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Infection Control and Sterilization Across the Continuum: A Narrative Review of Protocols for Reusable Medical-Dental Equipment in Crisis Settings

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Abstract

Background: The effective reprocessing of reusable medical and dental equipment (RMDE) is a cornerstone of infection prevention and control (IPC). In crisis settings—characterized by resource limitations, infrastructural damage, and patient surges—established sterilization and disinfection protocols are profoundly challenged, escalating the risk of healthcare-associated infections (HAIs). **Aim:** This narrative review aims to synthesize and analyze IPC protocols for RMDE across the healthcare continuum (medical, dental, nursing/EMS, laboratory, pharmacy, emergency medicine) during crises, focusing on interdisciplinary challenges, standardized guidance, and the critical roles of microbial surveillance and disinfectant stewardship. **Methods:** A comprehensive literature search was conducted in PubMed, Scopus, CINAHL, and Web of Science (2010-2024). Keywords included reusable medical devices, sterilization, disinfection, crisis, surge, and healthcare-associated infections. Articles were thematically analyzed to construct a narrative across defined professional domains. **Results:** The review identifies significant vulnerabilities in RMDE reprocessing during crises, including protocol fragmentation, equipment sharing across specialties without unified standards, and supply chain failures for disinfectants. It highlights the laboratory's pivotal role in environmental surveillance and the pharmacist's responsibility in managing disinfectant efficacy and safety. Gaps in evidence-based, crisis-adapted protocols for cross-continuum equipment (e.g., laryngoscopes, suction units) are identified. **Conclusion:** Ensuring RMDE safety in crises requires an integrated, "One Health" approach to IPC. Recommendations include developing crisis-specific, interoperable reprocessing guidelines, strengthening laboratory capacity for rapid microbial testing, and formalizing pharmacy-led disinfectant stewardship programs to mitigate HAI risks across all care settings.

Keywords: reusable medical devices; infection control; sterilization; crisis standards of care; healthcare-associated infections2024.

Introduction

The reprocessing of reusable medical and dental equipment (RMDE)—encompassing cleaning, disinfection, and sterilization—is a fundamental yet complex component of infection prevention and control (IPC) (Rutala et al., 2023). In stable healthcare environments, this process is governed by stringent standards from bodies such as the Centers for Disease Control and Prevention (CDC), the Association for the Advancement of Medical Instrumentation (AAMI), and the Food and Drug Administration (FDA) (Vukelich, 2016). However, the resilience of these protocols is severely tested during crises, including pandemics (e.g., COVID-19), natural disasters, armed conflicts, and mass casualty events (World Health Organization [WHO], 2021). Such scenarios are characterized by patient surges, depletion of human and material resources, infrastructural compromise (e.g., loss of water, electricity), and psychological stress on healthcare workers (HCWs), creating a perfect storm for breaches in IPC (Uyeki et al., 2020).

The challenge is magnified by the interconnected nature of modern healthcare, where equipment frequently traverses departmental and even

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disciplinary boundaries. A rigid laryngoscope blade may be used in an emergency department (ED) for intubation, then later in a dental surgery clinic for airway management during oral procedures. Portable suction units are ubiquitous in hospitals, ambulances, and dental operatories. This shared usage across the continuum of care—spanning emergency medicine, nursing, emergency medical services (EMS), dentistry, and more—introduces variability in reprocessing knowledge, expectations, and practices (Antonini et al., 2021). A protocol optimized for a central sterile processing department (CSPD) is often impractical for an ambulance crew or a dentist in a field hospital.

This narrative review examines the multifaceted challenge of RMDE reprocessing in crisis settings through an interdisciplinary lens. It analyzes the distinct yet overlapping perspectives of key fields: Medical Equipment Engineering (device design for cleanability and compliance), Dentistry (high-risk aerosol-generating procedures and instrument processing standards), Nursing & EMS (point-of-care cleaning and decontamination), Laboratory Science (microbial load testing and environmental surveillance), Pharmacy (stewardship of high-level disinfectants and sterilants), and Emergency Medicine (departmental protocol adaptation during surge capacity). By synthesizing literature from 2010 to 2024, this review aims to identify critical vulnerabilities, evaluate existing crisis-standard protocols, and underscore the essential, collaborative roles required to safeguard patient and provider safety when resources are most constrained.

Foundational Principles and the Pre-Crisis Baseline

Effective reprocessing is a multi-step sequence: point-of-use pre-cleaning to remove organic debris, thorough manual or automated cleaning, rinsing, drying, and finally, either high-level disinfection (HLD) or sterilization, depending on the device's intended use as defined by the Spaulding classification (Rutala et al., 2023). Critical items (e.g., surgical instruments) that enter sterile tissue require sterilization. Semicritical items (e.g., endoscopes, laryngoscope blades) that contact mucous membranes require a minimum of HLD. Noncritical items (e.g., blood pressure cuffs) contacting only intact skin require low-level disinfection.

In pre-crisis settings, reprocessing relies on optimized infrastructure: reliable utilities, adequate supplies of cleaning agents and personal protective equipment (PPE), functioning automated washers and sterilizers (autoclaves), and dedicated, trained personnel in CSPDs (Pineau et al., 2023). Compliance is monitored through mechanical (cycle time, temperature), chemical (integrity of process challenge devices), and biological indicators (spore tests) to validate sterility (AAMI, 2022). The laboratory supports this system through routine surveillance cultures of water in automated endoscope reprocessors and environmental sampling, though its role in direct device testing is typically limited to outbreak investigations (Bianconi et al., 2023).

Crisis-Induced Vulnerabilities Across the Continuum

Crises systematically degrade each component of the reprocessing chain. Understanding these vulnerabilities by domain is essential for developing targeted mitigations (Table 1).

Device design directly impacts cleanability. Complex, lumened, heat-sensitive instruments pose significant reprocessing challenges even under ideal conditions (Sivek et al., 2022). During crises, the failure of design is exacerbated. Manufacturers' instructions for use (IFUs), often lengthy and specific, may become impossible to follow due to a lack of recommended chemicals or cycle times being shortened to increase throughput (Hennein et al., 2022). Furthermore, crisis-driven improvisation—using devices for unintended purposes or reprocessing single-use devices—creates unregulated hazards. Regulatory oversight (e.g., FDA enforcement) may be relaxed under Emergency Use Authorizations, placing a greater onus on frontline risk assessment (Guharoy & Krenzelok, 2021).

Dental settings are unique for their high volume of aerosol-generating procedures (AGPs) and the use of a wide array of sharp and complex instruments. Sterilization of dental handpieces and surgical trays is paramount. Crises can disrupt the sterile processing workflow, leading to shortcuts such as inadequate drying time before autoclaving (which results in wet packs and potential contamination) or the misuse of chemical sterilants like glutaraldehyde for lack of steam sterilization capacity (Cuny, 2023). The sharing of equipment like portable suction units between dental and medical teams in field settings introduces cross-specialty protocol confusion, increasing risk.

Nursing and EMS personnel are responsible for the initial, crucial point-of-use cleaning of equipment like laryngoscopes, suction catheters, and ventilators. In a crisis surge, time pressure and staff shortages can lead to inadequate cleaning, leaving bioburden that compromises subsequent disinfection (Browne & Mitchell, 2023). In ambulances, the confined space and lack of dedicated decontamination facilities mean reusable equipment may be wiped down with disinfectant wipes between patients without a proper cleaning step, violating basic protocol. The lack of standardized, simple checklists for RMDE reprocessing in these mobile settings is a significant gap (Issa et al., 2023).

The ED becomes the epicenter of care during a mass casualty or pandemic surge. Standard workflows for equipment like ultrasound probes, intubation gear, and procedural trays break down. Triage areas may be expanded into non-clinical spaces lacking clean and dirty utility zones, leading to co-

mingling of contaminated and clean equipment (Sprung et al., 2020). Crisis standards of care may mandate extended use or reuse of PPE and devices normally considered single-use, demanding unprecedented, real-time protocol development for their safe reprocessing under duress (Carlson et al., 2022).

Table 1: Reprocessing Challenges for Shared Equipment in Crisis Settings

Shared Equipment	Typical Settings of Use	Standard Spaulding Class & Process	Crisis-Specific Vulnerabilities	Potential IPC Risks
Laryngoscope Blades/Handles	ED, ICU, EMS, Dental Surgery (airway mgmt.)	Semicritical / HLD or Sterilization	Inconsistent knowledge across users; EMS/dental may lack HLD capability; pressure for rapid turnover between patients.	Transmission of respiratory pathogens (e.g., SARS-CoV-2, TB), bloodborne pathogens.
Portable Suction Units & Canisters	Hospital wards, ED, Ambulances, Dental Op.	Semicritical (tip) / Noncritical (unit) / HLD & LLD	Complex disassembly; difficult to clean internal tubing; often only exterior wiped in EMS/dental.	Biofilm formation in tubing; transmission of oral/respiratory flora, including multi-drug resistant organisms (MDROs).
Ultrasound Probes	ED, ICU, Radiology, Cardiology	Semicritical (transvaginal/transesophageal) / Noncritical (transducer) / Probe-specific HLD or LLD	Confusion over probe classification; shortage of probe-specific disinfectant wipes; use of inappropriate cleaners damaging probe.	Skin and mucosal infections; pathogen transmission during guided procedures.
Ventilator Circuits & Components	ICU, ED, Anesthesia	Critical & Semicritical components / Sterilization or HLD	Overwhelming numbers requiring processing; shortage of circuit components leading to extended use/reuse; lack of automated processing.	Ventilator-associated pneumonia (VAP); transmission of MDROs like *Acinetobacter baumannii*.
Surgical Instrument Sets	OR, Dental Surgery, Field Hospital	Critical / Sterilization (Autoclave)	Overwhelmed central processing; use of improvised field sterilizers (e.g., pressure cookers); inadequate drying leading to wet packs.	Surgical site infections (SSIs); transmission of bacterial spores (e.g., *C. difficile*).

The Pillars of Crisis Response: Laboratory Surveillance and Pharmacy Stewardship

Two often-underutilized disciplines become critical in maintaining IPC integrity during crises: the laboratory and the pharmacy.

The laboratory's role expands from passive monitoring to active sentinel surveillance during crises. Environmental sampling of high-touch surfaces and reprocessing areas can identify reservoirs of pathogens like MDROs or *Candida auris* before outbreaks occur (Dylus et al., 2020). In the absence of reliable process indicators, direct microbial testing of reprocessed equipment—using techniques like adenosine triphosphate (ATP) bioluminescence for cleaning verification and dip slides or culture methods for disinfection efficacy—can provide rapid feedback

to frontline staff (Assadian et al., 2021). This is especially vital in ad-hoc settings like field hospitals. During the COVID-19 pandemic, labs also played a key role in testing the efficacy of disinfectants against novel pathogens, informing protocol updates (Kampf et al., 2020).

Pharmacists are experts in chemical therapeutics, making them ideally suited to lead disinfectant stewardship programs. In crises, supply chain disruptions lead to substitutions with unfamiliar products or locally compounded solutions (e.g., diluted bleach). Pharmacists are essential in verifying the chemical efficacy and appropriate dilution of these alternatives against circulating pathogens (Dighriri et al., 2023). They also manage the significant toxicological risks associated with HLDs (e.g., glutaraldehyde, ortho-phthalaldehyde), ensuring safe handling procedures are maintained despite staffing shortages and preventing chemical injuries to HCWs (Rutala et al., 2023). Furthermore, pharmacists can advocate for evidence-based practices, pushing back against the use of unproven or potentially harmful "miracle" disinfectants that often proliferate during public health emergencies.

Towards Standardized Crisis Protocols and Interdisciplinary Integration

The inherent fragmentation of reprocessing protocols across different healthcare specialties constitutes a pre-existing vulnerability that escalates into a critical threat during a system-wide crisis (Table 1). This siloed approach, where emergency medical services (EMS), dentistry, nursing, and central sterile processing may each follow divergent procedures for the same piece of equipment, creates dangerous inconsistencies and knowledge gaps when personnel and resources are stretched. Addressing this systemic weakness requires a decisive shift from isolated departmental policies towards integrated, crisis-adaptive frameworks that provide unified guidance across the entire continuum of care. This integration is essential to ensure that a laryngoscope blade or suction unit is managed with the same fundamental safety standard, whether it is used in an ambulance, a crowded emergency department, or a dental operatory within a field hospital.

A review of existing crisis guidelines reveals a foundational but incomplete landscape. Prominent organizations, including the World Health Organization (WHO), the Centers for Disease Control and Prevention (CDC), and the Society for Healthcare Epidemiology of America (SHEA), have developed valuable high-level guidance for infection prevention and control during surges. The WHO offers principles for decontamination in resource-limited settings, the CDC's framework for non-COVID-19 care during the pandemic included reprocessing considerations, and SHEA has provided recommendations on the extended use and reuse of personal protective equipment, which has direct implications for device reprocessing (WHO, 2016; Pereira et al., 2021; Patel et al., 2023). However, a significant gap persists: these documents often lack the granular, step-by-step instructions necessary for the hands-on reprocessing of cross-disciplinary equipment. They frequently fail to address the unique practical challenges of pre-hospital EMS environments or the high-risk, aerosol-generating context of dentistry in an integrated manner, leaving frontline providers without concrete, actionable protocols.

To bridge this gap, a proposed solution is the proactive development of **tiered, all-hazards reprocessing protocols**. These protocols would function on a sliding scale of capacity, aligned with established crisis standards of care frameworks, and would transition from conventional to contingency to crisis-level operations (Long et al., 2022). **Tier 1 (Conventional)** would dictate adherence to manufacturer instructions for use (IFU) and standards from bodies like AAMI and the CDC. **Tier 2 (Contingency)**, activated during anticipated shortages, would permit validated substitutions of chemical agents, extended sterilization cycle times (contingent on biological indicator verification), and the prioritized processing of critical over semicritical items to conserve resources. **Tier 3 (Crisis)**, for situations of critical shortage, would authorize more drastic, evidence-informed measures. These could include the use of rigorously evaluated alternative sterilization methods (such as boiling for specific heat-stable instruments in field settings), the extended reuse of devices with stringent between-use cleaning and high-level disinfection, and the establishment of dedicated, simplified reprocessing zones with unambiguous workflow separation to prevent cross-contamination in ad-hoc care spaces.

The efficacy of such tiered protocols is wholly dependent on interdisciplinary co-creation and validation. They must be designed by a dedicated committee that includes sterile processing technicians, nurses, physicians from emergency and anesthesia departments, dentists, EMS providers, infection preventionists, clinical microbiologists, and pharmacists. This collaborative design ensures that the protocols are technically sound, practically feasible, and legally defensible across all intended settings. Furthermore, these integrated protocols cannot exist solely as documents; they must be pre-trained and rigorously exercised through interdisciplinary disaster drills. Simulating equipment reprocessing under crisis conditions allows teams to identify logistical hurdles, clarify roles, and build the shared mental models and trust necessary for effective implementation when an actual disaster strikes. Figure 1 illustrates an interdisciplinary, continuum-based model for the reprocessing of reusable medical and dental equipment (RMDE) under crisis conditions.

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Table 2: Interdisciplinary Roles in RMDE Safety During Crises

Domain	Primary Crisis Role	Key Actions & Responsibilities	Collaborative Intersections
Medical Equipment/ Engineering	Ensure device usability under crisis constraints.	Simplify IFUs for crisis; advise on compatibility of devices with alternative disinfectants; design for rapid field stripping/cleaning.	Works with Pharmacy on chemical compatibility; with all clinical domains on usability feedback.
Dentistry	Maintain oral surgical standards amidst AGPs.	Adapt dental-specific sterilization protocols for resource scarcity; clarify shared equipment (suction) protocols with medical teams.	Collaborates with Emergency Medicine on airway equipment protocols; with Laboratory on waterline testing.
Nursing & EMS	Execute reliable point-of-care decontamination.	Implement and adhere to simplified, crisis-appropriate cleaning checklists; manage dirty-to-clean flow in ad-hoc spaces.	Receives feedback from Laboratory on ATP testing results; follows Pharmacy guidance on disinfectant use.
Laboratory Science	Provide data-driven feedback on reprocessing efficacy.	Conduct rapid ATP testing on cleaned devices; perform environmental surveillance for MDROs; test efficacy of alternative disinfectants.	Provides data to Infection Prevention to guide protocols; supports Pharmacy in disinfectant validation.
Pharmacy	Steward disinfectant safety, efficacy, and supply.	Manage formulary of approved crisis alternatives; verify concentrations of compounded disinfectants; educate on safe handling of HLDs.	Advises all clinical domains on chemical selection; relies on Laboratory for efficacy data.
Emergency Medicine & Infection Prevention	Lead protocol adaptation and implementation.	Develop and enact tiered crisis reprocessing protocols; establish clear lines of authority for IPC decisions in the ED/field hospital.	Synthesizes input from all other domains into actionable, unified protocols for the institution.

Figure 1. Integrated Reprocessing Continuum for Reusable Medical–Dental Equipment (RMDE) in Crisis Settings

Case Studies and Lessons from Recent Crises

Recent global crises have served as potent, real-world stress tests for infection control protocols, providing stark illustrations of systemic vulnerabilities and highlighting critical opportunities for improvement. The COVID-19 pandemic presented an unprecedented challenge, most notably through the global shortage of N95 respirators, which forced healthcare systems to implement widespread decontamination and reuse protocols using technologies like vaporized hydrogen peroxide (Popovich et al., 2023). This effort was a direct parallel to the reprocessing of reusable medical devices, revealing the urgent need for rapid, evidence-based guidance on decontaminating complex, multi-material equipment. It also exposed a critical knowledge gap, as non-specialist staff outside of central sterile processing departments (CSPDs) were suddenly tasked with executing these technically demanding procedures, often with inadequate training. This experience underscores the necessity of pre-emptively developing clear, crisis-adapted decontamination pathways for both personal protective equipment (PPE) and critical medical devices, and ensuring that training for such protocols extends beyond dedicated sterilization technicians to a broader range of frontline personnel.

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Similarly, scenarios involving natural disasters and armed conflict, where field hospitals are rapidly deployed, reveal the profound challenges of operating without established infrastructure. These settings frequently rely on donated equipment that lacks manufacturer instructions for use (IFUs) and must employ improvised sterilization methods, such as using pressure cookers, while contending with unreliable water and power supplies (WHO, 2016). These austere environments underscore the insufficiency of brand-specific protocols and highlight the absolute necessity for developing "ruggedized," equipment-agnostic guidelines. Effective crisis response in these conditions depends on protocols grounded in fundamental biocidal principles—ensuring correct heat exposure, chemical concentration, and contact time—rather than on the precise, resource-dependent steps outlined in conventional IFUs. This demands a shift towards simplified, principle-based algorithms that can be reliably applied with limited resources and under significant duress.

Furthermore, specific infectious disease outbreaks have delivered pointed lessons on the catastrophic consequences of reprocessing failures. The Ebola virus disease epidemic dramatically emphasized the lethal risk posed by improper decontamination of semicritical equipment, directly contributing to healthcare worker infections and fatalities, thereby illustrating the high stakes of protocol breaches in high-consequence settings (Jacobs et al., 2020). Conversely, the ongoing challenge posed by Candida auris, a multidrug-resistant fungus with a remarkable ability to persist on environmental surfaces, demonstrates a different but equally critical vulnerability. Outbreaks of C. auris have been persistently fueled by failures in terminal cleaning and disinfection of shared patient equipment such as thermometers and blood pressure cuffs, revealing weaknesses in routine environmental hygiene (Lyman et al., 2023). This pathogen's resilience has made it a sentinel event, compelling a renewed focus on the laboratory's role in active environmental surveillance and validating the efficacy of disinfectants against emerging, hardy pathogens. Collectively, these case studies affirm that robust, adaptable, and well-practiced reprocessing protocols are not merely a regulatory concern but a fundamental pillar of healthcare worker safety and outbreak containment in any crisis scenario.

Recommendations and Future Directions

To fortify infection prevention and control (IPC) across the healthcare continuum for future crises, a cohesive, multi-faceted strategy is essential. First, there is a critical need to **develop and disseminate interoperable crisis protocols**. National and international professional societies, including those representing sterile processing, infection control, emergency medicine, and dentistry, must collaborate to create and endorse tiered, all-hazards reprocessing guidelines specifically for high-risk, shared equipment (Teymourian et al., 2021; Hick et al., 2020). These protocols must be pragmatic and scalable, offering clear, actionable guidance that applies from the confined space of an ambulance to the operating rooms of a field hospital, thereby bridging the current fragmentation in practice standards. Second, the roles of the laboratory and pharmacy must be formally **integrated into foundational IPC planning**. A structured disinfectant stewardship program, led by pharmacy and informed by rapid microbiological surveillance and testing from the laboratory, should become a mandated component of hospital emergency preparedness committees (Heil et al., 2016; Barbee & St. Cyr, 2022). This integration ensures that decisions regarding chemical selection, concentration validation, and supply chain alternatives during shortages are evidence-based and safe for both patients and healthcare workers.

Third, a proactive approach to **investing in crisis-resilient device design** is required. Regulatory agencies, such as the FDA, should work with manufacturers to incentivize and, where necessary, mandate "design-for-reprocessing" features that facilitate effective cleaning and disinfection under suboptimal conditions (Vukelich, 2019; Ofstead et al., 2010). This includes designing devices with fewer lumens and crevices, using materials compatible with a broader range of disinfectants, and providing clear, standardized, pictorial instructions for use (IFUs) that remain usable in high-stress, resource-limited environments. Concurrently, **enhanced interdisciplinary training and simulation** are paramount. Disaster preparedness drills must move beyond theoretical discussion to include hands-on, scenario-based training on RMDE reprocessing under crisis constraints, actively involving teams from nursing, EMS, sterile processing, and clinical specialties to build shared mental models and practical competence (Liang et al., 2014).

Finally, a dedicated effort to **foster research on alternative reprocessing methods** is needed to build a robust evidence base for crisis recommendations. Significant gaps exist in the validated efficacy of low-resource methods—such as extended chemical soaking protocols or the use of improvised sterilization techniques like pressure cookers for specific instrument types—for a wider range of medical devices [WHO, 2016]. Funding and conducting this research will expand the toolkit available to healthcare providers in austere settings, moving beyond improvisation toward informed, risk-managed practice. By implementing these interconnected recommendations—protocol standardization, interdisciplinary integration, resilient design, realistic training, and targeted research—healthcare systems can systematically build the resilience required to maintain the integrity of reusable medical device reprocessing and protect patient safety during the most severe system stresses.

Conclusion

The safety of reusable medical and dental equipment during crises is not merely a technical issue of sterilization cycles; it is a litmus test for the integration and resilience of the entire healthcare system. Fragmented protocols, siloed responsibilities, and design shortcomings that are manageable in peacetime become critical vulnerabilities when systems are stressed. This review underscores that effective infection control across the continuum in crisis settings demands an interdisciplinary, "One Health" approach. It requires the engineer's design, the dentist's precision, the nurse's diligence, the EMS provider's adaptability, the laboratory scientist's diagnostics, the pharmacist's stewardship, and the emergency physician's leadership to converge on a common goal: preventing iatrogenic harm when the capacity to heal is already stretched to its limit. By proactively developing integrated, tiered protocols and strengthening the collaborative pillars of surveillance and stewardship, healthcare systems can build the resilience needed to protect both patients and providers during the most challenging of times.

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