International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Review Article)

Check for updates

Carbon monoxide in United States Homes: Installation quality, the inspection gap, and why alarms are not a cure

Joseph Agate *

Independent Researcher.

International Journal of Science and Research Archive, 2026, 20(01), 322–337

Publication history: Received on 02 June 2026; revised on 07 July 2026; accepted on 10 July 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.20.1.1466

Abstract

Carbon monoxide (CO) remains a leading cause of unintentional non-fire poisoning death in the United States, killing several hundred people and generating tens of thousands of emergency department visits each year despite decades of awareness campaigns and the near-universal spread of CO alarm laws. This review re-centres the problem on the US domestic context and argues that the great majority of these exposures originate from ordinary fuel-burning appliances—furnaces, gas water heaters, ranges, and, during power outages, portable generators—whose safety is determined by the quality of their installation, servicing, and inspection. Drawing on peer-reviewed literature published from 2020 onwards, supplemented by official US data where necessary, it develops four linked arguments. First, the installation and maintenance defects that generate CO—incomplete combustion, cracked or fouled heat exchangers, blocked or disconnected flues, and inadequate ventilation—are identifiable by established engineering tests and are therefore rectifiable. Second, the United States has a structural inspection gap, because periodic safety inspection and servicing of fuel-burning appliances are not mandatory in owner-occupied homes, in contrast to the annual landlord duty operating in the United Kingdom, so that latent defects accumulate undetected. Third, appliance safety decays over time without routine servicing, converting sound installations into hazards. Fourth, CO alarms, although valuable and required by law in most US states, are a reactive last line of defence: they warn only once CO is already present and can be defeated by expired sensors, dead or removed batteries, incorrect siting, or absence. The review concludes that reducing US CO deaths depends principally on a competent, well-trained installer workforce and on closing the inspection gap, with alarms retained as a secondary safeguard.

Keywords: Carbon monoxide; United States; Domestic poisoning; Gas appliances; Installation defects; Inspection; Servicing; Heat exchanger; Flue; Ventilation; Carbon monoxide alarms; Preventability

1. Introduction

Carbon monoxide is a colourless, odourless, and tasteless gas produced whenever carbon-based fuels burn without enough oxygen for complete combustion. Because it cannot be sensed and because its early clinical effects mimic common illnesses such as influenza, it poisons and kills quietly, often before its victims recognise that anything is wrong (Veiraiah, 2024; Coburn and Tift, 2026). In the United States, the everyday sources of this gas are the appliances on which households depend: natural-gas and propane furnaces, gas or oil water heaters, gas ranges and ovens, wood and pellet stoves, and—during the increasingly frequent power outages that accompany hurricanes, winter storms, and grid failures—portable petrol generators (Hampson, 2023; Northrop et al., 2025; Portillo et al., 2024). When these appliances are correctly installed, serviced, and vented, the risk to occupants is negligible. When they are not, the same appliances silently fill the living space with a lethal toxin.

* Corresponding author: Joseph Agate

The scale of the problem in the United States is substantial and stubbornly persistent. National surveillance covering 2005–2018 documented that unintentional, non-fire-related CO poisoning was responsible on the order of a hundred thousand emergency department visits, more than ten thousand hospitalisations, and several hundred deaths every year, with a sharp concentration in the winter months (Shin et al., 2023). A more recent analysis of US mortality for 2015–2021, drawn from national vital-statistics files, confirmed that CO poisoning continues to kill and identified the elderly as bearing the highest accidental death rate (Hampson, 2023). Global Burden of Disease estimates place these US figures within a worldwide pattern in which CO poisoning remains a leading environmental cause of poisoning death even as rates fall in many high-income countries (GBD 2021 Carbon Monoxide Poisoning Collaborators, 2023; Wang et al., 2025; Long et al., 2021). The editors of a leading public-health journal have summarised the essential feature of this burden in three words: it is largely preventable (The Lancet Public Health, 2023).

That preventability is the organising theme of this review. Unlike many environmental hazards whose sources are diffuse or whose mechanisms are contested, domestic CO almost always traces back to a discrete, physical, correctable fault in a specific appliance or its installation. An over-gassed burner, a cracked heat exchanger, a blocked flue, an appliance connected without commissioning tests, a room sealed against draughts without provision for combustion air—each is a condition that a competent installer can find and fix. It follows that CO poisoning in the American home is, to an unusual degree, an engineering and inspection problem before it is a medical one, and that the professionals who install and inspect fuel-burning appliances occupy the decisive position in the chain of prevention.

This article re-centres the CO problem on the United States, retaining the United Kingdom as a useful comparator because the two countries have taken markedly different regulatory paths on appliance inspection. It advances four connected arguments. First, the installation and maintenance defects that cause CO are identifiable by established tests and are therefore rectifiable. Second, the United States has a structural inspection gap, because safety checks and servicing of fuel-burning appliances are not mandatory in owner-occupied homes, unlike the annual gas-safety inspection required of landlords in the United Kingdom. Third, appliance safety decays over time without routine servicing, so that a home that was safe when built drifts toward danger. Fourth, CO alarms, although valuable and now required in most US states, are a reactive last line of defence and no substitute for correct installation, servicing, and inspection. Throughout, the review is written with the practising gas and heating engineer in mind and seeks to make explicit the public-health value of the installer's craft. Only the minimum clinical background needed to motivate prevention is included, in Section 2; the remainder of the article concerns sources, defects, inspection, servicing, training, and alarms.

2. Why domestic carbon monoxide matters: a brief clinical and epidemiological orientation

A full account of the toxicology of CO is beyond the scope of this review, but a compact orientation explains why preventing exposure is so valuable. CO harms principally by binding haemoglobin, for which it has an affinity two to three hundred times that of oxygen, forming carboxyhaemoglobin and depriving the tissues—above all the brain and heart—of oxygen; contemporary work adds that CO also acts directly at the cellular level, impairing mitochondrial respiration and driving oxidative and inflammatory injury, which is one reason blood carboxyhaemoglobin correlates only loosely with clinical severity (Coburn and Tift, 2026; Veiraiah, 2024). Because that correlation is weak and because CO clears quickly once a patient breathes fresh air, laboratory confirmation is often equivocal, and both clinical and forensic diagnosis frequently depend on circumstantial evidence and on inspection of the appliances in the home (Oliverio and Varlet, 2020; Stephenson et al., 2024). Non-invasive pulse CO-oximetry, though convenient, has limited sensitivity and can miss true poisonings (Ramponi et al., 2023; Papin et al., 2023; Babacan, 2023; Yu et al., 2024).

The consequences of exposure extend well beyond the acute event. A substantial minority of significantly poisoned patients sustain acute myocardial injury detectable by troponin elevation and electrocardiographic change, sometimes with lasting structural damage on cardiac imaging, and such injury predicts worse outcomes and higher mortality, especially in older adults (Cho et al., 2021; Nakajima et al., 2020; Küçükkelepçe et al., 2024; Kim et al., 2020b; Li et al., 2022). The most feared long-term complication is the delayed neurological (or neuropsychiatric) sequelae syndrome, in which patients who appear to recover develop cognitive impairment, movement disorders, and personality change days to weeks later; a large body of recent work has sought to predict this syndrome from imaging, clinical scores, and biomarkers, underscoring both its frequency and the difficulty of managing it once it occurs (Ahn et al., 2022; Namgung et al., 2022; Sert et al., 2021; Liang and Feng, 2024; Kokulu et al., 2020; Sarı Doğan et al., 2020; Gao et al., 2021; Lee et al., 2022; Elmansy et al., 2024; Onda et al., 2025; Zhang et al., 2025; Wen et al., 2024; Zhu et al., 2025; Tekin, 2024). Even the mainstay of treatment beyond high-flow oxygen—hyperbaric oxygen therapy—remains genuinely contested, with authoritative arguments on both sides and continuing uncertainty about dosing and the timing of treatment (Juurlink, 2023; Sethuraman and Thom, 2023; Freytag et al., 2023; Han and Cho, 2021; Lee et al., 2023; Choi et al., 2024; Aykut et al., 2025). The persistence of this therapeutic debate is itself an argument for prevention: where even the best treatment is uncertain, avoiding the exposure is unambiguously preferable.

Susceptibility is uneven. The fetus is especially vulnerable, because fetal haemoglobin binds CO even more avidly than adult haemoglobin and clears it more slowly, so maternal poisoning can injure or kill a fetus even when the mother's own poisoning seems moderate (Arslan, 2021; Özgök-Kangal, 2021; Odegard and Mullins, 2023). Children are over-represented in family incidents and can suffer lasting cognitive effects (Kaplan et al., 2026; Güven and Sarıcı, 2023; Wen et al., 2024). Older adults, with reduced cardiorespiratory reserve, bear the highest fatality rates (Hampson, 2023). Risk also concentrates in cold weather, when appliances run hardest and homes are sealed against the cold, and during power outages that drive people to improvised heat and generators (Mehrpour and Sadeghi, 2024; Northrop et al., 2025; Portillo et al., 2024), a seasonal, appliance-related pattern also documented in emergency-department series elsewhere (Acharya et al., 2021). These patterns matter for the present argument because they concentrate risk in exactly the housing and circumstances where appliances are least likely to have been competently installed and regularly inspected. The clinical message, in short, is that CO poisoning is not an all-or-nothing event but a source of death and of lasting cardiac and neurological disability, and that the only intervention that acts before any harm is done is prevention at the appliance.

3. Sources of domestic carbon monoxide and the primacy of installation

3.1. The appliances that produce carbon monoxide in US homes

Every fuel-burning appliance in a dwelling is a potential CO source, because CO is an inevitable product of combustion whenever the fuel-to-air ratio departs from the ideal. In the American housing stock the most numerous such appliances are natural-gas and propane forced-air furnaces and gas or oil water heaters, and these dominate the winter incident pattern. Gas ranges and ovens, which are typically flueless and vented only by a range hood or an open window, are a distinct source: correctly adjusted and used for cooking in a ventilated kitchen they contribute little CO, but a poorly adjusted or contaminated flame, prolonged operation, or use of the oven as a space heater can raise indoor concentrations appreciably (Lebel et al., 2022; Kashtan et al., 2023; Salthammer, 2024). Wood and pellet stoves, still used for primary or supplementary heat in millions of US homes, emit CO that rises steeply when the appliance is poorly controlled or badly maintained (Illerup et al., 2020; Mack et al., 2023; Mehta et al., 2023). Instantaneous gas water heaters installed in or near small, poorly ventilated rooms have caused severe poisoning, including neurological injury in people overcome while bathing (Pradhan and Das, 2020).

Portable petrol generators deserve particular emphasis in the US context. Pressed into service during the power outages that follow hurricanes, ice storms, and grid failures, and frequently run in garages, porches, or even indoors, they can raise indoor CO to lethal concentrations within minutes; experimental and monitoring work confirms their capacity to overwhelm the air of an enclosed space, and epidemiological studies link power outages directly to spikes in CO poisoning, especially among children (Adefeso et al., 2020; Teleszewski and Gładyszewska-Fiedoruk, 2025; Northrop et al., 2025). The 2021 Texas grid failure during Winter Storm Uri produced one of the worst CO poisoning episodes in recent US history, and it fell disproportionately on lower-income, limited-English-proficiency, and socially vulnerable neighbourhoods—an illustration of how the generator hazard interacts with social vulnerability (Portillo et al., 2024). Understanding CO as a general property of combustion, rather than a fault peculiar to one fuel or appliance, is the first step toward systematic prevention.

3.2. How installation determines whether an appliance is safe

Whether a given appliance harms the people around it is determined less by its inherent design than by the conditions of its installation and upkeep. Three linked requirements must be satisfied for safe operation. The appliance must achieve complete combustion; it must have an adequate and unobstructed path to vent its products of combustion to the outside; and the room or space must supply enough air for combustion and, for open-flued appliances, for the safe operation of the flue. A failure in any one of these can turn a sound appliance into a source of CO.

Combustion quality is fixed at commissioning: the appliance must be set up to the manufacturer's specification for gas rate and burner pressure, with the correct orifices and a clean, correctly aligned burner and heat exchanger. An appliance that is over-gassed, under-aerated, or fouled produces elevated CO even when everything downstream is intact. Venting determines whether those combustion products leave the building: a flue or vent that is correctly sized, correctly routed, sealed at its joints, properly terminated in free air, and free of blockage will carry the products away, whereas one that is undersized, disconnected, corroded, blocked, or badly terminated will not. Ventilation completes the picture, because atmospherically vented and open-flued appliances depend on replacement air; sealing a home for energy efficiency without maintaining combustion-air provision can starve an appliance, degrade its combustion, and in the worst case cause a vent to reverse and spill products of combustion into the living space (Ojima, 2022; Salthammer, 2024; Antonopoulos et al., 2023). Studies that treat indoor CO as an air-quality parameter show quantitatively how sensitive indoor concentrations are to the balance between generation and air change, and how readily they accumulate when that balance is disturbed (Salthammer, 2024; Buonanno and Kumar, 2025; Teleszewski and Gładyszewska-Fiedoruk, 2025).

3.3. Installation as the principal determinant of exposure

The implication of this triad is that installation is not a preliminary to safety but its principal determinant. An appliance is only as safe as the installation that surrounds it, and the decisions the installer makes at commissioning—selecting and sizing the vent, verifying combustion-air provision, setting the appliance to specification, and testing that combustion products actually leave the building—fix the safety of that appliance for years. Where these decisions are made competently, the appliance will not poison its occupants short of a subsequent physical failure; where they are made carelessly or by an unqualified person, the appliance may be dangerous from the day it is switched on. Because the US epidemiological evidence identifies domestic appliances, their venting, and their ventilation as the dominant sources of poisoning (Shin et al., 2023; Hampson, 2023; Close et al., 2022), the quality of installation work emerges as the single most powerful lever on domestic CO risk. This is the foundation for the argument developed next: that the faults which cause CO are the faults of installation and maintenance, that they are identifiable, and that they are therefore rectifiable.

4. Installer defects as identifiable, rectifiable causes of carbon monoxide hazard

4.1. The central argument

The proposition at the heart of this review is that most domestic CO hazards arise from a limited, well-characterised set of installation and maintenance defects; that these defects are identifiable by established inspection methods; and that once identified they can almost always be corrected. If this holds, then CO poisoning in the American home is, to a substantial degree, a preventable failure of workmanship and upkeep rather than an irreducible accident—and it follows that investment in installer competence and inspection yields direct returns in lives saved (The Lancet Public Health, 2023).

4.2. The recurring defects

Engineering understanding of combustion and venting, together with the incident and forensic record, identifies a recurring catalogue of faults. Incomplete combustion at the appliance itself—caused by incorrect gas rate, wrong or damaged orifices, distorted or blocked burners, fouled or cracked heat exchangers, and simple lack of servicing—raises the CO content of the flue gases at source. The cracked or corroded furnace heat exchanger is a signature US example: as the metal is repeatedly heated and cooled it becomes brittle and can fissure, allowing combustion products to mix with the circulating room air, and this failure mode is one of the most common ways CO enters homes heated by forced-air gas furnaces. Venting defects form a second category: undersized or unsuitable vents, disconnected or poorly sealed joints, corrosion, blockage by debris or nests, inadequate or wrongly positioned terminals, and vents routed so that leakage can enter other rooms. Ventilation defects form a third: absent or undersized combustion-air provision, vents blocked or sealed by occupants seeking to reduce draughts, and the interaction of atmospherically vented appliances with kitchen and bathroom exhaust fans, clothes dryers, and the progressive air-tightening of a dwelling, any of which can depressurise the house and cause a vent to spill or backdraft (Antonopoulos et al., 2023; Kang et al., 2022; Ojima, 2022). A fourth category concerns the installation as a system: appliances installed in prohibited or ill-advised locations, appliances connected and left in use without commissioning tests, and gas installations that were never tightness-tested. Forensic reconstructions of fatal incidents repeatedly implicate these same categories of appliance and installation failure (Close et al., 2022; Pradhan and Das, 2020).

4.3. Why these defects are identifiable

Each of these defects has a signature that competent inspection can detect. Incomplete combustion reveals itself through combustion analysis: an electronic flue-gas analyser measures the CO and carbon dioxide content of the products and the ratio between them, giving a direct, quantitative index of combustion quality that will flag an over-gassed or under-aerated appliance long before occupants are harmed. Vent integrity and performance can be assessed by visual inspection of the vent route and terminal, by confirming that the vent draws, and by spillage testing to confirm that combustion products are actually being carried away rather than escaping into the room. The tendency of a house to depressurise and backdraft its appliances can be evaluated by operating exhaust equipment and observing the effect on the vent. Ventilation adequacy can be checked against the appliance's requirements and the room's provisions, and the soundness of the gas installation itself is verified by a tightness (pressure) test (Antonopoulos et al., 2023; Salthammer, 2024). None of these techniques is exotic; they are the standard tools of the competent gas engineer, and their significance is that the very faults that cause CO are the faults these tests are designed to expose. A hazard that can be measured is a hazard that can be found, and a hazard that can be found before it harms anyone is a hazard that can be corrected.

4.4. Why these defects are rectifiable

Identification leads to remedy. Unlike a disease process, an installation defect has a definite physical cause and a definite physical solution: an over-gassed appliance can be re-commissioned to specification; a fouled heat exchanger can be cleaned and a cracked one replaced; a blocked vent can be cleared; a disconnected or leaking vent can be reconnected, sealed, or renewed; a badly positioned terminal can be relocated; missing combustion air can be provided; and an appliance in a prohibited location can be removed or replaced with a sealed-combustion alternative. In the rare case where an appliance cannot be made safe, it can be disconnected and condemned, removing the hazard entirely. This rectifiability distinguishes CO hazards sharply from many other environmental exposures and is precisely what makes the installer and inspector so consequential: they intervene at the point where a lethal but correctable condition can be turned into a safe one. Evidence that acting deliberately on the causes of poisoning produces measurable benefit comes from intervention studies: a recent multimodal prevention programme that combined targeted risk reduction with attention to seasonal factors was associated with a reduction in the incidence of CO poisoning and in myocardial injury among those exposed (Ling et al., 2026), and detector-deployment studies show reductions in poisoning where the safeguard is present (Christensen et al., 2020). These interventions differ in mechanism but share the underlying logic of this section: because the causes of domestic CO are concrete and addressable, deliberate action against them works.

4.5. A systems view: defects as breaches in successive defences

It is useful to view domestic CO safety as a series of successive defences, each of which must fail for an occupant to be harmed: the appliance must burn cleanly; if it does not, the vent must carry the products away; if the vent fails, ventilation must dilute what escapes; and if all of these are breached, an alarm must warn the occupants in time to leave. A serious poisoning is therefore rarely the result of a single fault but of several deficiencies aligning—an over-gassed appliance behind a partly blocked flue in a depressurised house whose combustion-air vent has been sealed, with no working alarm to sound. This layered picture reinforces rather than weakens the case for installation and inspection, because it is precisely the installer and inspector who maintain the first three defences—the ones that prevent the hazard rather than merely announce it. Each defect corrected during installation or inspection removes one of the holes that would otherwise have to align for a fatal outcome. The systems view also explains why single-measure strategies disappoint: mandating alarms while tolerating poor installation and skipped servicing simply relies on the last and most fallible layer to compensate for failures in the robust early ones.

4.6. The limits of the argument

Honesty requires acknowledging the boundaries of this claim. Not every exposure arises from a classic installation defect; some result from occupant behaviour, such as running a generator indoors or using an oven for heat, and some from appliance failures that occur despite sound installation. The peer-reviewed evidence base dealing directly with gas installers and inspection outcomes is, moreover, thinner than the clinical literature, and much of the case for installation quality rests on combining US source and incident data with the mechanistic understanding of combustion and venting rather than on trials of installer competence. These caveats temper the strength of the claim but do not overturn it: the convergence of source epidemiology, incident reconstruction, combustion engineering, and intervention studies supports the conclusion that identifiable, rectifiable installation and maintenance defects are the dominant, and most tractable, cause of domestic CO hazard.

5. The inspection gap: safety checks are not mandatory in US homes

5.1. Inspection as the mechanism that finds defects before they harm

If installation determines whether an appliance is safe and defects are the causes of harm, then inspection is the mechanism by which defects are found before they injure anyone. Inspection converts the latent, invisible danger of a developing fault into a visible, documented, correctable finding, and its value derives directly from the identifiability of CO defects established above: because incomplete combustion, vent failure, and inadequate ventilation each leave a measurable signature, a structured inspection that looks for those signatures will detect the hazard. A thorough safety inspection verifies combustion quality, ideally through flue-gas analysis; assesses the vent along its accessible length and confirms through spillage testing that products of combustion are removed from the room; checks that combustion-air provision is present and adequate and considers the interaction of the appliance with the wider house; and confirms the soundness of the gas installation. The output is a determination of whether the appliance is safe to use and, where it is not, of the action required.

5.2. The United States has no periodic inspection mandate for owner-occupied homes

Here the United States differs sharply from some peer countries, and the difference is consequential. There is no federal requirement, and in most jurisdictions no state requirement, that fuel-burning appliances in owner-occupied homes be periodically inspected or serviced by a competent person. A homeowner may operate a gas furnace, water heater, and range for decades without any obligation to have them checked, and the decision to arrange servicing is entirely voluntary and often deferred on grounds of cost or inconvenience. Home inspections in the United States are concentrated at the point of sale and are conducted by generalist home inspectors whose remit and competence with respect to combustion safety vary; they are not a substitute for periodic combustion-safety servicing by a qualified heating technician, and they occur only when a property changes hands. The result is that, for the large majority of the housing stock most of the time, no systematic mechanism exists to detect the very defects that this review has argued are identifiable and rectifiable.

The contrast with the United Kingdom is instructive. Under UK law, landlords are required to arrange an annual gas safety check of gas appliances and flues in rented dwellings, carried out by a registered engineer, and gas work may lawfully be undertaken only by engineers on a national competent-persons register. This does not cover owner-occupied homes, and it is not claimed here that the UK regime is complete; but it establishes, for a large segment of the housing stock, a recurring, legally mandated, professionally conducted inspection that has no US equivalent. Detailed UK studies of fatal unintentional non-fire CO poisoning, which reconstruct the appliances and circumstances involved, provide exactly the kind of surveillance data that flows from such a system and that is harder to assemble in the United States (Close et al., 2022; Stephenson et al., 2024). The essential point is not that one country has solved the problem but that the United States has a structural gap: the professional, periodic inspection that could detect accumulating defects is, for most American homes, simply not required.

5.3. How the inspection gap contributes to risk

The consequence of the gap is that defects accumulate undetected. Because acute CO poisoning is so easily mistaken for other illnesses, the diagnosis in the medical setting frequently depends on evidence from the home, and the systematic inspection of appliances after a suspected incident closes the loop between clinical suspicion and physical cause (Oliverio and Varlet, 2020; Stephenson et al., 2024). But in a system without routine inspection, that loop is closed only after someone has already been harmed. The seasonal concentration of US poisonings in the coldest months, when appliances are worked hardest, and their clustering around cold-weather power outages, indicate that latent faults are most likely to be exposed by heavy demand precisely when no inspection has intervened to find them (Shin et al., 2023; Mehrpour and Sadeghi, 2024; Northrop et al., 2025). Inspection timed ahead of the heating season is the natural remedy, and its near-absence as a requirement in owner-occupied US homes is a plausible contributor to the residual, preventable burden. Documentation is a further casualty of the gap: routine inspection generates records of combustion readings, ventilation provision, and appliance condition against which deterioration can be judged and from which patterns of dangerous appliances can be recognised, and where inspection does not occur, that evidence base is never created.

6. Servicing and maintenance decay: how appliance safety degrades over time

6.1. Safety is not established once and for all

A single competent installation does not guarantee lifelong safety, because appliances and their vents deteriorate. Heat exchangers foul with soot and scale and eventually crack; burners distort and corrode; gaskets and seals perish; vents corrode and become blocked by debris, corrosion products, or animal nests; terminals are obstructed; and occupants alter ventilation by sealing vents, adding exhaust fans, or tightening the building envelope. Risk therefore accumulates between services, which is the rationale for periodic servicing and safety checks rather than a one-off commissioning test. An installation that was sound at commissioning can lose its defences one by one, so that a home which was safe for years drifts silently toward the point at which the remaining defences are insufficient. Only routine servicing and inspection can detect this drift; the engineer who services and re-tests an appliance is, in effect, rebuilding defences that time and use have eroded, restoring the margin between normal operation and harm before that margin is exhausted.

6.2. The mechanisms of decay

The specific mechanisms of decay map directly onto the combustion–venting–ventilation triad. On the combustion side, an unserviced burner and heat exchanger accumulate deposits that disturb the flame, promote incomplete combustion, and raise CO output; controlled studies of appliance operation show how strongly combustion quality and CO emission depend on correct air supply and appliance condition, and how automatic control or careful set-up can hold CO low while neglect allows it to rise (Illerup et al., 2020; Mack et al., 2023; Ojima, 2022). Solid-fuel appliances are particularly sensitive: wood and pellet stoves emit far more CO and particulate matter than well-tuned gas appliances, and their emissions depend heavily on fuel quality, loading, and operation, so that a poorly maintained or badly operated stove is both a CO source and a broader indoor-air-quality hazard (Illerup et al., 2020; Mack et al., 2023; Kuye and Kumar, 2025; Mehta et al., 2023). On the venting side, corrosion and blockage progressively impair the removal of combustion products. On the ventilation side, the interaction between an ageing atmospherically vented appliance and a home that has been retrofitted for energy efficiency is especially dangerous: tightening the envelope and adding powerful exhaust equipment can depressurise the house enough to reverse a natural-draft vent, and studies of ventilation retrofits and of indoor air quality in tightly built and weatherised US homes show both the risk of trapping combustion pollutants and the protective value of properly designed mechanical ventilation (Antonopoulos et al., 2023; Kang et al., 2022). The general lesson is that the drive for energy efficiency, pursued without attention to combustion safety and ventilation, can quietly convert a formerly safe installation into a hazard—exactly the kind of change that routine servicing is placed to catch.

6.3. Servicing as a public-health measure

Framed this way, routine servicing is not merely appliance care but a public-health measure. It is the temporal complement to competent installation and the practical answer to the inspection gap: installation sets the appliance up safely, and servicing keeps it safe as it ages. Because the mechanisms of decay are physical and predictable, they are anticipatable and preventable; a heat exchanger inspected before it cracks through, a vent cleared before it blocks, a combustion problem corrected before it worsens, and a depressurisation problem identified before it reverses a vent are all exposures prevented. The absence of any requirement for such servicing in owner-occupied US homes therefore compounds the inspection gap described in Section 5, leaving the decay of appliance safety to proceed unchecked in the majority of the housing stock.

7. The preventability of carbon monoxide incidents in the United States

7.1. A large and avoidable burden

Bringing together the arguments so far, the striking feature of the US CO problem is how avoidable it is. Several hundred Americans die and tens of thousands attend emergency departments each year from unintentional, non-fire CO poisoning, with the elderly at highest risk of death and a strong winter concentration (Shin et al., 2023; Hampson, 2023). Global analyses confirm that these deaths sit within a worldwide pattern that is falling where prevention is pursued, demonstrating that the burden is not fixed but responsive to intervention (GBD 2021 Carbon Monoxide Poisoning Collaborators, 2023; Wang et al., 2025; Long et al., 2021). Because the sources are known appliances, the defects are identifiable, and the remedies are physical and effective, a large share of this burden is preventable—an assessment shared by public-health commentators (The Lancet Public Health, 2023). The gap between what is preventable and what is prevented is, in essence, the gap left by non-mandatory inspection and servicing and by reliance on alarms as a substitute for correct installation.

7.2. Disasters, outages, and disparities

Two features of the US pattern sharpen the preventability argument. First, the American reliance on portable generators during power outages creates a recurrent, foreseeable hazard. Outages are consistently associated with spikes in CO poisoning, and children are particularly affected; the mechanism—generators operated in or too near the home—is well understood and, in principle, entirely avoidable through safe siting and, ultimately, safer appliance design and public education (Northrop et al., 2025; Adefeso et al., 2020; Teleszewski and Gładyszewska-Fiedoruk, 2025). Winter Storm Uri in Texas in 2021 showed how a grid failure can generate a mass CO poisoning event, and it showed something more: the harm fell disproportionately on lower-income, limited-English-proficiency, and socially vulnerable communities (Portillo et al., 2024). CO poisoning is thus not socially neutral; the households least able to afford servicing, to replace ageing appliances, or to avoid improvised heat are also those most exposed, which strengthens the ethical case for treating prevention as a matter of public health rather than individual responsibility alone.

7.3. Chronic and lower-level exposures

Preventability is not only about dramatic acute events. The same appliances that can kill can also expose occupants to lower, sub-acute concentrations that never trigger an alarm yet may cause harm over time. Studies of gas cooking in US homes show that ordinary use can raise indoor concentrations of combustion pollutants, and work on chronic exposure links sustained low-level CO and related combustion products to measurable health effects (Lebel et al., 2022; Kashtan et al., 2023, 2024, 2025; Gruenwald et al., 2023; Seltenrich, 2024; He et al., 2023; McCord et al., 2024; Salthammer, 2024). While much of this literature concerns pollutants beyond CO, it reinforces the general point that combustion appliances shape the healthfulness of indoor air continuously, not only in emergencies, and that ventilation and correct appliance operation matter across the whole range of exposure. That a meaningful part of the burden is chronic and silent makes the case for source control—correct installation, servicing, and ventilation—stronger still, because chronic exposures are precisely those an alarm is least likely to catch.

7.4. Why avoidability makes the status quo a serious concern

The upshot is that the persistence of CO death and injury in a wealthy country with mature building codes and near-universal alarm laws is not an unavoidable background rate but a signal of preventable failure. When a hazard is invisible, its sources are known, its defects are detectable, and its remedies are effective, the continued toll becomes an indictment of the systems meant to control it. The United States has, in effect, chosen to rely heavily on a downstream warning device—the CO alarm—while leaving the upstream controls of installation quality, periodic inspection, and routine servicing largely to voluntary action. Sections 8 and 9 argue that this ordering is inverted: the upstream controls are primary and depend on a competent workforce, while the alarm, valuable as it is, is a reactive last resort.

8. Training and education of installers and engineers

8.1. Competence as the precondition for everything else

Every argument advanced so far depends on a single human input: the competence of the person who installs, services, and inspects the appliance. Measuring combustion, sizing and testing vents, assessing ventilation and depressurisation, and correctly classifying and remedying defects are skilled tasks requiring knowledge, practical ability, and judgment. An analyser is useful only in the hands of someone who can interpret its readings; a spillage test protects occupants only if the person performing it knows when and how to carry it out and what to do with the result. Workforce competence is therefore not one factor among many but the precondition on which the entire preventive system rests, which makes training and continuing education the highest-leverage investment available in this field: they determine the quality of the installation, servicing, and inspection work that everything else depends upon.

8.2. What installers need to know, and how the US and UK differ

The knowledge base required of a competent gas or heating engineer spans combustion theory, appliance-specific commissioning, vent design and testing, ventilation and depressurisation, gas-carcass soundness and tightness testing, recognition and classification of unsafe situations, and the correct procedures for making appliances safe. Just as important is the tacit skill that distinguishes genuine competence from mere certification: the habit of testing rather than assuming, the pattern recognition that flags an unusual vent arrangement or an implausible reading, and the discipline to condemn an appliance that cannot be made safe even when doing so is inconvenient. Because appliances, fuels, controls, and building practices evolve—tighter construction, new appliance technologies, heat pumps and hybrid systems, changing fuel compositions—this knowledge cannot be acquired once and left static; continuing education and periodic reassessment of competence are necessary to keep the workforce aligned with the homes and appliances it actually encounters.

The United States and the United Kingdom again differ in the structures that sustain competence. The United Kingdom restricts gas work to engineers on a national competent-persons register, backed by required reassessment. The United States regulates the trades primarily through state and local licensing and mechanical codes, with considerable variation between jurisdictions in what qualifications are required and in whether combustion-safety testing is routinely taught and practised. The point is not to adjudicate between the systems but to note that the reliability with which a US household can expect competent, test-based work varies with locality, and that strengthening training, certification, and continuing education is a direct lever on the quality of the installation and servicing that prevents CO.

8.3. Education as a determinant of carbon monoxide mortality

Framing training as a determinant of CO mortality is not rhetorical. The chain of causation runs from the engineer's knowledge and skill, through the quality of installation, servicing, and inspection, to the presence or absence of the defects that cause poisoning, to the exposures that injure and kill. Each link is supported by the evidence reviewed here: defects cause exposures (Close et al., 2022); exposures cause acute and chronic harm (Shin et al., 2023; Cho et al., 2021; Ahn et al., 2022); and organised action against the causes reduces that harm (Ling et al., 2026; Christensen et al., 2020). Because the engineer sits at the head of this chain, improving the engineer's competence propagates through every subsequent link. Education has complementary roles beyond the trade: the frequent misdiagnosis of CO poisoning as viral illness means clinicians, too, benefit from education about when to suspect CO, and the public needs enough awareness to arrange servicing, to use qualified installers, not to defeat ventilation, and to operate generators safely (Veiraiah, 2024; Stephenson et al., 2024; Northrop et al., 2025). But public awareness and its most tangible product, the CO alarm, are complements to competent installation, not substitutes for it—the subject of the next section.

9. Carbon monoxide alarms: a reactive last-line safeguard, not a cure

9.1. What alarms do and do not do

Carbon monoxide alarms detect the gas once it is present in the air and warn occupants to leave and seek help. They are inexpensive, widely available, and now required by law in most US states, and their value is real and evidenced: analysis of detector deployment found that the presence of a functioning CO detector was associated with reduced poisoning, consistent with the alarm's role in interrupting an exposure before it becomes severe (Christensen et al., 2020). But an alarm is, by design, a detection-and-warning device. It does not prevent CO from being produced, does not prevent it from entering the living space, and does not correct the fault that generates it. It acts at the very end of the causal chain, after the hazard has already been created and released, giving occupants a chance to escape a danger that competent installation, servicing, and inspection should have prevented from arising. In the language of risk control, the alarm is a reactive, last-line safeguard, not a primary control.

9.2. Alarms are reactive: warning can come too late

The reactive nature of the alarm is its fundamental limitation. Because an alarm can only respond to CO that is already in the air, it necessarily allows the hazard to exist before it acts, and the protection it offers depends on the gas accumulating gradually enough, and the occupants being alert and able enough, for escape to succeed. In a rapidly developing exposure—a generator running in an attached garage, a severe venting failure on a cold night—concentrations can rise quickly, and sleeping occupants, young children, older adults, and those already made drowsy or confused by early CO exposure may not respond in time even to a sounding alarm. The audibility and design of the alarm signal themselves affect whether a warning produces timely escape, and are not guaranteed to rouse every occupant (Lee, 2021). An alarm that sounds as a household is already being overcome has failed to protect in any meaningful sense, even though it functioned exactly as designed. Prevention at the appliance, by contrast, removes the hazard before any such race against time begins.

9.3. Alarms can fail: expired sensors, dead batteries, wrong siting, and absence

Beyond their reactive character, alarms are a fallible, human-dependent technology, and each of their failure modes is common. The sensing element of a domestic CO alarm—typically an electrochemical cell—has a finite service life, usually of the order of a few years, after which its response degrades and the unit must be replaced; an alarm kept in service past the end of its sensor life may give a false sense of security while no longer reliably detecting CO. Alarms are powered by batteries or mains with battery backup, and depleted, removed, or missing batteries are a recurrent cause of non-functioning units, often because occupants remove batteries to stop nuisance alarms or fail to replace them. Correct siting matters, because an alarm must sample the air the occupants actually breathe and be positioned according to the manufacturer's and standards' guidance to respond usefully; a unit placed where it cannot sense a developing exposure offers little protection. And, most simply, many homes have no alarm at all, or have one only in some areas. Surveys of alarm ownership and maintenance among patients presenting to emergency departments confirm that ownership is far from universal and that even installed alarms are frequently unmaintained, with expired units, absent batteries, and incorrect placement undermining their protective value (Jarman et al., 2025; Jarman et al., 2022). None of this diminishes the alarm's usefulness as a safeguard; it demonstrates that alarms cannot be assumed to be present, powered, unexpired, correctly sited, and heeded, and therefore cannot bear the weight of being the primary defence.

9.4. Alarms miss chronic low-level exposure

A further limitation follows from how alarms are designed to behave. To avoid nuisance activations, CO alarms are engineered to sound only above defined concentration-and-time thresholds, and they are not intended to respond to the low, chronic concentrations that can arise from a slightly maladjusted appliance or marginal ventilation. Yet such sustained low-level exposures may still be harmful over time and are exactly the exposures that source control—correct combustion, venting, and ventilation—is designed to prevent (Salthammer, 2024; McCord et al., 2024). Treating indoor CO as a continuous air-quality parameter, rather than only as an emergency to be announced, points again toward the appliance and its installation rather than toward the alarm. Emerging low-cost continuous sensors and connected indoor-air-quality monitors may in time supplement alarms by making low-level CO visible, but they are monitoring aids, not controls, and they share the alarms' dependence on correct siting, calibration, and upkeep.

9.5. The regulatory picture and the correct place of alarms

US policy has leaned heavily on the alarm. Most states now require CO alarms in homes—commonly in new construction, near sleeping areas, or in rental units—and federal policy has funded alarm distribution to vulnerable households, reflecting a genuine and worthwhile commitment to the safeguard. This is welcome, but it achieves its full value only when paired with measures that secure the quality of installation, servicing, and inspection. An alarm requirement unaccompanied by attention to installer competence and to periodic combustion-safety servicing substitutes a warning device for the prevention that should precede it—treating the symptom of an uncontrolled hazard rather than its cause. The constructive conclusion is not that alarms are unimportant but that they occupy a defined and subordinate place in a coherent strategy: correct installation prevents the hazard; routine servicing and inspection keep it prevented as appliances age; a competent, well-trained workforce delivers both; and a properly specified, correctly sited, unexpired, and maintained alarm stands as a final safeguard against the residual chance that something has nonetheless gone wrong. To rely on the alarm as the main line of defence, as current US practice substantially does, is to accept the routine creation of a lethal hazard on the assumption that a battery-powered device will always be present, working, correctly placed, and heeded when it sounds.

10. Discussion

The evidence assembled here supports a coherent and, for the practising engineer, empowering account of carbon monoxide poisoning in United States homes. CO remains a significant cause of preventable death and of acute and chronic morbidity, killing several hundred Americans and sending tens of thousands to emergency departments each year, with the burden concentrated in winter, among the elderly, and around power outages, and falling hardest on socially vulnerable communities (Shin et al., 2023; Hampson, 2023; Northrop et al., 2025; Portillo et al., 2024). The harms extend beyond acute death to structural cardiac injury and a substantial risk of delayed neurological disability, and even the best treatments remain contested, which magnifies the value of preventing exposure in the first place (Cho et al., 2021; Ahn et al., 2022; Juurlink, 2023; Sethuraman and Thom, 2023).

What distinguishes CO from many other hazards is the tractability of its causes. Domestic CO originates overwhelmingly from known fuel-burning appliances, and whether those appliances harm their occupants is determined by a small number of installation and maintenance conditions—combustion quality, vent integrity, and ventilation adequacy—each of which can be measured, tested, and corrected (Salthammer, 2024; Antonopoulos et al., 2023; Ojima, 2022; Illerup et al., 2020). The defects that cause poisoning are, in consequence, identifiable and rectifiable, and the professionals who install and inspect appliances are positioned to find and fix them before anyone is harmed. Intervention studies confirm that deliberate action against the causes reduces both the incidence and the clinical severity of poisoning (Ling et al., 2026; Christensen et al., 2020). The logical structure of the field therefore places competent installation and routine servicing and inspection as the primary controls, training and education as the input that makes those controls reliable, and CO alarms as a valuable but secondary, reactive safeguard.

Three implications follow for the United States specifically. First, the inspection gap deserves policy attention: the absence of any requirement for periodic combustion-safety servicing of appliances in owner-occupied homes leaves the majority of the housing stock without the mechanism that could detect accumulating, correctable defects, in contrast to the annual landlord duty that operates in the United Kingdom. Second, the heavy US reliance on portable generators during outages is a foreseeable and addressable hazard that warrants continued attention to safe siting, safer appliance design, and targeted public education, especially for vulnerable communities. Third, the near-universal spread of CO alarm laws, welcome in itself, should not be mistaken for a solution; alarm mandates need to be paired with measures that secure installation quality, workforce competence, and routine servicing, or they will continue to place a reactive warning device where a primary control belongs. For the individual engineer building a record of professional contribution, this framing locates their daily work squarely within a chain of causation that ends in lives saved: every appliance correctly commissioned, every defect found and remedied, and every unsafe appliance condemned is an exposure prevented.

The account also clarifies the relationship between the engineering and medical responses. Clinicians manage the consequences of exposure, and debate continues over aspects of treatment, but the clinical encounter by definition begins only after exposure has occurred, and the diagnostic difficulties created by CO's non-specific presentation and rapid clearance mean that even the medical response depends on evidence from the home (Oliverio and Varlet, 2020; Stephenson et al., 2024; Papin et al., 2023). Prevention at source acts earlier and more reliably than any treatment, because it prevents the exposure that treatment would otherwise have to address. The two responses are complementary, but the engineering response carries the greater preventive leverage.

11. Limitations

Several limitations qualify this review. First, it is a narrative synthesis rather than a systematic review, and the selection of studies, while drawn from recent peer-reviewed sources, does not follow a pre-registered protocol; relevant work may have been omitted. Second, and most importantly for the central theme, the peer-reviewed evidence evaluating gas installers, inspection regimes, servicing, and their effect on CO outcomes is limited; much of the case for installation and inspection quality is built by combining US source and incident data with the mechanistic understanding of combustion and venting, rather than resting on controlled evaluations of installer competence, so the argument is strong in its logic and consistent with the available evidence but under-served by direct trials. Third, several statements about US regulation and about the comparison with the United Kingdom rest on the general regulatory landscape rather than on peer-reviewed studies, and because CO alarm laws, licensing requirements, and building codes vary by state and locality and change over time, readers should verify the specific rules that apply in their jurisdiction. Fourth, some of the indoor-air-quality literature cited concerns combustion pollutants beyond CO, such as nitrogen dioxide and particulate matter, and is used to illustrate general principles of appliance emissions and ventilation rather than CO-specific dose–response. Fifth, US burden estimates are affected by under-diagnosis and inconsistent coding and should be read as indicative. Finally, where a key mortality or regulatory statistic exists only in an official government source, that source has been used and identified as such; the bulk of the argument, however, rests on the peer-reviewed literature. These limitations point to a clear research need: rigorous evaluation of the effect of installer training, licensing, periodic inspection, and routine servicing on CO exposure and outcomes in the United States would substantially strengthen the evidence base for what this review argues on mechanistic and epidemiological grounds.

12. Conclusion

Carbon monoxide poisoning in United States homes continues to kill and to injure, causing acute deaths, lasting cardiac damage, and delayed neurological disability, and falling most heavily on the elderly and on socially vulnerable communities. Yet the striking feature of this hazard is how thoroughly its causes are understood and how directly they can be controlled. Domestic CO comes from fuel-burning appliances, and whether those appliances are safe is decided by the quality of their installation, servicing, and inspection. The defects that generate CO—incomplete combustion, cracked or fouled heat exchangers, blocked or unsound vents, and inadequate ventilation—are identifiable by established tests and, once identified, are almost always rectifiable. Competent installation is therefore the primary control of domestic CO risk; routine servicing and inspection keep that control effective as appliances age; and the training and continuing education of installers and engineers are the foundational investment that makes both possible. The United States has a structural gap here, because periodic safety inspection and servicing of appliances are not mandatory in owner-occupied homes, allowing correctable defects to accumulate undetected. Carbon monoxide alarms are a genuine and worthwhile safeguard, rightly required in most states, but they are reactive by nature—they warn only once CO is already present, and can be defeated by expired sensors, dead or removed batteries, incorrect siting, or simple absence. They are a last line of defence, not a substitute for correct installation, servicing, and inspection. The clearest path to fewer CO deaths in the United States runs through a skilled, well-trained, and well-regulated workforce of installers and inspectors, empowered to find and fix the correctable faults that would otherwise cost lives, with alarms retained as the final safeguard they were always meant to be.

References

[1] Acharya, S.P., Purpura, A., Kao, L. and House, D.R. (2021) 'Incidence and risk factors for carbon monoxide poisoning in an emergency department in Nepal', *Toxicology Communications*, 6(1), pp. 13–19. doi:10.1080/24734306.2021.2010955.

[2] Adefeso, I.B., Sonibare, J.A. and Isa, Y.M. (2020) 'Further evidence on environmental impacts of carbon monoxide from portable power generator on indoor air quality', *Cogent Engineering*, 7(1), 1809771. doi:10.1080/23311916.2020.1809771.

[3] Ahn, C., Oh, J., Kim, C.W., Lee, H., Lim, T.H. and Kang, H. (2022) 'Early neuroimaging and delayed neurological sequelae in carbon monoxide poisoning: a systematic review and meta-analysis', *Scientific Reports*, 12(1), 3529. doi:10.1038/s41598-022-07191-7.

[4] Antonopoulos, C.A., Rosenberg, S.I., Zhao, H., Walker, I.S., Delp, W.W., Chan, W.R. and Singer, B.C. (2023) 'Mechanical ventilation and indoor air quality in recently constructed U.S. homes in marine and cold-dry climates', *Building and Environment*, 244, 110480. doi:10.1016/j.buildenv.2023.110480.

[5] Arslan, A. (2021) 'Hyperbaric oxygen therapy in carbon monoxide poisoning in pregnancy: maternal and fetal outcome', *American Journal of Emergency Medicine*, 43, pp. 41–45. doi:10.1016/j.ajem.2021.01.007.

[6] Aykut, A., Günsoy, E., Karabulut, B.Ö., Aktaş, R.S., Öncül, M.V. and Karabulut, A.E. (2025) 'Serum lactate and carboxyhemoglobin as predictors of hyperbaric oxygen therapy in carbon monoxide poisoning: a retrospective study', *BMC Emergency Medicine*, 25(1). doi:10.1186/s12873-025-01410-w.

[7] Babacan, A. (2023) 'Diagnostic accuracy of carboxyhemoglobin saturation with pulse CO-oximetry in patients with carbon monoxide poisoning', *Toxicology Research*, 12(5), pp. 964–969. doi:10.1093/toxres/tfad090.

[8] Buonanno, G. and Kumar, P. (2025) 'Household air pollution and health: rethinking indoor exposure in the places we call home', *Scientific Reports*, 15(1). doi:10.1038/s41598-025-20056-z.

[9] Cho, D.-H., Ko, S.M., Son, J.-W., Park, E.J. and Cha, Y.S. (2021) 'Myocardial injury and fibrosis from acute carbon monoxide poisoning', *JACC: Cardiovascular Imaging*, 14(9), pp. 1758–1770. doi:10.1016/j.jcmg.2021.02.020.

[10] Choi, S., Nah, S. and Han, S. (2024) 'Correlation between time to hyperbaric oxygen therapy and delayed neurological sequelae in acute carbon monoxide poisoning patients', *Diagnostics*, 14(2), 186. doi:10.3390/diagnostics14020186.

[11] Christensen, G.M., Creswell, P.D., Theobald, J. and Meiman, J.G. (2020) 'Carbon monoxide detector effectiveness in reducing poisoning, Wisconsin 2014–2016', *Clinical Toxicology*, 58(12), pp. 1335–1341. doi:10.1080/15563650.2020.1733592.

[12] Close, R.M., Iqbal, N., Jones, S.J., Kibble, A., Flanagan, R.J., Crabbe, H. and Leonardi, G.S. (2022) 'Fatal unintentional non-fire related carbon monoxide poisoning: data from narrative verdicts in England and Wales, 1998–2019', *International Journal of Environmental Research and Public Health*, 19(7), 4099. doi:10.3390/ijerph19074099.

[13] Coburn, R.F. and Tift, M.S. (2026) 'A carbon monoxide cycle drives carbon monoxide uptake and poisoning', *Physiological Reports*, 14(8). doi:10.14814/phy2.70858.

[14] Elmansy, A.M., Hannora, D.M. and Khalifa, H.K. (2024) 'Serum glucose/potassium ratio as an indicator of early and delayed outcomes of acute carbon monoxide poisoning', *Toxicology Research*, 13(5), tfae168. doi:10.1093/toxres/tfae168.

[15] Freytag, D.L., Schiefer, J.L., Beier, J.P. and Grieb, G. (2023) 'Hyperbaric oxygen treatment in carbon monoxide poisoning – does it really matter?', *Burns*, 49(8), pp. 1783–1787. doi:10.1016/j.burns.2023.06.007.

[16] Gao, H., Sun, L., Wu, H., Chen, J., Cheng, Y. and Zhang, Y. (2021) 'The predictive value of neutrophil–lymphocyte ratio at presentation for delayed neurological sequelae in carbon monoxide poisoning', *Inhalation Toxicology*, 33(4), pp. 121–127. doi:10.1080/08958378.2021.1887410.

[17] GBD 2021 Carbon Monoxide Poisoning Collaborators (2023) 'Global, regional, and national mortality due to unintentional carbon monoxide poisoning, 2000–2021: results from the Global Burden of Disease Study 2021', *The Lancet Public Health*, 8(11), pp. e839–e849. doi:10.1016/S2468-2667(23)00185-8.

[18] Gruenwald, T., Seals, B.A., Knibbs, L.D. and Hosgood, H.D. (2023) 'Population attributable fraction of gas stoves and childhood asthma in the United States', *International Journal of Environmental Research and Public Health*, 20(1), 75. doi:10.3390/ijerph20010075.

[19] Güven, D. and Sarıcı, D. (2023) 'Clinical and laboratory characteristics predicting the severity of carbon monoxide poisoning in children', *Pediatric Emergency Care*, 39(4), pp. 207–215. doi:10.1097/pec.0000000000002927.

[20] Hampson, N.B. (2023) 'Carbon monoxide poisoning mortality in the United States from 2015–2021', *Clinical Toxicology*, 61(7), pp. 483–491. doi:10.1080/15563650.2023.2237667.

[21] Han, S. and Cho, Y.S. (2021) 'Hyperbaric oxygen therapy in carbon monoxide poisoning: still controversial', *Journal of Emergency Medicine*, 61(5), pp. 619–620. doi:10.1016/j.jemermed.2021.07.018.

[22] He, Y., Nishandar, S.R., Edwards, R.D. and Princevac, M. (2023) 'Air quality modeling of cooking stove emissions and exposure assessment in rural areas', *Sustainability*, 15(7), 5676. doi:10.3390/su15075676.

[23] Illerup, J.B., Hansen, B.B., Lin, W., Nickelsen, J., Pedersen, V.H., Eskerod, B. and Dam-Johansen, K. (2020) 'Performance of an automatically controlled wood stove: thermal efficiency and carbon monoxide emissions', *Renewable Energy*, 151, pp. 640–647. doi:10.1016/j.renene.2019.11.057.

[24] Jarman, H., Atkinson, R.W., Babu, A. and Moss, P. (2022) 'Cross-sectional study of carbon monoxide alarm use in patients attending the emergency department: a multicentre survey protocol', *BMJ Open*, 12(11), e061202. doi:10.1136/bmjopen-2022-061202.

[25] Jarman, H., Atkinson, R.W. and Machado, M. (2025) 'Carbon monoxide alarm ownership and maintenance in patients attending the emergency departments: a cross-sectional study', *Journal of Public Health*, 47(4), pp. 791–797. doi:10.1093/pubmed/fdaf091.

[26] Juurlink, D.N. (2023) 'Hyperbaric oxygen should not be used routinely for carbon monoxide poisoning', *British Journal of Clinical Pharmacology*, 89(3), pp. 942–945. doi:10.1111/bcp.15603.

[27] Kang, I., McCreery, A., Stephens, B. et al. (2022) 'Indoor air quality impacts of residential mechanical ventilation system retrofits in existing homes in Chicago, IL', *Science of the Total Environment*, 804, 150129. doi:10.1016/j.scitotenv.2021.150129.

[28] Kaplan, O., Kleinhaus, N., Test, G., Tawatha, I., Kestenbom, I. and Tavor, O. (2026) 'Pediatric carbon monoxide poisoning in Southern Israel—causality and outcome', *Pediatric Emergency Care*, 42(5), pp. 385–390. doi:10.1097/pec.0000000000003565.

[29] Kashtan, Y., Nicholson, M., Finnegan, C., Ouyang, Z., Lebel, E.D., Michanowicz, D.R., Shonkoff, S.B.C. and Jackson, R.B. (2023) 'Gas and propane combustion from stoves emits benzene and increases indoor air pollution', *Environmental Science & Technology*, 57(26), pp. 9653–9663. doi:10.1021/acs.est.2c09289.

[30] Kashtan, Y., Nicholson, M., Finnegan, C.J., Ouyang, Z., Garg, A., Lebel, E.D. et al. (2024) 'Nitrogen dioxide exposure, health outcomes, and associated demographic disparities due to gas and propane combustion by U.S. stoves', *Science Advances*, 10(18), eadm8680. doi:10.1126/sciadv.adm8680.

[31] Kashtan, Y., Wang, C., Nadeau, K.C. and Jackson, R.B. (2025) 'Integrating indoor and outdoor nitrogen dioxide exposures in US homes nationally by ZIP code', *PNAS Nexus*, 4(12), pgaf341. doi:10.1093/pnasnexus/pgaf341.

[32] Kim, J.H., Lim, A.-Y. and Cheong, H.-K. (2020a) 'Trends of accidental carbon monoxide poisoning in the Republic of Korea, 1951–2018', *Epidemiology and Health*, 42, e2020062. doi:10.4178/epih.e2020062.

[33] Kim, J.S., Ko, B.S., Sohn, C.H., Kim, Y.J. and Kim, W.Y. (2020b) 'High-sensitivity troponin I and creatinine kinase-myocardial band in screening for myocardial injury in patients with carbon monoxide poisoning', *Diagnostics*, 10(4), 242. doi:10.3390/diagnostics10040242.

[34] Kokulu, K., Mutlu, H. and Sert, E.T. (2020) 'Serum netrin-1 levels at presentation and delayed neurological sequelae in unintentional carbon monoxide poisoning', *Clinical Toxicology*, 58(12), pp. 1313–1319. doi:10.1080/15563650.2020.1743302.

[35] Küçükkelepçe, O., Yılmaz, E. and Çamcı, S. (2024) 'The relationship between fragmented QRS and myocardial injury in patients with acute carbon monoxide poisoning', *Medicina*, 60(6), 891. doi:10.3390/medicina60060891.

[36] Kuye, A. and Kumar, P. (2025) 'Particulate matter exposure from different heating stoves and fuels in UK homes', *Scientific Reports*, 15, 21394. doi:10.1038/s41598-025-05886-1.

[37] Lebel, E.D., Finnegan, C.J., Ouyang, Z. and Jackson, R.B. (2022) 'Methane and NOx emissions from natural gas stoves, cooktops, and ovens in residential homes', *Environmental Science & Technology*, 56(4), pp. 2529–2539. doi:10.1021/acs.est.1c04707.

[38] Lee, H., Oh, J., Kang, H., Ahn, C., Namgung, M., Kim, C.W. et al. (2022) 'Association between early phase serum lactate levels and occurrence of delayed neuropsychiatric sequelae in adult patients with acute carbon monoxide poisoning: a systematic review and meta-analysis', *Journal of Personalized Medicine*, 12(4), 651. doi:10.3390/jpm12040651.

[39] Lee, J.S., Cha, Y.S. and Lim, J. (2023) 'Association between number of hyperbaric oxygen therapy sessions and neurocognitive outcomes of acute carbon monoxide poisoning', *Frontiers in Medicine*, 10, 1127978. doi:10.3389/fmed.2023.1127978.

[40] Lee, M. (2021) 'Subjective response to the conditions of audible fire alarm signals through a jury evaluation test', *Fire Technology*, 58(2), pp. 1039–1060. doi:10.1007/s10694-021-01186-y.

[41] Li, B., Gao, X., Wang, W., Zhu, B. and Xiao, Q. (2022) 'Effect of early intervention on short-term prognosis of patients with myocardial injury induced by acute carbon monoxide poisoning', *ESC Heart Failure*, 9(2), pp. 1090–1097. doi:10.1002/ehf2.13777.

[42] Liang, X.Z. and Feng, S.Y. (2024) 'Serum neurofilament light chain for predicting delayed neurological sequelae after acute carbon monoxide poisoning', *Acta Neurologica Belgica*, 124(1), pp. 73–79. doi:10.1007/s13760-023-02334-7.

[43] Ling, Y., Xiong, X., Huang, H., Ye, C. and Wang, W. (2026) 'Multimodal intervention reduces seasonal carbon monoxide poisoning incidence and myocardial injury: a retrospective cohort study accounting for environmental temperature', *BMC Public Health*, 26(1). doi:10.1186/s12889-026-27222-6.

[44] Long, J., Sun, Y., Zhao, J., Liu, J. and Peng, X. (2021) 'Temporal trends of carbon monoxide poisoning mortality at the global, regional and national levels: a cross-sectional study from the Global Burden of Disease study, 1990 and 2017', *BMJ Open*, 11(11), e053240. doi:10.1136/bmjopen-2021-053240.

[45] Mack, R., Schön, C., Kuptz, D., Hartmann, H., Brunner, T., Obernberger, I. et al. (2023) 'Influence of wood species and additives on emission behavior of wood pellets in a residential pellet stove and a boiler', *Biomass Conversion and Biorefinery*, 14(17), pp. 20241–20260. doi:10.1007/s13399-023-04204-x.

[46] McCord, R., Parsons, S., Bittner, A.S., Jumbe, C.B.L., Kabwe, G., Pedit, J., Serenje, N., Grieshop, A.P. and Jagger, P. (2024) 'Carbon monoxide exposure and risk of cognitive impairment among cooks in Africa', *Indoor Air*, 2024, 7363613. doi:10.1155/2024/7363613.

[47] Mehrpour, O. and Sadeghi, M. (2024) 'The occurrence of unusually cold weather could contribute to the incidence of carbon monoxide poisoning', *Clinical and Experimental Emergency Medicine*, 11(2), pp. 231–232. doi:10.15441/ceem.23.091.

[48] Mehta, S.S. et al. (2023) 'Indoor wood-burning from stoves and fireplaces and incident lung cancer among Sister Study participants', *Environment International*, 178, 108128. doi:10.1016/j.envint.2023.108128.

[49] Nakajima, M., Aso, S., Matsui, H., Kaszynski, R.H., Fushimi, K., Yamaguchi, Y. and Yasunaga, H. (2020) 'Prevalence of myocardial injury requiring percutaneous coronary intervention after acute carbon monoxide poisoning', *European Journal of Emergency Medicine*, 27(3), pp. 213–216. doi:10.1097/mej.0000000000000645.

[50] Namgung, M., Oh, J., Ahn, C., Kim, C.W., Lee, H. and Kang, H. (2022) 'Association between Glasgow Coma Scale in early carbon monoxide poisoning and development of delayed neurological sequelae: a meta-analysis', *Journal of Personalized Medicine*, 12(4), 635. doi:10.3390/jpm12040635.

[51] Northrop, A.J., Do, V., Flores, N.M., Wilner, L.B., Sheffield, P.E. and Casey, J.A. (2025) 'Power outages and carbon monoxide poisoning in children', *Pediatrics*, 155(6), e2024068213. doi:10.1542/peds.2024-068213.

[52] Odegard, D.T. and Mullins, M.E. (2023) 'Perinatal carbon monoxide poisoning with fetal and maternal carboxyhemoglobin measurements', *Clinical and Experimental Emergency Medicine*, 10(4), pp. 453–455. doi:10.15441/ceem.23.097.

[53] Ojima, J. (2022) 'Prevention against carbon monoxide poisoning emanating from burning coal briquettes – generation rate of carbon monoxide and ventilation requirement', *Industrial Health*, 60(3), pp. 236–241. doi:10.2486/indhealth.2021-0112.

[54] Oliverio, S. and Varlet, V. (2020) 'New strategy for carbon monoxide poisoning diagnosis: carboxyhemoglobin (COHb) vs total blood carbon monoxide (TBCO)', *Forensic Science International*, 306, 110063. doi:10.1016/j.forsciint.2019.110063.

[55] Onda, H., Nishino, T., Kojima, M. et al. (2025) 'A scoring system with high predictive performance for poor outcomes in acute carbon monoxide poisoning', *Scientific Reports*, 15, 14491. doi:10.1038/s41598-025-98162-1.

[56] Özgök-Kangal, K. (2021) 'Long-term infant outcomes after hyperbaric oxygen treatment for acute carbon monoxide poisoning during pregnancy', *Diving and Hyperbaric Medicine*, 51(3), pp. 248–255. doi:10.28920/dhm51.3.248-255.

[57] Papin, M., Latour, C., Leclère, B. and Javaudin, F. (2023) 'Accuracy of pulse CO-oximetry to evaluate blood carboxyhemoglobin level: a systematic review and meta-analysis of diagnostic test accuracy studies', *European Journal of Emergency Medicine*, 30(4), pp. 233–243. doi:10.1097/mej.0000000000001043.

[58] Portillo, E.N., Quiñones, C., Foughty, Z.C., Ramphul, R., Morrow, A.T., Fisher, K. et al. (2024) 'Communities disproportionately affected by carbon monoxide exposure after Winter Storm Uri', *Journal of Pediatric Clinical Practice*, 200114. doi:10.1016/j.jpedcp.2024.200114.

[59] Pradhan, S. and Das, A. (2020) 'Amnesia following hot water bath from gas geyser', *Annals of Indian Academy of Neurology*, 23(6), p. 823. doi:10.4103/aian.aian_310_19.

[60] Ramponi, G. et al. (2023) 'The diagnostic accuracy of carbon monoxide pulse oximetry in adults with suspected acute carbon monoxide poisoning: a systematic review and meta-analysis', *Frontiers in Medicine*, 10, 1250845. doi:10.3389/fmed.2023.1250845.

[61] Salthammer, T. (2024) 'Carbon monoxide as an indicator of indoor air quality', *Environmental Science: Atmospheres*, 4(3), pp. 291–305. doi:10.1039/d4ea00006d.

[62] Sarı Doğan, F., Güneysel, Ö., Gökdağ, E., Güneş, M. and Sümen, S.G. (2020) 'Demographic characteristics and delayed neurological sequelae risk factors in carbon monoxide poisoning', *American Journal of Emergency Medicine*, 38(12), pp. 2552–2556. doi:10.1016/j.ajem.2019.12.037.

[63] Seltenrich, N. (2024) 'Clearing the air: gas stove emissions and direct health effects', *Environmental Health Perspectives*, 132(2), 024001. doi:10.1289/ehp14180.

[64] Sert, E.T., Kokulu, K. and Mutlu, H. (2021) 'Clinical predictors of delayed neurological sequelae in charcoal-burning carbon monoxide poisoning', *American Journal of Emergency Medicine*, 48, pp. 12–17. doi:10.1016/j.ajem.2021.04.001.

[65] Sethuraman, K. and Thom, S.R. (2023) 'Hyperbaric oxygen should be used for carbon monoxide poisoning', *British Journal of Clinical Pharmacology*, 89(3), pp. 939–941. doi:10.1111/bcp.15605.

[66] Shin, M., Bronstein, A.C., Glidden, E., Malone, M., Chang, A., Law, R., Boehmer, T.K., Strosnider, H. and Yip, F. (2023) 'Morbidity and mortality of unintentional carbon monoxide poisoning: United States 2005 to 2018', *Annals of Emergency Medicine*, 81(3), pp. 309–317. doi:10.1016/j.annemergmed.2022.10.011.

[67] Stephenson, L., Tiemensma, M., Van Den Heuvel, C. and Byard, R.W. (2024) 'The spectrum of presentations of unintentional carbon monoxide poisoning', *Medicine, Science and the Law*, 64(4), pp. 310–318. doi:10.1177/00258024231221349.

[68] Tekin, Y.K. (2024) 'Optic nerve sheath diameter measurements to predict delayed neurological sequelae after carbon monoxide poisoning', *Clinical Toxicology*, 62(2), pp. 88–93. doi:10.1080/15563650.2024.2323092.

[69] Teleszewski, T.J. and Gładyszewska-Fiedoruk, K. (2025) 'Carbon monoxide concentration in the garage of a single-family house—experiment and one-dimensional model of carbon monoxide concentration', *Applied Sciences*, 15(3), 1146. doi:10.3390/app15031146.

[70] The Lancet Public Health (2023) 'Carbon monoxide poisoning: largely preventable' (Editorial), *The Lancet Public Health*, 8(11). doi:10.1016/S2468-2667(23)00249-9.

[71] Veiraiah, A. (2024) 'Poisoning by carbon monoxide', *Medicine*, 52(6), pp. 372–373. doi:10.1016/j.mpmed.2024.03.001.

[72] Wang, W., Ling, Y., Xiong, X. and Zhou, J. (2025) 'Global patterns and trends of carbon monoxide poisoning: a comprehensive spatiotemporal analysis using joinpoint regression and ARIMA modeling, 1990–2021', *PLOS One*, 20(8), e0330778. doi:10.1371/journal.pone.0330778.

[73] Wen, T., Liang, J., Wei, Y., Lin, W. and Pan, L. (2024) 'Analysis of prognosis of neurological sequelae in children with carbon monoxide poisoning', *Scientific Reports*, 14(1), 29972. doi:10.1038/s41598-024-81634-1.

[74] Yu, J., Lee, J., Cho, Y., Oh, J., Kang, H., Lim, T.H. et al. (2024) 'Correlation between carboxyhemoglobin levels measured by blood gas analysis and by multiwave pulse oximetry', *Journal of Personalized Medicine*, 14(2), 168. doi:10.3390/jpm14020168.

[75] Zhang, Y., Wang, T., Zhou, C., Wang, S., Liu, Z. and Lei, J. (2025) 'Brain functional and structural alteration following acute carbon monoxide poisoning contribute to delayed neurological sequelae', *Scientific Reports*, 15(1). doi:10.1038/s41598-025-94787-4.

[76] Zhu, Y., Mei, T., Xu, D., Lu, W., Weng, D. and He, F. (2025) 'Predicting delayed neurological sequelae in patients with carbon monoxide poisoning using machine learning models', *Clinical Toxicology*, 63(2), pp. 102–111. doi:10.1080/15563650.2024.2437113.

[77] Official and regulatory sources (non–peer-reviewed, cited for specific US/UK statistics and rules)

[78] Centers for Disease Control and Prevention (CDC) (2024) *Carbon Monoxide Poisoning: Fact Sheets and Prevention Guidance*. Atlanta, GA: CDC. Available at: https://www.cdc.gov/carbon-monoxide/ (Accessed: July 2026).

[79] U.S. Consumer Product Safety Commission (CPSC) (2022) *Carbon Monoxide Poisoning Prevention and Portable Generator Hazards; Nicholas and Zachary Burt Carbon Monoxide Poisoning Prevention Act Grant Program*. Bethesda, MD: CPSC. Available at: https://www.cpsc.gov/ (Accessed: July 2026).

[80] National Fire Protection Association (NFPA) (2022) *NFPA 720 / carbon monoxide alarm siting guidance* and Underwriters Laboratories *UL 2034 Standard for Single and Multiple Station Carbon Monoxide Alarms*. Quincy, MA: NFPA. (Cited for CO alarm siting and sensor-life standards.)

[81] UK Health and Safety Executive (HSE) and Gas Safe Register (2024) *Gas Safety (Installation and Use) Regulations 1998: landlords' annual gas safety check duties; registration of competent gas engineers*. Available at: https://www.gassaferegister.co.uk/ and https://www.hse.gov.uk/gas/ (Accessed: July 2026).

[82] World Health Organization (WHO) (2021) *WHO Guidelines for Indoor Air Quality: Selected Pollutants — Carbon Monoxide*. Geneva: WHO. (Cited for indoor CO exposure guideline values.).