

Reuse of N95 respirators: a systematic review on effectiveness and occupational safety for healthcare professionals

Reutilização de respiradores N95: revisão sistemática sobre efetividade e segurança ocupacional para profissionais de saúde

Reutilización de respiradores N95: revisión sistemática sobre efectividad y seguridad ocupacional para profesionales de salud

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ABSTRACT

Objective: To analyze the evidence on the effectiveness of extended use and reuse protocols of N95 respirators, with a focus on the occupational safety of healthcare professionals.

Method: Systematic review of articles published between 2003 and 2024 in the Medline/PubMed, Web of Science, SCOPUS, Embase, and CENTRAL databases. Experimental, quasi-experimental and observational studies were included. Methodological quality was assessed using the Joanna Briggs Institute tool. Narrative synthesis was used to present the results.

Results: The review encompassed 21 articles. The most investigated aspect was sealing (71.4%), followed by structural integrity (33.3%), filtration efficiency (19.0%), and, finally, tensile testing of the fastening straps (4.8%). Damage such as dirt accumulation, broken nose clips, and strap breakage, as well as degradation of elastic resistance, were observed, leading to inadequate fit and reduced filtration capacity. Four studies were classified as high quality, while 17 were of moderate quality.

Conclusion: Extended use and reuse of N95 respirators are not recommended, as they increase occupational risk. Although they maintain adequate filtration efficiency in different contexts, this is not sufficient to ensure user protection. When unavoidable, strict evidence-based protocols must be followed.

Descriptors: N95 respirators; Equipment reuse; Health personnel; Occupational health.

RESUMO

Objetivo: Analisar as evidências sobre a eficácia dos protocolos de uso estendido e reutilização dos respiradores N95, com foco na segurança ocupacional dos profissionais de saúde.

Método: Revisão sistemática de artigos publicados entre 2003 e 2024, nas bases de dados Medline/PubMed, Web of Science, SCOPUS, Embase e CENTRAL. Foram incluídos estudos experimentais, quase-experimentais e observacionais. A qualidade metodológica foi avaliada por meio da ferramenta do Joanna Briggs Institute. Síntese narrativa foi utilizada para a apresentação dos resultados.

Resultados: A revisão abrangeu 21 artigos. O aspecto mais investigado foi vedação (71,4%), seguido da integridade estrutural (33,3%), eficiência de filtração (19,0%) e, por fim, ensaio de tração das tiras de fixação (4,8%). Foram observados danos como sujidade, quebras do clipe nasal e rompimento das tiras de fixação, além da degradação da resistência elástica, resultando em ajuste inadequado e perda da capacidade de filtração. Quatro estudos foram classificados como de alta qualidade e 17 como de qualidade moderada.

Conclusão: Uso estendido e reutilização dos respiradores N95 são contraindicados, pois aumentam o risco ocupacional. Embora mantenham a eficiência de filtração adequada em diferentes contextos, isso não é suficiente para garantir a proteção ao usuário. Quando inevitáveis, protocolos rigorosos baseados em evidências devem ser seguidos.

Descritores: Respiradores N95; Reutilização de equipamentos; Pessoal de saúde; Saúde ocupacional.

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RESUMEN

Objetivo: Analizar la evidencia sobre la eficacia de los protocolos de uso prolongado y reutilización de respiradores N95, con el foco en garantizar la seguridad ocupacional de los profesionales de la salud.

Método: Revisión sistemática de artículos publicados entre 2003 y 2024 en *Medline/PubMed*, *Web of Science*, *SCOPUS*, *Embase* y *CENTRAL*. Se incluyeron estudios experimentales, cuasiexperimentales y observacionales. La calidad metodológica fue evaluada con la herramienta del *Joanna Briggs Institute*. Se utilizó una síntesis narrativa para presentar los resultados.

Resultados: Se identificaron 21 artículos. El aspecto más investigado fue el ajuste (71,4%), seguido de la integridad estructural (33,3%), eficiencia de filtración (19,0%) y ensayo de tracción de tiras de sujeción (4,8%). Se observaron daños como suciedad, rotura del clip nasal y de las tiras, además de degradación de la resistencia elástica, lo que resultó en un ajuste inadecuado y una reducción de la capacidad de filtración. Cuatro estudios fueron clasificados como de alta calidad y 17 de calidad moderada.

Conclusión: El uso prolongado y la reutilización de respiradores N95 están desaconsejados, ya que aumentan el riesgo ocupacional. Aunque mantienen adecuada eficiencia de filtración, esto no garantiza la protección. Cuando sea inevitable, deben seguirse protocolos rigurosos basados en evidencia.

Descriptores: Respiradores N95; Equipo reutilizado; Personal de salud; Salud laboral.

■ INTRODUCTION

Respiratory pathogens, such as *Mycobacterium tuberculosis* (the causative agent of tuberculosis) and the measles virus, are transmitted through the air. During procedures that generate aerosols, other viruses, such as influenza H1N1 and severe acute respiratory syndrome coronavirus (SARS-CoV-2), can also spread via this route⁽¹⁻³⁾. These agents represent a threat in the epidemiological scenario, highlighting the vulnerability of healthcare professionals to respiratory infections and the need for effective protective measures⁽⁴⁻⁵⁾.

The N95 respirator is a fundamental piece of personal protective equipment (PPE) to reduce occupational risk, especially when caring for patients with airborne diseases and during aerosol-generating procedures⁽¹⁻³⁾. The Centers for Disease Control and Prevention (CDC) recommends its single use, followed by immediate disposal⁽⁶⁾. However, health crises such as the SARS epidemic in 2003, the H1N1 influenza pandemic in 2009, the emergence of Middle East respiratory syndrome coronavirus (MERS-CoV) in 2012, and the recent COVID-19 pandemic have resulted in a global shortage of these devices due to high demand and limited production capacity⁽⁶⁻⁹⁾.

The National Institute for Occupational Safety and Health (NIOSH) has approved guidelines proposed by the CDC, advising health care services to implement protocols for extended use (use of the same N95 respirator

for an extended period, treating multiple patients before discarding) and limited reuse (reuse of the device in multiple visits or shifts, followed by storage for later use)^(10,11). These protocols are not restricted to periods of crisis to address equipment shortages. In countries with a high incidence of respiratory diseases, such as tuberculosis and measles, their adoption helps to reduce costs and ensure healthcare worker protection in different risk contexts^(4,11,12).

The lack of evidence proving the integrity and functionality of N95 respirators after extended use or reuse raises concerns about occupational safety. These practices can increase the risk of exposure of healthcare professionals to infectious agents during activities such as donning, doffing, adjusting and repositioning the device⁽¹²⁾. Additionally, with prolonged use and successive reuses, N95 respirators become more susceptible to structural degradation, including folds, tears, holes, stretching or rupture of the fastening components, as well as breakage of the nose clip. These changes substantially compromise the device's performance by reducing its ability to maintain an adequate seal⁽¹³⁾.

Recommendations on the reuse of N95 respirators vary among health institutions. The CDC establishes a maximum limit of five times, that is, five cycles of donning and doffing⁽¹¹⁾. However, there is no consensus among health authorities in different countries regarding the safe number of reuses, whether in terms of days or hours of use⁽⁸⁾.

The effectiveness of N95 respirators should be assessed considering their structural integrity, including the fastening components, and their functionality, with an emphasis on sealing, which is essential for a proper fit to the face to protect the mouth and nose. Additionally, the efficiency of the filter material must be sufficient to block at least 95% of airborne particles with an average diameter of 0.3 microns (μm)⁽¹⁴⁾.

Before starting this systematic review, a preliminary search was conducted in the main databases recommended by the Joanna Briggs Institute (JBI), including the Cochrane Database of Systematic Reviews and the International Prospective Register of Ongoing Systematic Reviews (PROSPERO), to identify existing or ongoing systematic reviews and meta-analyses on the topic⁽¹⁵⁾. This search revealed important gaps, especially regarding the comprehensive assessment of the structural integrity, sealing, elastic resistance of the fastening straps and filtration efficiency of N95 respirators subjected to extended use and reuse protocols in clinical practice.

The identification of these gaps justifies this review, which aims to support protocols that ensure the occupational safety of healthcare workers. Thus, this study aims to analyze the evidence on the effectiveness of extended use and reuse protocols for N95 respirators, focusing on the occupational safety of healthcare professionals.

■ METHOD

This is a systematic review of effectiveness, conducted according to the Joanna Briggs Institute guidelines and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol⁽¹⁶⁾. The study was registered with PROSPERO under number CRD42024574896. The methodological steps included the formulation of the guiding question, literature search, study selection, data extraction, assessment of the level of evidence and methodological quality, narrative synthesis of the data, as well as writing and publishing the results⁽¹⁷⁾.

The research question was developed using the PICO strategy, defined as follows: P (Population): N95 respirators; I (Intervention): extended use/reuse of N95 respirators; C (Comparison): structural integrity, filtration efficiency (airborne particle retention capacity), and

sealing (adequate fit) of new N95 respirators; (Outcome): maintenance of integrity, filtration and sealing of N95 respirators, aiming at the occupational safety of healthcare professionals. Thus, the following question was formulated: Are protocols for extended use and reuse of N95 respirators effective in maintaining structural integrity, filtration efficiency and sealing, compared to new N95 respirators, ensuring the occupational safety of healthcare professionals?

The search was conducted in the Medical Literature Analysis and Retrieval System Online (MEDLINE) databases via PubMed, SCOPUS, Web of Science Core Collection, Cochrane Central Register of Controlled Trials (CENTRAL) and Excerpta Medica Database (EMBASE) via Elsevier.

Controlled descriptors in the English language were used, according to the corresponding database, including Medical Subject Headings (MeSH) in MEDLINE/PubMed and Emtree exclusively in EMBASE, as well as uncontrolled descriptors (keywords) to broaden the retrieval of studies. The terms were combined using the Boolean operators OR and AND.

The search strategy, except in EMBASE, was: [(“N95 Respirators” OR Masks OR “Respiratory Protective Devices” OR “N95 Respirator” OR “Respirators” OR “N95 Face Masks” OR “N95 Face Mask” OR “N95 Masks” OR “N95 Mask” OR Filtering facepiece respirators) AND (“Equipment Reuse” OR “Equipment Recycling” OR “Product Recycling” OR Reuse OR Reusability OR Reusable OR Reusing OR Usability OR Reliably) AND (“Occupational Health” OR “Health Personnel” OR “Health Care Professional” OR “Health Care Professionals” OR “Health Professionals” OR “Healthcare Worker” OR “Healthcare Workers” OR “Occupational Safety” OR Respiratory Protection)]. In EMBASE, the following strategy was used: [(mask OR n95 OR “minimally 94 percent efficient filtering facepiece respirator” OR “PFF2 mask”) AND (recycling OR reuse) AND (“occupational health” OR “health care personnel”)]. The search terms were developed with the assistance of a librarian specialized in bibliographic research, and a manual review of the references of the articles found was conducted to identify additional relevant studies.

The inclusion criteria encompassed only publications available in indexed scientific journals, peer-reviewed and fully accessible for data extraction. Studies published between January 1, 2003, and October 15, 2024

were considered, which assessed the effectiveness of extended use and reuse protocols for N95 respirators, analyzing their structural integrity, filtration efficiency and sealing compared to new N95 respirators, with a focus on the occupational safety of healthcare professionals.

No language restrictions were applied. The search included experimental studies, such as randomized clinical trials, as well as quasi-experimental and observational studies. The selection period was defined based on the onset of recommendations for extended use and reuse of N95 respirators, developed in response to the SARS epidemic in 2003 and the H1N1 pandemic in 2009.

Articles that did not address protocols for N95 respirators reuse or extended use were excluded, as well as letters to the editor, opinions without scientific basis and studies available exclusively in preprint format.

The study selection was conducted independently by two researchers using the Rayyan[®] software. Initially, duplicate articles identified in the databases were removed. Then, the titles and abstracts were screened for pre-selection. In the subsequent stage, the full texts of the pre-selected articles were read in full by both reviewers to confirm final eligibility, based on the previously established inclusion and exclusion criteria. Any disagreements were resolved by consensus among the reviewers, and the intervention of a third researcher was not necessary.

Data extraction was performed independently by two reviewers using a structured form based on the JBI recommendations⁽¹⁵⁾. The form included the following information: author, year of publication, language, country, study design, sample size, extended use time, number of donning cycles, methods used for evaluation (tests applied), and damages identified as outcomes. It was not necessary to contact the authors of the studies to obtain additional information. The extracted data were organized in a Microsoft Excel 2019 spreadsheet for subsequent analysis.

This systematic review adopted a narrative synthesis approach, considering the heterogeneity of the included studies. The classification of the levels of evidence followed the guidelines of the Agency for Healthcare Research and Quality (AHRQ), although this classification was not used as an exclusion criterion. The studies were categorized as follows: Level 1:

meta-analyses of randomized controlled clinical trials; Level 2: experimental studies, such as randomized clinical trials; Level 3: quasi-experimental studies without randomization; Level 4: descriptive or qualitative studies, including observational research; Level 5: case reports or practical experiences; and Level 6: expert opinions or consensus⁽¹⁸⁾.

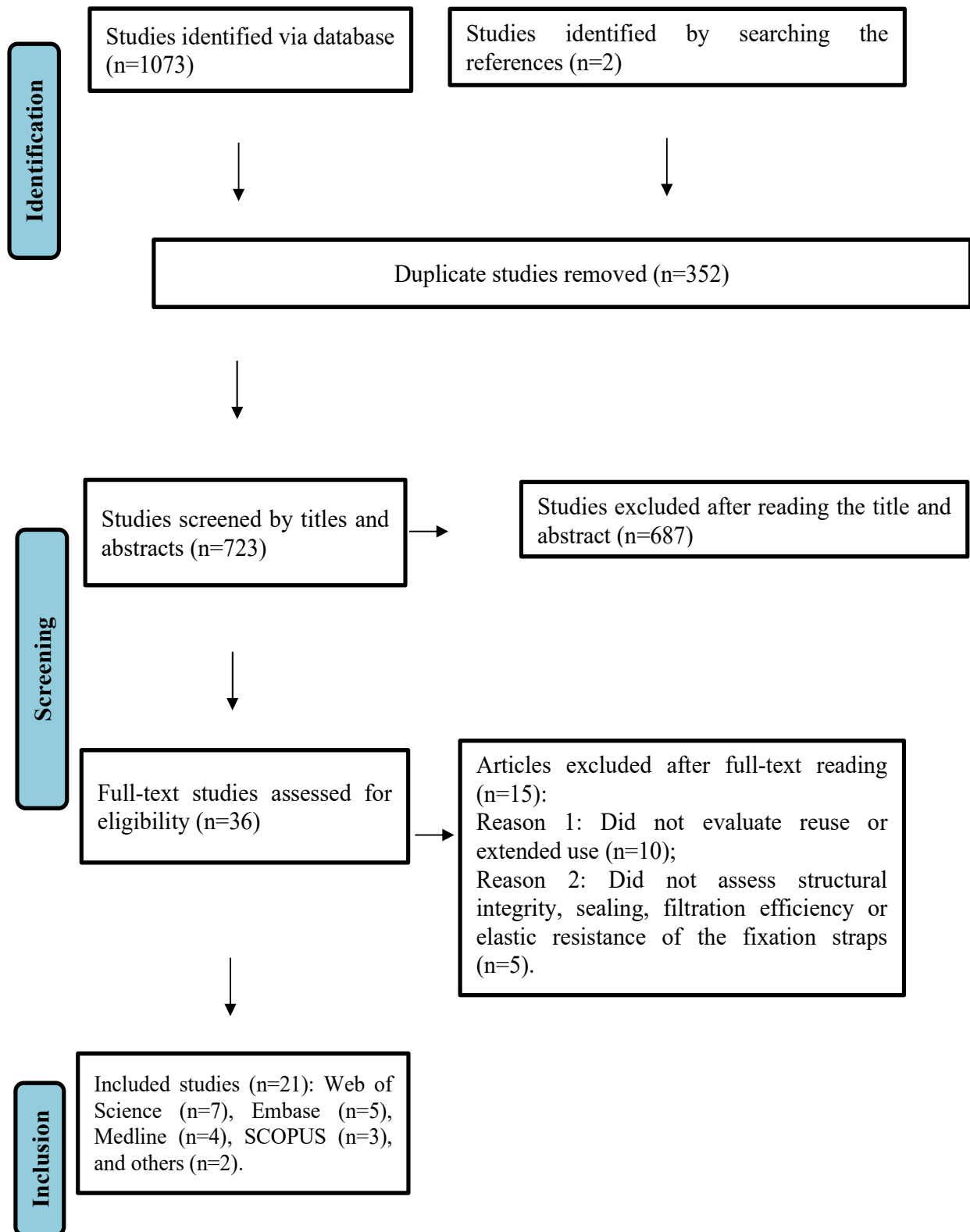
Methodological quality was assessed using JBI tools. For quasi-experimental studies, the Critical Appraisal for Quasi-Experimental Studies was applied, and for observational studies, the Critical Appraisal Checklist for Studies Reporting Prevalence Data^(19,20). Studies with all “yes” responses were classified as high quality; those with one to three negative responses (“no”, “unclear” or “not applicable”) as moderate quality; and those with four or more negative answers as low quality. The score was not used as an exclusion criterion but helped in the synthesis and interpretation of results.

As this is a systematic literature review, submission to the Research Ethics Committee (REC) was not necessary. All cited studies were properly referenced in accordance with ethical principles.

■ RESULTS

A total of 1,073 publications were identified in the following databases: Medline (n=477), Embase (n=270), Web of Science (n=220), CENTRAL (n=56), and SCOPUS (n=50), in addition to two additional articles obtained from the references of the selected studies. After removing duplicates (n=352), 723 articles were screened based on titles and abstracts, resulting in the selection of 36 articles for full-text reading. During this phase, there were minimal disagreements between the reviewers, which were resolved by consensus, without need for intervention by a third reviewer.

Upon full-text analysis, 15 articles were excluded because they did not meet the previously defined criteria, either because they did not evaluate protocols for extended use or reuse of N95 respirators, or because they did not analyze the established outcomes (structural integrity, filtration efficiency, sealing, and elastic resistance of straps). Thus, 21 articles were considered eligible and included in the final evidence synthesis. Figure 1 presents the detailed flowchart of the article selection process across the analyzed databases.

Figure 1. Flow of identification, screening and inclusion of studies. Belo Horizonte, Minas Gerais, Brazil, 2024Source: Adapted from Page *et al* (2021)⁽¹⁶⁾

All articles included in the review were published in English in the years 2010⁽²¹⁾, 2012^(13,22), 2017⁽²³⁾, 2019⁽²⁴⁾, 2020⁽²⁵⁻²⁸⁾, 2021⁽²⁹⁻³⁴⁾, 2022⁽³⁵⁾, 2023⁽³⁶⁾ and 2024⁽³⁷⁻⁴⁰⁾. The publications originated from the United States^(13,23,25,26,29-34,37,40), England^(22,24,27,28), Brazil^(21,38), Netherlands⁽³¹⁾, Taiwan⁽³⁶⁾ and Australia⁽³⁹⁾.

The studies were classified according to their design and level of evidence. Of the total, 12 were quasi-experimental, corresponding to Level 3 evidence^(13,22-24,26-29,32,35,36,40), while nine were observational (cohort and cross-sectional) studies conducted in health-care settings and classified as Level 4^(21,25,30,31,33,34,37-39). Methodological quality was assessed based on JBI criteria, and detailed results are presented in Chart 1.

Among the 12 quasi-experimental studies, four met all nine items of the tool, being classified as high quality^(28,35,36,40). Seven studies obtained “yes” in eight items^(13,23,24,26,27,29,32), and one study obtained “yes” in seven items⁽²²⁾, being classified as moderate quality. None of the studies used randomization, but all described similarity between groups at baseline, reducing selection bias. Only four studies^(28,35,36,40) included a control group, strengthening the comparative analysis.

Quasi-experimental studies had a positive assessment regarding outcomes measurement, using standardized tests, such as tensile test, filtration efficiency and seal test. However, no study reported additional strategies to minimize measurement bias,

Chart 1. Assessment of methodological quality using Joanna Briggs Institute tools: Critical Appraisal for Quasi-Experimental Studies (n=12) and Checklist for Studies Reporting Prevalence Data (n=9). Belo Horizonte, Minas Gerais, Brazil, 2024.

Studies	Methodological quality of quasi-experimental studies								
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Study 1 (2012) ⁽¹³⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 2 (2012) ⁽²²⁾	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Study 3 (2017) ⁽²³⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 4 (2019) ⁽²⁴⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 5 (2020) ⁽²⁶⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 6 (2020) ⁽²⁷⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 7 (2020) ⁽²⁸⁾	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Study 8 (2021) ⁽²⁹⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 9 (2021) ⁽³²⁾	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Study 10 (2022) ⁽³⁵⁾	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Study 11 (2023) ⁽³⁶⁾	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Study 12 (2024) ⁽⁴⁰⁾	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Studies	Methodological quality of observational studies								

Chart 1. Cont.

Studies	Methodological quality of quasi-experimental studies								
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Study 13 (2010) ⁽²¹⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 14 (2020) ⁽²⁵⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 15 (2021) ⁽³⁰⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 16 (2021) ⁽³¹⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 17 (2021) ⁽³³⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 18 (2021) ⁽³⁴⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 19 (2024) ⁽³⁷⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 20 (2024) ⁽³⁸⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-
Study 21 (2024) ⁽³⁹⁾	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	-

Note: Q1 to Q9 for quasi-experimental studies: Q1: Was the "cause" and "effect" relationship clearly defined? Q2: Were the participants in the groups similar? Q3: Did the participants in the groups receive similar treatment, apart from the intervention or exposure of interest? Q4: Was there a control group? Q5: Were pre- and post-intervention measurements taken for comparison? Q6: Was follow-up complete or, in case of losses, were the differences between the groups described and analyzed? Q7: Were the outcomes measured uniformly across the groups? Q8: Were the outcomes measured in a valid and reliable way? Q9: Was the statistical analysis appropriate? Q1 to Q9 for observational studies: Q1: Was the sample representative of the target population? Q2: Was the participant selection appropriate? Q3: Was the sample size adequate? Q4: Were the participants described in detail? Q5: Was a sufficient proportion of the sample included in the analysis? Q6: Were valid methods used to identify the condition of interest? Q7: Was the statistical analysis appropriate? Q8: Was the response rate appropriate? If low response, was it adequately addressed?

such as blinding of evaluators, which may compromise the reproducibility and internal validity of the studies.

In the evaluation of cohort and cross-sectional studies, all presented moderate methodological quality, with seven items marked as "yes"^(21,25,30,31,33,34,37-39). This outcome is due to the partial sample exclusion in the analysis, which may impact the representativeness of the findings.

The overall risk of bias was considered moderate, mainly due to the lack of randomization and blinding. Although the methods applied were standardized, the interpretation of the findings should be done with caution. Additionally, the methodological quality was

influenced by the lack of blinding of the evaluators, as this is not a common practice in observational studies.

The analysis of the integrity and functionality of N95 respirators is presented in Table 2, covering the main characteristics of the studies: year and country of publication, study design, sample size, extended use time, number of donning cycles, evaluation method and observed outcomes.

Below, all studies are presented according to the tests applied and the damages identified regarding occupational safety of healthcare professionals, in accordance with the PICO strategy.

Chart 2. Description of studies according to year of publication, country, design, sample size, extended use time, number of donning cycles, assessment method (including tests applied) and outcomes (n=21). Belo Horizonte, MG, Brazil, 2024.

Study (Year/Country)	Study design Sample	Extended use	Number of donning cycles	Evaluation method	Damage identified (Outcome)
Study 1 (2010) ⁽²¹⁾ Brazil	Cross-sectional (n=551)	1, 5, 15 and 30 shifts (6-12 h)	Not evaluated	Visual inspection	Personal identification marks in 100% after 1 day. Dirt or stains in 100% and folds in 80% (n=441) after 5 days. Greater dirt on the inner face, especially after 12 hours versus 6 hours of use (p < 0.05).
Study 2 (2012) ⁽¹³⁾ USA	Quasi-experimental (n=60)	5-25min 30-50min 55-75min 80-100min	1-5 6-10 11-15 16-20	Visual inspection Seal test	Rupture of the fixing straps in 8 cases: 1 after 15, 20, 40 and 90 minutes; 2 after 25 and 85 minutes. Nose clip breakage in 5 cases: 2 after 40 minutes and 3 between 80-90 minutes, all associated with 3 consecutive failures in the fit test. Fit test approval rate: 81-93% (≤ 25 minutes), reducing to 53-75% (80-100 minutes).
Study 3 (2012) ⁽²²⁾ England	Quasi-experimental (n=45)	2.5h	5 (1 every 15 min)	Tensile test	Degradation of the elastic resistance of the fixing straps was progressive throughout use, with greater loss after the first donning, corresponding to 15 minutes of use.
Study 4 (2017) ⁽²³⁾ USA	Quasi-experimental (n=120)	10min	Not evaluated	Seal test	Fit failure in 33.3% (n=40) after 10 minutes of the nursing procedure. Reduction in average fit factor from 184.8 to 134.7.
Study 5 (2019) ⁽²⁴⁾ England	Quasi-experimental (n=25)	30min	6 (1 every 5 min)	Visual inspection Seal test	No damage identified in the fastening components. Fit failure in 48% (n=12). Reduction in fit factor after the 1 st and 6 th donning (195 versus 150; p = 0.0271).
Study 6 (2020) ⁽²⁵⁾ USA	Cross-sectional (n=68)	1-5 shifts (median 12h)	8-15 (median)	Seal test	Fit failure in 38.2% (n=26), associated with increased shifts (median 4 versus 2; p < 0.001), donning (median 15 versus 8; p < 0.001) and hours of use (14 hours versus 12 hours; p $\leq$ 0.05).

Chart 2. Cont.

Study (Year/Country)	Study design Sample	Extended use	Number of donning cycles	Evaluation method	Damage identified (Outcome)
Study 7 (2020) ⁽²⁶⁾ USA	Quasi-experimental (n=44)	~ 15min	Not evaluated	Visual inspection Seal test	Strap loosening in 18% (n=8). Fit failure in 73% (n=32) in at least one of the 3 cardiopulmonary resuscitation simulations.
Study 8 (2020) ⁽²⁷⁾ England	Quasi-experimental (n=104)	10min	Not evaluated	Seal test Filtration	Fit failure in 33.7% (n=35), after the simulated nursing procedure. Reduction in the average fit factor from 185.1 to 135.5 ($p > 0.05$). Filtration efficiency of 99.0% maintained at 100% (n=20).
Study 9 (2020) ⁽²⁸⁾ England	Quasi-experimental (n=7)	30,25h (5 shifts of 6,25h)	19 (~ 4 per shift)	Visual inspection Seal test	Rupture of the fixing straps in 28.6% (n=2): 1 after 19, 25 hours (3rd donning) and another after 25.67 hours (4 th donning). Degradation of elasticity reported by most users. Delamination in the inner layer in 14.3% (n=1) ~30h (5 shifts). Fit failure in 85.7% (n=6) after 30, 25 hours. Reduction in the fit factor , becoming lower than the initial one after the 18 th and 19 th donning ($p < 0.05$).
Study 10 (2021) ⁽²⁹⁾ USA	Quasi-experimental (n=50)	4h, 1-7 and 14 shifts (8h)	Not evaluated	Filtration	Average filtration efficiency of 97% after 3 shifts, reducing to 80.4% after 14 shifts (112 h).
Study 11 (2021) ⁽³⁰⁾ USA	Cross-sectional (n=127)	1 and ≥ 5 shifts (6-12h)	Not evaluated	Seal test	Increased fit failure rate after 2 days: 33.3% on day 3, 42.9% on day 4, and 50% on day 5 or more. Higher incidence after 2 days (41.8% ≥ 3 days versus 8.3% ≤ 2 days; $p < 0.0001$).

Chart 2. Cont.

Study (Year/Country)	Study design Sample	Extended use	Number of donning cycles	Evaluation method	Damage identified (Outcome)
Study 12 (2021) ⁽³¹⁾ USA	Cross-sectional (n=92)	2,5h (median)	40 (median)	Visual inspection Seal test	No N95 respirator showed structural damage. Fit failure in 17% (n=16) after median of 40 donnings.
Study 13 (2021) ⁽³²⁾ USA	Quasi-experimental (n=10)	1h, 2h, 3h	~ 4	Seal test	Fit failure in 60% (n=6), 70% (n=7), and 90% (n=9) after the 2 nd , 3 rd , and 4 th donnings, respectively, after 1 h. After 3 h, 50% (n=5) failed after the 1st donning and 70% (n=7) after the 2nd. After 1 h of use, 50% (n=5) failed; after 2 h, 30% (n=3).
Study 14 (2021) ⁽³³⁾ USA	Cross-sectional (n=41)	6h (3 shifts of 2h)	Not evaluated	Seal test	Fit failure in 14.6% (n=6).
Study 15 (2021) ⁽³⁴⁾ USA	Cohort (n=127)	1 to ≥ 5 shifts (8-12h)	Not evaluated	Seal test	Fit approved in 61.2% (n=19) after ≥ 2h of use. Among those that passed the initial test and were used in > 5 shifts, 88% (n=45) maintained the fit. Higher failure rate in use > 2 shifts compared to ≤ 2 shifts (p < 0.0001).
Study 16 (2022) ⁽³⁵⁾ Netherlands	Quasi-experimental (n=60)	8h, 16h, 24h, 32h and 40h	19 (~ 4 per shift)	Filtration	Filtration efficiency maintained in 100% of samples after 24 hours, reducing from 98% to 92% after 32h.
Study 17 (2023) ⁽³⁶⁾ Taiwan	Quasi-experimental (n=30)	36h (3 shifts of 12h)	Not evaluated	Filtration	Filtration efficiency of 97% maintained in 100% of samples.

Chart 2. Cont.

Study (Year/Country)	Study design Sample	Extended use	Number of donning cycles	Evaluation method	Damage identified (Outcome)
Study 18 (2024) ⁽³⁷⁾ USA	Cohort (n=803)	1-5 shifts (8-12h)	~ 5 per shift	Seal test	Fit failure in 38.7% (n=309) after one shift and 92.8% (n=745) after 5 shifts.
Study 19 (2024) ⁽³⁸⁾ Brazil	Cross-sectional (n=10)	7 and 15 shifts (12h)		Visual inspection	Personal identification marks and dirt on the outer layer in 40% (n=2), internal dirt in 60% (n=3). Loosening/rupture of the fixing straps in 20% (n=1). Nose clip damage in 100% (n=5) after seven shifts. Dirt, nose clip damage, and loose straps in 100% (n=5); folds in 80% (n=4); internal layer delamination in 20% (n=2) after 15 shifts.
Study 20 (2024) ⁽³⁹⁾ Australia	Cohort (n=45)	2h10min (median); IQR: 2h07-2h20min	Not evaluated	Seal test	Fit failure in 31.1% (n=14) after a median of 2 hours and 10 minutes of use.
Study 21 (2024) ⁽⁴⁰⁾ USA	Quasi-experimental (n=10)	Not evaluated	5	Seal test	Fit failure in 50% (n=5) after five donning (p > 0.05).

Note: USA: United States of America; IQR: Interquartile Range
Source: Prepared by the authors (2024)

Integrity of the N95 respirator structure and components

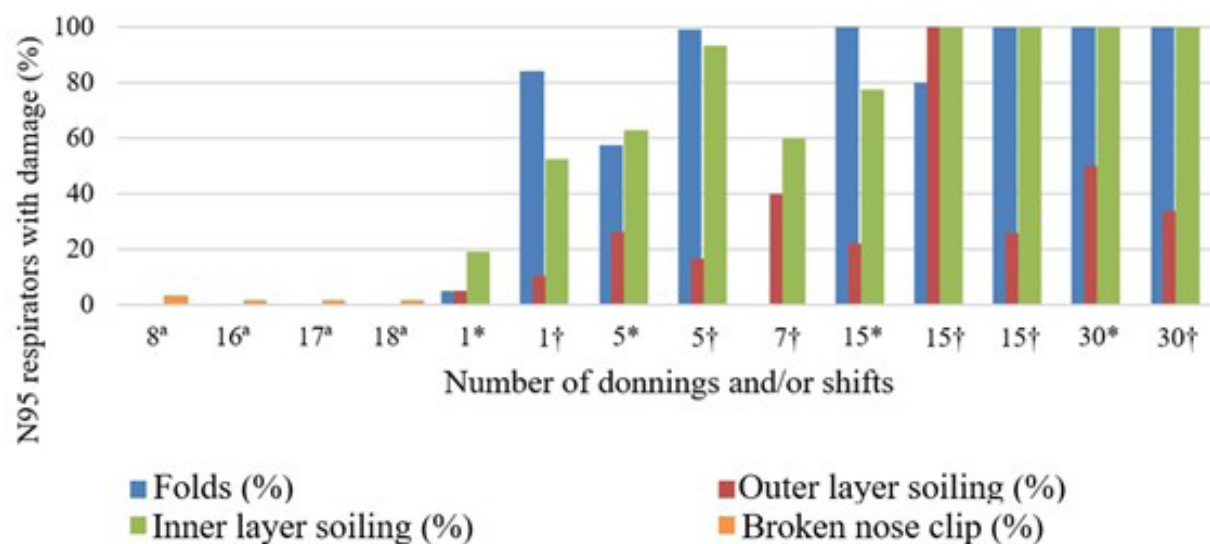
Seven articles (33.3%) evaluated, through visual inspection, the compromise of structural integrity and fastening components of N95 respirators after the application of different protocols^(13,21,24,26,28,31,38). These studies covered from one to 30 shifts, with durations varying between six and twelve hours and up to 19 donnings per shift^(21,28,38). Shorter periods of use were also analyzed, such as five to 25 minutes for one to five donnings; 30 to 50 minutes for six to 10 donnings; 55 to 75 minutes for 11 to 15 donnings; and 80 to 100 minutes for 16 to 20 donnings⁽¹³⁾. In a specific protocol, the N95 respirator was used for 30 minutes, with donnings performed every five minutes⁽²⁴⁾. Another study reported the use of respirators for approximately 15

minutes in cardiopulmonary resuscitation simulations, while another investigation described a median of 2.5 hours of extended use, with 40 donnings^(26,31).

The absence of visible damage to the structures of N95 respirators was reported, including soiling, tears, folds, holes, breakage of the nose clip or rupture of the straps, after 30 minutes of use with six donnings, performed every five minutes, and a median of 2.5 hours of use [interquartile range (IQR), 1-2 hours] with 40 donnings (IQR, 17-100), respectively^(24,31).

On the other hand, four studies identified damage to N95 respirators, such as folds and soiling of the layers, as well as damage to fastening components, including nose clip breakage. These analyses were performed by visual inspection, considering the number of donnings and the duration of the shifts^(13,21,28,38). Detailed results can be found in Figure 2.

Figure 2. Damage identified in the structural integrity and fastening components of N95 respirators, evaluated by visual inspection according to the number of donnings and shift duration (n =4). Belo Horizonte, MG, Brazil, 2024



Note: ^aSix-hour shift; [†]12-hour shift.

Four studies identified damage to the integrity of the N95 respirators fastening straps during extended use or reuse^(13,27,28,38). In a simulation with 20 consecutive donning procedures, representing a 10-hour shift, 13.3% (8/60) of the devices presented strap breaks, with incidents occurring at varying times: two breaks in the fifth and 17th donning, and one in the third, fourth, eighth and 18th⁽¹³⁾. After five shifts, lasting approximately 6.25 hours and up to four donnings per day, 28.6% (2/7) of the fastening straps broke on days three and four of use, and most users (4/7) reported loss of elasticity

over five shifts⁽²⁸⁾. After 15-minute chest compression simulations, 18% (8/44) of the N95 respirators presented loosening of the fastening straps⁽²⁶⁾. Furthermore, in visual inspections of N95 respirators reused in seven- and 15-shift protocols, 20% (1/5) and 100% (5/5), respectively, exhibited strap loosening and/or breakage⁽³⁸⁾.

Partial delamination of the inner layer was observed in 14.3% (1/7) of the N95 respirators after five shifts of approximately six hours each, totaling 19 donnings⁽²⁸⁾. This aspect was also noted in 20% (2/5) of the devices reused in 15-day protocols⁽³⁸⁾.

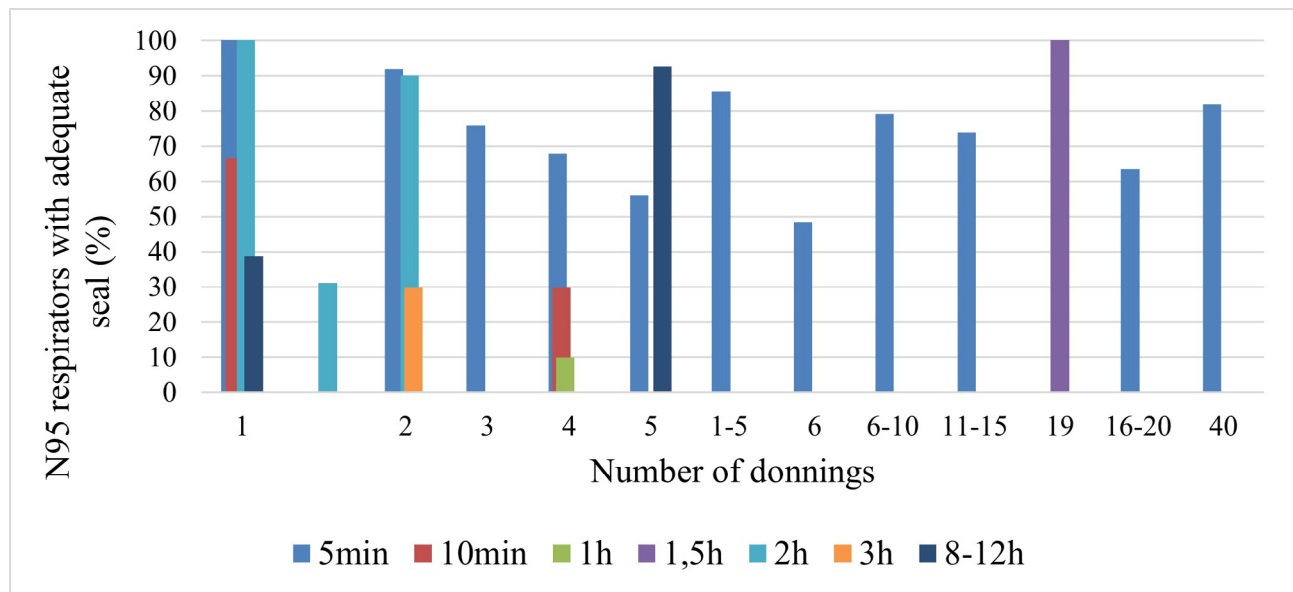
Sealing

From the studies evaluated, 71.4% (15/21) analyzed the functionality of N95 respirators, focusing on adequate sealing to the user's face through the fit test^(13,23,24-28,30-34,37,39,40). Among them, nine applied the quantitative fit test and six used the qualitative method.

Figure 3 shows the proportion of N95 respirators that maintained an adequate seal, as assessed by the fit test, in relation to the total usage time and the number of donning and doffing procedures.

The ability of N95 respirators to maintain an adequate seal, assessed by the fit test in relation to the number of shifts, was analyzed in five studies^(25,30,33,34,37). One of the studies showed that, after a shift of eight to 12 hours, 100% of N95 respirators (11/11) maintained an adequate seal; however, this proportion decreased to 91.7% after two shifts, 76.9% after three shifts, and only 33.3% maintained a satisfactory seal after more than three shifts, evidencing a significant association between usage time and loss of seal ($p < 0.001$)⁽²⁵⁾. Another study reported that 90.6% (29/32)

Figure 3. Frequency at which N95 respirators maintained an adequate seal, as assessed by the fit test in the studies analyzed (n=21), in relation to the total usage time and the number of donnings (n=14). Belo Horizonte, Minas Gerais, Brazil, 2024.



of the devices remained effective in the first shift, 92.9% (26/28) in the second, declining to 66.7% (18/27) in the third shift, 57.1% (8/14) in the fourth and 50% (13/26) from the fifth onwards⁽³⁰⁾.

Complementary investigations reinforce these results. In one of them, 100% of the N95 respirators (41/41) maintained a satisfactory seal in the first shift, reducing to 90% (37/41) in the second and 85.4% (35/41) in the third⁽³³⁾. Similarly, another study indicated that the fit was maintained in 95% (37/39) of devices after two shifts, but efficacy dropped to 86.2% (25/29) after three or more shifts, with a significant increase in seal failure with extended use ($p < 0.0001$)⁽³⁴⁾. Finally,

it was found that 38.7% (309/802) of N95 respirators failed to fit after one shift, and 92.8% (745/802) failed after five consecutive shifts⁽³⁷⁾. When only the number of donnings was analyzed, it was observed that 50% (5/10) of N95 respirators failed to fit after five donning and doffing procedures⁽⁴⁰⁾.

Filtration efficiency

Four articles (19.0%; 4/21) investigated the maintenance of N95 respirators functionality after extended use and reuse, focusing on the retention capacity of particles up to 0.3 μ , presenting a minimum efficiency of 95%^(27,29,35,36). All tests were conducted in compliance

with the standards established by NIOSH. The analyses of filtration efficiency, both in simulated environments and after the use of N95 respirators in 10-minute procedures (n=104), in up to seven eight-hour shifts (n=19) and in devices reused for three 12-hour shifts (n=30) in the Sterile Processing Department (SPD), showed a high performance in the filtration of aerosolized particles, ranging from 94% to 99%^(27,35,36). However, it was recorded that a single N95 respirator, when reused for 14 days in eight-hour shifts, presented a filtration efficiency of 80.7%⁽²⁹⁾.

Integrity/degradation of the elastic resistance of the fastening straps

Only one study (4.8%), conducted by the National Institute for Occupational Safety and Health, assessed the degradation of the elastic resistance of the fastening straps (top and bottom) of N95 respirators⁽²²⁾. This study used the tensile test to simulate the reuse of the device over a period of 2.5 hours, with five donnings, each followed by 15 minutes of use⁽²²⁾. The findings showed that from the first donning onwards there was a progressive decline in the elastic resistance of these components, with the greatest decrease recorded after the first 15 minutes⁽²²⁾.

Recommendations regarding the total usage time and/or number of donnings of N95 respirators, for occupational safety of healthcare professionals

Recommendations for N95 respirator use aimed at healthcare professionals' safety vary in terms of the total usage time and the number of donnings. Six studies suggest avoiding both reuse and prolonged use, even for short periods, highlighting the need for caution^(23,26,27,32,39,40). Other evidence points out that reuse may be feasible for limited intervals, lasting up to 30 minutes and between two to six donning cycles^(22,24).

The shift limits for safe reuse also present discrepancies. The minimum recommended includes a 12-hour shift or a median of 2.5 hours, with up to 40 donning cycles^(21,31). The maximum suggested is five shifts, with around four donning cycles or up to 8 hours per shift^(28,35). In another recommendation, safe reuse is suggested for

up to five shifts of 8 to 12 hours, if the N95 respirators pass the initial seal test⁽³⁴⁾. Alternatively, three articles indicate that reuse is adequate for up to two shifts of 6 to 12 hours or up to three shifts of 8 or 12 hours^(29,30,36). In addition, extended use is recommended for up to three 2-hour shifts⁽³³⁾. Regarding donning cycles, the maximum recommended limit is five cycles, although some studies do not establish a specific time^(22,23,37,38).

DISCUSSION

The results of this systematic review, based on visual inspections, indicate that N95 respirators may show signs of degradation of the nose clip and fastening straps, as well as the formation of folds and accumulation of dirt, both after extended use and reuse protocols and even during single use^(13, 21,28). Additionally, devices used in 12-hour shifts demonstrated greater deterioration of the inner layer compared to those used for six hours ($p \leq 0.05$)⁽²¹⁾. These findings are corroborated by a clinical study conducted in a tertiary hospital in India during the COVID-19 pandemic, in which 9% of healthcare professionals reported loosening of the fastening straps after five reuses in eight-hour shifts, which is one of the main factors for the early disposal of N95 respirators⁽⁴¹⁾.

The regulations recommend the immediate disposal of N95 respirators that show signs of dirt, moisture, tears, wrinkles or creases^(1,11). However, implementing these guidelines in clinical routines is complex, especially due to the lack of regular training focused on visual inspection and checking the sealing of these devices before each use^(25,42). This issue is aggravated during public health crises and during periods of long working hours for healthcare professionals, when the demand and the need for frequent replacement increase costs and pose challenges to the efficient management of available resources⁽⁴³⁾.

An important gap identified in many of the analyzed studies was the lack of information on the storage of N95 respirators after use. The lack of infrastructure and effective actions to raise awareness among healthcare professionals about this practice has resulted in improvised and inadequate storage, with respirators being kept in backpacks or personal bags^(21,31,38).

Studies corroborate these findings. One of them identified N95 respirators with insufficient sealing and musty or chemical odors, suggesting poor storage conditions⁽⁴⁴⁾. Moreover, a systematic review on the extended use and reuse of N95 respirators during the COVID-19 pandemic reinforced the need for strict protocols for storing and labeling PPE between uses, preventing inappropriate sharing among healthcare professionals⁽⁴⁵⁾.

The preservation of the characteristics and effectiveness of N95 respirators directly depends on proper storage, preferably in brown paper envelopes or porous plastic bags, in designated areas within hospital institutions⁽¹⁾. The environment must have temperature control between 21 and 23 °C and relative humidity of 40%⁽⁴⁶⁾. Otherwise, moisture retention in N95 respirators, associated with insufficient drying time, can favor the proliferation of microorganisms, increasing the risk of contamination and compromising occupational safety in the hospital environment^(12,47).

In extended use and reuse protocols, the risk of cross-transmission of pathogens between patients and healthcare professionals is high⁽¹⁴⁾. This phenomenon occurs mainly during donning and doffing procedures, as well as when adjusting the N95 respirator, when users inevitably touch the external and internal surfaces of the equipment, facilitating the transfer of microorganisms to their hands and spreading pathogens⁽¹²⁾. In this context, the adoption of standardized protocols for donning and doffing, combined with simulation-based training or demonstration by infection control specialists, is essential to minimize these risks⁽⁴⁸⁾.

The reuse of N95 respirators is particularly critical in intensive care units (ICU), where aerosol-generating procedures such as tracheostomies, intubations, and cardiopulmonary resuscitation are frequent in patients with more severe conditions, who have higher viral loads in respiratory secretions^(1-3,47). Additionally, prolonged exposure and inadequate ventilation in these environments increase the concentration of viral particles in the air, increasing the risk of aerosol-based contamination^(49,50). These conditions make nursing professionals particularly vulnerable, since they represent a significant portion of the clinical workforce and have prolonged contact with infected patients^(51,52).

During the COVID-19 pandemic, the National Nurses United (NNU) in the United States, expressed strong objections to the CDC guidelines on the reuse and extended use of N95 respirators, highlighting the lack of sufficient scientific evidence to ensure the safety of these practices⁽⁵³⁾. Similarly, in Brazil, at the height of the pandemic in March 2021, five out of every three thousand individuals who died due to complications from COVID-19 were healthcare professionals, highlighting the challenges faced and reinforcing NNU's concerns about the safety of the protective measures implemented⁽⁵⁴⁾.

In the systematic review, most studies evaluated the efficiency of N95 respirators through seal tests, demonstrating that adjustment failures increase with the number of work shifts and donning cycles performed^(25,30,34). A progressive reduction in the adjustment factor was also observed as the usage time or donning frequency increased^(24,27,28). Seal test failures greater than 5% are considered unacceptable, since lateral leakage allows the entry of aerosol particles containing infectious agents, even when the filter material is highly efficient^(12,55,56). In clinical contexts, these problems are aggravated, due to anatomical variations between users, the repetition of donning and doffing cycles, and the frequent need for adjustments or repositioning of N95 respirators, motivated by discomfort or the need for communication, further compromise the seal^(12,14,56-58).

The National Institute for Occupational Safety and Health recommends periodic fit test, both quantitative and qualitative, to ensure that N95 respirators fit correctly on the user's face⁽⁵⁹⁾. However, the systematic adoption of this test in healthcare services faces challenges, especially in low- and middle-income countries, due to the lack of regulations that make it mandatory, the unavailability of N95 respirators in different sizes, and the lack of clinical teams trained to deliver specialized training⁽⁵⁵⁾.

This gap was also highlighted in the systematic review, in which most studies analyzed the seal through laboratory tests, without consistent application in clinical practice. International health organizations emphasize the importance of ongoing training of healthcare professionals in strategies such as user seal checks, an

essential measure that minimizes adjustment failures and ensures occupational safety^(1,11).

The tensile test, which assessed the elastic resistance of the fastening straps of N95 respirators, revealed a progressive decline after 2.5 hours of use, distributed in five 15-minute donning cycles⁽²²⁾. Although small isolated changes may not directly compromise the performance of N95 respirators, due to natural variations in length and head positioning, repeated wear throughout work shift exacerbates the deterioration of the straps, reducing the seal and, consequently, the device's effectiveness^(56-58,60).

The filtration capacity of N95 respirators, designed to filter particles up to 0.3 µm with a minimum efficiency of 95%, remained high in several clinical situations. In procedures involving the insertion and suction of a nasogastric tube for 10 minutes, as well as in reuse during five consecutive shifts of 8 to 12 hours, the filtration capacity of these devices remained high, ranging from 94% to 99%^(27,35,36). However, during prolonged use for up to 14 days, a decrease in filtration efficiency to 80% was observed⁽²⁹⁾. This divergence underscores the urgent need to simultaneously evaluate other attributes of N95 respirators, especially in extended use or reuse protocols.

Scanning electron microscopy has been employed for objective analyses of N95 fibers morphology, identifying damage such as porosity, cracks and microholes not visible to the naked eye⁽⁶¹⁾. However, only one study included in this review, conducted in intensive care units using reuse protocols of 7 and 15 days, confirmed these changes, evidencing the impact of this practice on fiber integrity⁽³⁸⁾. The lack of resources for this type of analysis may justify the lack of further studies using this approach, which limits the understanding of possible morphological changes resulting from these protocols.

The lack of microscopic analyses, although important, is not the only factor that makes it difficult to determine a safe maximum number of reuses. National and international guidelines differ and, in many cases, do not establish clear limits for reuse or extended use,

further increasing uncertainty⁽⁸⁾. Most protocols adopt visual inspections and seal tests, important measures, but are insufficient to assess the efficiency of N95 respirators over time.

Given this scenario, the safe reuse of N95 respirators requires the implementation of rigorous infection control and mitigation protocols, which include precise guidelines on visual inspection to verify structural integrity, seal tests before each use, safe storage, defined criteria for disposal, and limitation of the number of reuses based on evidence. In addition to these guidelines, ongoing training of professionals is essential to ensure the correct use of the N95 respirator and the proper execution of donning and doffing procedures. However, the lack of standardized guidelines, combined with the shortage of PPE and high costs, has led to the indiscriminate reuse of these devices, increasing occupational health risks⁽⁶²⁾.

This study has some limitations. Most of the research was conducted in laboratory settings, which may not accurately reflect clinical practice. Moreover, the small number of samples in some articles analyzed may compromise the generalization of the findings. Another factor to consider is that the review was based exclusively on major health science databases, such as PubMed, Embase, and SCOPUS, without the inclusion of gray literature, which may restrict the scope of the evidence analyzed.

■ CONCLUSION

N95 respirators are intended for single use, since extended use and reuse compromise essential safety attributes, such as structural integrity and sealing, increasing occupational risk. Although filtration efficiency has remained high in some clinical situations, ensuring the retention of at least 95% of airborne particles with an average diameter of 0.3 µm, this factor alone is not enough to ensure adequate user protection. Therefore, if extended use and reuse are unavoidable, it is essential to implement strict protocols for continuous monitoring of these critical attributes.

Healthcare institutions must ensure adequate infrastructure for the safe storage of N95 respirators and promote periodic training on safe use practices. These measures are essential to raise awareness among healthcare professionals about the risks of inappropriate reuse and ensure correct adherence of protocols.

This study supports the development of public policies within the Unified Health System (*Sistema Único de Saúde*), reinforcing the need for evidence-based guidelines to ensure the safe use of N95 respirators. The implementation of standardized protocols, combined with investments in training and infrastructure, is essential to ensure occupational safety and optimize the management of PPE in the public health system.

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■ Data and material availability

<https://www.crd.york.ac.uk/PROSPERO/view/CRD42024574896>

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