidents. After installing lockers for personal items, the severity was reduced to S = 1 (no real impact), since proper organization virtually eliminates all risk of accidents related to inadequate storage. The occurrence index was maintained at O = 4, since even with the installation of lockers, individual worker behavior can result in occasional inadequate storage. In detection, the index remained at D = 1 (direct visual detection), allowing a quick verification of organization and compliance with storage practices. These improvements are in line with the principles of ergonomics and organization of the work environment proposed by the ISO 45001 (2018) standard.

In the initial situation, the lack of rigid containers for the disposal of sharps waste generated a high severity index (S = 7), due to the risk of perforations and potentially serious contamination. With the installation of containers suitable for this type of waste, the severity index was reduced to S = 3, indicating that the risks were mitigated to a level in which possible injuries are limited to minor trauma. The occurrence index, which remained at O = 4, reflects the probability of human errors in waste disposal, regardless of structural improvements. Detection, however, was improved from D = 5 (moderately difficult detection by routine inspection) to D = 3 (detection by basic checklist), which facilitates verification and increases compliance with safe disposal standards. This modification is in accordance with the recommended practices for the disposal of biological and sharps waste, as described by the CDC (2020).

The corrective actions implemented demonstrated a significant reduction in the Severity (S) and Detection (D) indices, while the Occurrence (O) index remained constant, reflecting the influence of human and behavioral factors in risk assessment. The decrease in the Risk Priority Number (RPN) in each of the failure modes validates the effectiveness of the corrective measures and highlights the usefulness of OS-FMEA as a tool for occupational risk management. These structural and operational improvements made the work environment safer and in compliance with safety and biosafety standards (Marziale et al., 2012; ABNT NBR ISO 45001, 2018). Table 8 shows the RPNs before and after improvements.

Table 8. Reduction in Risk Priority Number (RPN) for each identified non-compliance before and after implementing corrective actions

Non-compliance	RPN Before Corrections	RPN After Corrections	RPN Reduction (%)
Lack of proper waste disposal signage	324	36	88.9%
Inadequate furniture	60	48	20.0%
Lack of adequate PPE	144	8	94.4%
Improper storage of personal items	8	4	50.0%
Absence of containers for sharp and biological waste	140	36	74.3%

Source: Authors, 2024.

The lack of clear signage for waste disposal presented a high risk, with an initial RPN of 324 due to the difficulty of detection and high severity. With the installation of appropriate signage and disposal procedures, the RPN was reduced to 36, representing a reduction of 88.9%. This significant change indicates that the intervention was effective in minimizing the potential for cross-contamination and improving the overall safety of the environment. The use of signage and inspection checklists helped to reduce the complexity of detecting deficiencies and facilitate the identification of risks.

The inadequate furniture resulted in physical discomfort and ergonomic problems, with an initial RPN of 60. After replacing the furniture with ergonomic furniture, the RPN was reduced to 48, a 20% reduction. This reduction reflects improvements in the severity of the effects of the failure, but the occurrence and possibility of physical discomfort remains due to the nature of the activities, which involve prolonged postures. Although ergonomic furniture provides greater physical support, it does not eliminate the risk of discomfort, especially in repetitive activities.

The lack of appropriate PPE exposed workers to high risks of contamination with biological agents, resulting in an initial RPN of 144. With the adequate provision of PPE, the RPN was reduced to 8, a 94.4% reduction. The presence of PPE and the ease of direct visual inspection contributed to reducing both the severity and the difficulty of detection, significantly minimizing the risk of contamination. This result highlights the importance of PPE in mitigating biological risks, as it is a highly effective measure to promote a safer work environment.

Inadequate storage of personal items had an initial RPN of 8, due to the risk of minor accidents associated with disorganization. After installing cabinets for adequate storage, the RPN was reduced to 4, representing a 50% reduction. The intervention allowed personal items to be stored in an organized manner, which helped to minimize the chance of minor accidents and to improve the safety and organization of the environment.

The lack of adequate containers for the disposal of sharps represented a significant risk, with an initial RPN of 140. With the installation of rigid and marked containers, the RPN was reduced to 36, representing a reduction of 74.3%. The measure allowed for better detection and facilitated safe disposal, minimizing the risk of punctures and serious contamination. The intervention proved to be effective in reducing the severity of potential accidents, providing a safer environment for handling hazardous waste.

The reductions in RPN demonstrate the effectiveness of the suggested corrective actions in mitigating occupational risks. The most significant reduction occurred in cases where severity and detection were the main risk factors, such as lack of PPE and adequate signage. These improvements reflect the importance of a preventive and structured approach, such as OS-FMEA, to effectively identify and mitigate risks, in addition to the ability of AI to generate effective analyses.

CONCLUSIONS

This study contributes significantly to the understanding and management of occupational risks in healthcare facilities, especially in the role of administering vaccines in environments with high contact with biological materials. The introduction of OS-FMEA and artificial intelligence tools proved to be an innovative and effective strategy for identifying, quantifying, and mitigating risks, in line with Brazilian Regulatory Standards, such as NR-32, and international guidelines. The data collected highlighted that vaccination environments contain multiple nonconformities that can represent critical risks to the health of workers, such as exposure to biological agents and inadequate ergonomic conditions.

The proposed methodology, by combining the survey of nonconformities, application of OS-FMEA, and use of AI to identify risks, provided a robust diagnosis and an efficient hierarchy of risks, with corrective measures based on best practices. Quantitative risk analysis using the Risk Priority Number (RPN) showed that the implementation of corrective actions resulted in a significant reduction in RPN rates, proving the effectiveness of the suggested interventions. Notably, the reorganization of sharps disposal areas, the appropriate use of Personal Protective Equipment (PPE), and improved signage were key measures that increased safety and compliance with regulations.

Thus, the joint application of OS-FMEA and IA proved promising for improving occupational safety in healthcare services, reducing risk rates and promoting a safer and more sustainable work environment. Although the results are promising, implementing the suggested measures may face challenges related to costs, equipment adherence or technological specifications, and difficulty by AI applications. By providing a replicable framework, this model can be adapted to other areas of healthcare and related sectors, suggesting that the incorporation of emerging technologies can revolutionize the way occupational health and safety is handled in complex contexts with high exposure to risks.

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