Medical Science

To Cite:
Al-Batool W, Al-Batool H, Hassan A, Zarecka I, Hassan S, Bienia S, Kossakowska A, Leicht J, Konieczna K. Carbon monoxide poisoning: Pathophysiology, diagnosis, symptoms and advances in acute and chronic management. *Medical Science* 2025; 29: e9ms3482
doi: https://doi.org/10.54905/dissi.v29i155.e9ms3482

Authors' Affiliation:
[1]Wroclaw Medical University, wyb. Ludwika Pasteura 1, 50-367 Wrocław, Poland
[2]Cardinal Stefan Wyszyński University in Warsaw, Wóycickiego 1/3, 01-938 Warsaw, Poland
[3]Medical University of Silesia, Medyków 18, 40-752 Katowice, Poland
[4]Medical University of Silesia, Dr. Henryka Jordana 19, 41-808 Zabrze, Poland

*Corresponding Author
Wroclaw Medical University, wyb. Ludwika Pasteura 1, 50-367 Wrocław, Poland
Email: szafahebanowa@gmail.com

Contact List

Wafa Al-Batool	szafahebanowa@gmail.com
Hiba Al-Batool	albatoolhiba@gmai.com
Aisha Hassan	114039@student.uksw.edu.pl
Izabela Zarecka	zareckaaizaa@gmail.com
Sara Hassan	sara.hassan2605@gmail.com
Szymon Bienia	szymonbienia1@gmail.com
Aleksandra Kossakowska	kossakowska.aleksandra00@gmail.com
Jakub Leicht	jakubleicht@icloud.com
Klaudia Konieczna	klodika01@gmail.com

ORCID List

Wafa Al-Batool	0009-0002-8666-5400
Hiba Al-Batool	0009-0003-5419-9588
Aisha Hassan	0009-0001-5078-7724
Izabela Zarecka	0009-0000-1376-4040
Sara Hassan	0009-0009-3297-8250
Szymon Bienia	0009-0000-7632-5125
Aleksandra Kossakowska	0009-0003-5338-0182
Jakub Leicht	0009-0000-8512-2776
Klaudia Konieczna	0009-0008-4729-9798

Peer-Review History
Received: 27 September 2024
Reviewed & Revised: 01/October/2024 to 02/January/2025
Accepted: 06 January 2025
Published: 12 January 2025

Peer-review Method
External peer-review was done through double-blind method.

Medical Science
pISSN 2321–7359; eISSN 2321–7367

DISCOVERY SCIENTIFIC SOCIETY

Carbon monoxide poisoning: Pathophysiology, diagnosis, symptoms and advances in acute and chronic management

Wafa Al-Batool[1*], Hiba Al-Batool[1], Aisha Hassan[2], Izabela Zarecka[1], Sara Hassan[3], Szymon Bienia[3], Aleksandra Kossakowska[2], Jakub Leicht[2], Klaudia Konieczna[4]

ABSTRACT

Carbon monoxide (CO) poisoning is most important contributor to toxic gas-related morbidity and mortality. Acute poisoning is well-documented, but chronic exposure remains poorly understood, often presenting with non-pathognomonic symptoms that complicate the diagnosis. Carbon monoxide (CO) attaches strongly to hemoglobin, hindering the transport of oxygen and disrupting cellular respiration. Acute exposure leads to injuries caused by a lack of oxygen, while prolonged exposure may contribute to nerve damage, memory and thinking problems, and heart-related complications. Typical sources of CO include exhaust fumes from vehicles, defective heating equipment, cigarette smoke, and certain industrial substances. Acute poisoning causes headache, dizziness, and potential neurological damage, while chronic exposure leads to fatigue, cognitive impairment, and delayed neuropsychiatric syndrome (DNS). Diagnosis involves carboxyhemoglobin measurement and clinical evaluation. Oxygen therapy is the main approach to treating carbon monoxide poisoning, with hyperbaric oxygen therapy (HBOT) proving especially beneficial in severe cases by reducing the likelihood of delayed neurological issues. While HBOT shows promise, more research is needed to understand chronic exposure and improve outcomes through standardized protocols.

Keywords: Carbon monoxide intoxication, carbon monoxide, hyperbaric oxygen therapy, delayed neuropsychiatric syndrome

1. INTRODUCTION

Carbon monoxide (CO) is the leading toxin of death by poisoning worldwide Thom et al., (2006) and can result in significant brain damage and lasting cognitive issues in survivors. Although acute CO poisoning is well-studied, there

is limited understanding of the effects of chronic CO exposure. Diagnosis of chronic CO poisoning typically relies on assessing the patient's environmental conditions, medical history, and occupational exposure (kanburoglu et al., 2016). Epidemiological analyses show that the number of carbon monoxide (CO) poisoning cases worldwide varies greatly.

This variation is influenced by factors such as a country's economic status, the effectiveness of its safety regulations, and how much the public understands about CO risks (Can et al., 2019). In Low-and Middle-income Countries, poor ventilation standards and the widespread use of low-quality fuels lead to higher rates of accidental CO poisoning (Wesley et al., 1995). In contrast, High-income Countries have seen a reduction in accidental exposures thanks to advancements in technology and stricter safety laws. However, these nations still face challenges in dealing with chronic CO exposure cases and ensuring that diagnoses are made quickly and accurately (Ernst and Zibrak, 1998).

2. METHODOLOGY

To gather information for this review, keywords such as "carbon monoxide intoxication", "carbon monoxide", "hyperbaric oxygen therapy", and "delayed neurological syndrome" were used to search accessible medical databases, including PubMed, ScienceDirect, and Google Scholar. The review focused on studies published between January 1960 and August 2024, selecting articles based on their relevance to the topic as indicated by their titles and abstracts. This review incorporates clinical research, systematic reviews, and meta-analyses that explore acute and chronic carbon monoxide poisoning, associated symptoms, and advancements in treatment. For the sake of accessibility and consistency of interpretation, we have excluded publications not written in English.

Our included criteria were:

Articles published in English

Articles focusing on acute and chronic carbon monoxide poisoning

Research on advancements in therapies, especially hyperbaric oxygen therapy

Clinical research, systematic reviews, and meta-analyses focusing on symptomatology of carbon monoxide poisoning and treatment

Excluded criteria:

Non-English publications

Studies with methodologies with flaws, such as missing control groups, ensuring the quality and reliability of the findings

3. RESULTS AND DISCUSSION

Carbon monoxide (CO) poisoning remains a critical global health issue, leading to significant morbidity and mortality (Hasan et al., 2024). Acute poisoning is relatively well-documented, but the effects of chronic exposure are still poorly understood due to its nonspecific symptoms, which make diagnosis challenging. From the studies we reviewed, hyperbaric oxygen therapy (HBOT) consistently shows promise in treating acute CO poisoning. It appears especially effective at minimizing the risk of delayed neurological syndromes (DNS), which can pose serious, long-term challenges for some patients. While (HBOT) shows great promise for acute CO poisoning, putting it into widespread practice can be challenging. A lot of hospitals simply do not have access to hyperbaric chambers, and there isn't a universally agreed-upon set of guidelines to follow.

More thorough research is needed to refine these methods, hoping that in the future, patients will receive the best possible care. Chronic exposure presents a different, yet equally significant problem. A significant numer of people expierience mild presentation (persistent fatigue, cognitive issues, and cardiovascular complications), which can easily be mistaken for other conditions. This diagnostic gray area highlights the need for improved testing methods and increased awareness among healthcare professionals. In essence, both acute and chronic CO poisoning are in need of vigilant recognition and prompt intervention. While HBOT holds significant potential for acute cases, much work remains in addressing the long-term effects of chronic exposure. Increasing research efforts, fine-tuning our treatment strategies, and building broader awareness, will help take meaningful steps toward safeguarding individuals from the serious risks posed by carbon monoxide.

Pathophysiology

Carbon monoxide (CO) has a strong affinity for hemoglobin and other heme-containing proteins, including myoglobin and cytochrome C oxidase. Carbon monoxide (CO) binds to hemoglobin with over 200 times the affinity of oxygen (Thom, 2008; Lettow et al., 2018).

This means that even small amounts of inhaled CO can lead to the formation of carboxyhemoglobin, reducing the blood's ability to carry oxygen. CO also raises heme levels in cells, triggering oxidative stress (Cronje et al., 2004). By binding to heme in platelets and cytochrome C oxidase, CO disrupts normal cellular respiration, produces harmful reactive oxygen species, and ultimately causes neuron damage, including cell death through necrosis and apoptosis (Thom, 2008). In the myocardium and skeletal muscle, CO binds to myoglobin. Since tissues absorb up to 15% of the body's total CO, it can gradually diffuse back into the bloodstream as the blood's saturation of CO-bound hemoglobin (CO-Hb) decreases (Roughton and Root, 1945).

Sources of carbon monoxide

Carbon monoxide is generated during the incomplete combustion of hydrocarbons. Typically, its atmospheric concentration is below 0.001 percent, with urban areas exhibiting higher levels than rural regions. Endogenous production of carbon monoxide occurs naturally as part of the normal biochemical breakdown of hemoglobin, resulting in a low baseline level of carboxyhemoglobin in all individuals (Ernst and Zibrak, 1998). Carbon monoxide poisoning can stem from various external sources, such as faulty heating systems, car exhaust fumes, and breathing in smoke (Wesley et al., 1995). Tobacco smoke is a major contributor to carbon monoxide exposure, with blood carboxyhemoglobin levels commonly reaching 10 percent in smokers and occasionally exceeding 15 percent, compared to 1 to 3 percent in nonsmokers (Ernst and Zibrak, 1998).

A recent study conducted at a regional hyperbaric treatment center revealed that waterpipe smoking was responsible for carbon monoxide exposure in 22% of the patients. Interestingly, individuals affected by this source were generally younger than those exposed through other means (Coppens et al., 2006). Methylene chloride, a standard solvent seen in paint strippers or varnish remover, is metabolized to CO (Ratney et al., 1974). Severe CO poisoning with CO-Hb saturation of up to 50 % has been reported following methylene chloride exposure (Fagin et al., 1980).

Table 1 Summary of Key Points in Carbon Monoxide Poisoning

Key Points	Summary
Acute CO poisoning	Leads to symptoms such as headache, dizziness, and potential neurological damage. Immediate intervention with oxygen therapy is critical.
Chronic CO exposure	Associated with nonspecific symptoms like fatigue and cognitive impairment. Diagnosis is challenging due to subtle presentation.
Hyperbaric Oxygen Therapy (HBOT)	HBOT accelerates recovery and reduces the risk of DNS in acute cases. Limited availability and lack of standardized protocols remain barriers.
Diagnosis of CO poisoning	Relies on carboxyhemoglobin levels, patient history, and environmental assessments. Pulse oximetry gap complicates diagnosis.
Pathophysiology of CO poisoning	CO binds to hemoglobin, disrupting oxygen transport and causing cellular hypoxia. Long-term effects include ischemia and oxidative

	stress.
Sources of CO	Generated from combustion, faulty appliances, and tobacco smoke. Occupational exposure and methylene chloride also contribute.
Clinical manifestations	Includes tachycardia, nausea, syncope, and in severe cases, seizures. Symptoms vary based on exposure levels and individual health conditions.
Delayed Neuropsychiatric Syndrome (DNS)	DNS can manifest weeks to months after acute exposure, causing cognitive and neurological impairments.
Management and treatment strategies	Immediate removal from exposure, high-flow oxygen therapy, and consideration of HBOT. Prevention strategies focus on awareness and safety regulations.

Carbon monoxide (CO) is a colorless, odorless, nonirritant toxic gas. Typically, it enters the body through inhalation, with the amount absorbed depending on factors such as the concentration of CO in the air, breathing rate, and exposure duration. Once inside the body, CO primarily binds to iron-containing molecules found in hemoglobin, myoglobin, and cytochrome C (Can et al., 2019). The body eliminates CO mainly through exhalation, with only minimal conversion to carbon dioxide (Kano, 2009). Its toxic effects occur through several mechanisms, some of which are still not fully understood.

Clinical manifestation

Manifestation of Acute CO Toxicity

The clinical presentation of carbon monoxide poisoning is often vague and not easily distinguishable, but it can suggest a broad range of diagnostic possibilities (Ernst and Zibrak, 1998). CO toxicity can cause a range of acute effects, from mild symptoms to critical illness. The degree of illness and severity of symptoms correlate with the degree of CO exposure and the patient's underlying comorbidities (Aubard and Magne, 2000). Nonlethal exposure to carbon monoxide can cause symptoms that are similar to those of a common viral illness. Since viral illnesses and carbon monoxide exposure bothpeak during the winter, a substantial number of initial misdiagnoses may occur (Ernst and Zibrak, 1998). In healthy individuals who do not smoke, the concentration of carboxyhemoglobin (CO-Hb) in the blood is typically less than 2%, while in smokers, this level can rise to as high as 15%.

Most people remain asymptomatic at CO-Hb levels below 10%. Once levels are above 10%, subtle neurological symptoms may appear, signaling the body's response to the increased presence of carbon monoxide. As CO-Hb levels rise further into the 30–50% range, the effects become more pronounced and alarming. The body may react with increased respiratory and heart rates, fainting spells (syncope), muscle weakness or paralysis, and mental confusion. The danger is significant at this stage, as these symptoms can impair a person's ability to recognize or respond to the threat. When CO-Hb concentrations exceed 50%, the situation becomes dire and poses a serious threat to life (Thomas, 1998; WHO, 1999; Powers and Dean, 2016; Tomaszewski, 2011). Patients with carbon monoxide poisoning often present with signs that reflect the body's struggle to cope with a lack of oxygen at the cellular level.

Common symptoms include tachycardia (a rapid heartbeat) and tachypnea (fast breathing), the body's natural attempts to compensate for the oxygen deficit. Many patients experience headaches, nausea, and vomiting as early signs of poisoning. In more severe cases, patients may experience presyncope (feeling faint), syncope (fainting), and even seizures. These occur due to cellular hypoxia (lack of oxygen in the cells) and the widening of brain blood vessels, resulting in cerebral edema (swelling in the brain). Increased cardiac output, a response to cellular hypoxia, can lead to additional complications such as angina (chest pain), pulmonary

edema (fluid in the lungs), and arrhythmias (irregular heartbeats). These issues arise from both the effects of carbon monoxide binding with myoglobin in muscles and a reduced ability of the blood to release oxygen (Turino, 1981; Becker and Haak, 1979; DeBias et al., 1976).

For patients with pre-existing heart or lung conditions, carbon monoxide poisoning can worsen their symptoms, making it even harder for the body to get the oxygen it needs (Williams et al., 1992). Classic signs often associated with carbon monoxide poisoning, such as cherry-red lips, cyanosis (bluish skin), and retinal hemorrhages, are rare. Some patients may develop erythematous (reddened) skin lesions or bullae (blisters) over bony areas, but these are not specific to carbon monoxide poisoning. On a microscopic level, necrosis of the sweat glands is a distinctive feature in some cases (Torne et al., 1991). Understanding these symptoms, especially in their early stages, is important for timely diagnosis and treatment of carbon monoxide poisoning (Table 1).

Delayed neuropsychiatric syndrome

Many individuals affected by carbon monoxide poisoning may not display immediate signs of brain dysfunction. However, in some cases, neurological or psychological symptoms can appear well after the acute phase, sometimes taking days, weeks, or even months to emerge, ranging from as early as three days to as late as eight months post-exposure. This delayed condition, known as delayed neuropsychiatric syndrome, is thought to affect roughly 10 to 30 percent of those who have experienced carbon monoxide poisoning, though reported rates can vary significantly (Hart et al., 1988; Sawa et al., 1981; Choi, 1983; Wong et al., 2016). Symptoms can be distressing and significantly impact a person's quality of life, including cognitive difficulties, changes in personality, parkinsonism (movement disorders similar to Parkinson's disease), loss of bladder or bowel control, dementia, and even psychosis (Choi, 1983; Min, 1986; Wong et al., 2016).

Manifestation of Chronic CO Toxicity

The issue of chronic carbon monoxide (CO) poisoning is a layered diagnostic challenge, as its symptoms are nonspecific and can easily be misdiagnosed as other conditions. Carbon monoxide doesn't have any color and is an odorless gas, which often leads to symptoms that do not immediately raise the alarm, making chronic poisoning particularly difficult to identify. In contrast to acute carbon monoxide poisoning, where symptoms such as sudden headache, dizziness, confusion, or even loss of consciousness are dramatic and typically prompt immediate medical attention, chronic poisoning develops gradually over time. Chronic or intermittent exposure to carbon monoxide, lasting more than 24 hours, can often go unnoticed as it occurs sporadically over weeks, months, or even years.

The exact prevalence of long-term exposure is unclear, but its effects can be subtle and easily mistaken for other conditions (Penney, 2008; Weaver, 2009). The long-term effects of prolonged carbon monoxide (CO) exposure remain debated. However, it is known that the hypoxia and ischemia caused by CO can trigger a series of reactions in the body that may continue even after the toxin is removed. Similar to acute poisoning, the long-term consequences primarily affect the cardiovascular and neurological systems, with the cardiovascular effects being particularly well-documented. To compensate for the lack of oxygen (anoxia), the body increases cardiac output and uses autoregulation to direct more blood flow to critical organs such as the brain and heart.

In individuals with pre-existing coronary artery disease, this mechanism may be insufficient, leading to reduced exercise tolerance, worsening myocardial ischemia, and an inability to boost cardiac output during physical exertion (Ekblom and Huot, 1972; Aronow and Isbell, 1973). Animal studies provide additional insight. For example, monkeys exposed to 250 ppm of CO over two weeks showed signs of coronary artery damage, including subendothelial swelling, fatty streak formation, and lipid-filled cells. Thesefindings underscore the potential for prolonged CO exposure to cause lasting cardiovascular damage (Thomsen, 1974). It is suggested that carbon monoxide (CO) may lead to reversible demyelination through direct toxicity to myelin or as a result of cerebral edema.

Imaging techniques such as CT scans, MRI, and positron emission tomography (PET) have identified changes in the brain's white matter and basal ganglia, which align with findings observed in autopsies (Wesley et al., 1995). The symptoms of chronic carbon monoxide poisoning can be very different from those of acute exposure and are often more subtle and wide-ranging. They may include fatigue, emotional exhaustion, memory issues, and difficulties concentrating or performing tasks at work. Other common symptoms are sleep disturbances, dizziness, nerve-related problems such as neuropathies and tingling sensations (paresthesias), recurring infections, increased red blood cell count (polycythemia), abdominal pain, and diarrhea (Penney, 2008). The gradual onset and wide range of symptoms often make it difficult to link them directly to carbon monoxide exposure (Table 1).

Diagnosis

The diagnostic approach carbon monoxide (CO) poisoning involves several critical steps. Unfortunetlny the condition lacks pathognomonic signs and symptoms. This makes it essential for primary care doctors and emergency medicine specialists to maintain high suspicion when evaluating. While measuring carbon monoxide levels in the body can be helpful, it is not always definitive, as levels might drop significantly when a patient reaches the hospital. However, in most cases, an elevated carboxyhemoglobin (COHb) level in the blood strongly indicates CO poisoning (Touger et al., 1995; Vegfors and Lennmarken, 1991; Buckley et al., 1994; Messier and Myers, 1991; Eichhorn et al., 2018). Key Diagnostic Considerations:

Confirming the Diagnosis

If CO poisoning is suspected, checking the air at the exposure scene or measuring CO in the patient's exhaled breath can support the diagnosis.

Blood samples collected at the scene by paramedics can also be beneficial, as COHb levels in the blood decline once a person starts breathing fresh air.

Blood Testing for COHb

Venous blood samples are sufficient to measure COHb levels.

Arterial blood may provide other information, such as identifying coexisting acidosis, which could be present in severe cases.

Measuring COHb requires specialized equipment, such as a spectrophotometer, as regular pulse oximeters cannot differentiate between carboxyhemoglobin and oxyhemoglobin. This limitation, known as the "pulse oximetry gap", means that standard pulse oximetry readings can be misleading.

The interpretation of the SpCO levels should be done in the setting of the clinical presentation

Zero to 5% is considered normal.

Five percent to 10% is considered normal in a smoker.

Greater than 10% is abnormal in any person (consider high flow oxygen)

More than 15% is significantly abnormal in any person, and treatment is mandatory.

Neurological and Psychological Assessment

Once CO poisoning is confirmed, a thorough neurological and psychological examination has to be performed.

Imaging Studies

Computed tomography (CT) of the head is actually not helpful in confirming CO poisoning. However, it can be useful for eliminating other possibilities of altered mental status, such as brain injuries or strokes (Touger et al., 1995; Vegfors and Lennmarken, 1991; Buckley et al., 1994; Messier and Myers, 1991; Eichhorn et al., 2018).

Treatment/Management

The carbon monoxide–intoxicated patient must first be removed from the source of carbon monoxide production without endangering the health of the rescuing personnel. It is critical to differentiate intentional from unintentional poisoning, but if the reason for poisoning is unknown, it is better to be suspicious of a potential suicide attempt. Highflow oxygen should be administered to the patient immediately, preferably 100 percent as normobaric oxygen. Oxygen shortens the half-life of carboxyhemoglobin by competing at the binding sites of hemoglobin and improves tissue oxygenation (Ilano et al., 1990).

The Role of Hyperbaric Oxygen Therapy

Hyperbaric oxygen therapy can be key in treating carbon monoxide (CO) poisoning and should be considered in emergency departments. This treatment involves patients breathing 100% oxygen inside a hyperbaric chamber pressurized to 1.4 atmospheres (Drinhaus et al., 2016). Physicians who rely on carboxyhemoglobin levels to determine the need for hyperbaric oxygen should know that these levels may not accurately reflect the initial severity of poisoning. By the time measurements are taken, carboxyhemoglobin

levels may have already decreased due to the body's natural elimination process, which is further accelerated by the administration of oxygen by first responders before hospital arrival.

Once the diagnosis of carbon monoxide poisoning is confirmed, physicians need to assess the need for hyperbaric oxygen therapy. The decision to treat the patient with hyperbaric oxygen therapy (HBO2) can be controversial. If the COHb is greater than 25%, this is considered severe poisoning, and most experts agree that HBO2 treatment is justified. It is reasonable to err on the side of treating with HBO2 because it is difficult to determine which patients are at risk of developing delayed neuropsychiatric syndrome (DNS), which is a significant problem in 40% of severe cases (Buboltz and Robins, 2023).

Normobaric versus Hyperbaric Oxygen Therapy

The process of eliminating carbon monoxide (CO) from the body depends on factors such as how deeply you breathe (minute ventilation), how long you were exposed, and the level of oxygen you are inhaling (fraction of inspired oxygen or FiO2). Under normal conditions, when breathing room air, it takes 4 to 6 hours for half of the carboxyhemoglobin—a harmful compound formed when CO binds to hemoglobin—to leave the bloodstream. Breathing 100% oxygen reduces this half-life to 40 to 80 minutes, and hyperbaric oxygen therapy (oxygen delivered under higher pressure) takes only 15 to 30 minutes. These treatments significantly speed up recovery from CO exposure.

Hyperbaric oxygen therapy (HBO2) plays a significant role in reducing the risk of delayed neuropsychiatric syndrome (DNS) by addressing ischemia-reperfusion injury in the central nervous system. HBO2 accelerates the removal of CO from hemoglobin, first it allows the rapid formation of normal oxyhemoglobin in red blood cells to happen. Additionally, HBO2 increases oxygen delivery to tissues by dissolving more oxygen directly into the plasma ensuring that oxygen reaches areas that may have compromised blood flow.

Another advantage of HBO2 is its ability to reduce inflammation in the brain. It limits the adhesion of neutrophils to the damaged endothelial lining of blood vessels, thereby decreasing tissue swelling and preventing lipid peroxidation. Moreover, the increased oxygen levels delivered to the tissue help displace CO bound to cytochrome proteins in cellular mitochondria, supporting the restoration of oxidative phosphorylation, a process essential for neuron survival and normal function, especially following ischemic damage (Akcan et al., 2021; Kuo et al., 2018).

4. CONCLUSIONS

Carbon monoxide (CO) poisoning remains a significant global health concern, as it is the leading cause of morbidity and mortality from toxic gas exposure. Both acute and chronic CO poisoning pose diagnostic and therapeutic challenges due to their nonspecific clinical presentations and potential for delayed complications. Hyperbaric oxygen therapy (HBOT) demonstrates promising benefits for reducing cognitive and neurological impairments associated with acute CO poisoning. Studies show that HBOT can effectively accelerate the elimination of carboxyhemoglobin and reduce the likelihood of ischemic injury to the brain.

Chronic CO poisoning represents a diagnostic challenge due to its vague onset and nonspecific symptoms. Cardiovascular and neurological long-term effects emphasize the need for early identification. Chronic exposure should be suspected in patients with unexplained fatigue, cognitive changes, or cardiovascular symptoms, especially when environmental or occupational risk factors are present. The decision to use HBOT should be guided by clinical factors such as the severity of exposure, carboxyhemoglobin levels, and neuropsychiatric or cardiovascular symptoms. It is crucial to continue the reasearch and standarization of treatment protocols in the term of HBOT.

Author's Contributions

Conceptualization: Wafa Al-Batool, Hiba Al-Batool
Methodology: Szymon Bienia, Sara Hassan
Formal analysis: Izabela Zarecka, Aisha Hassan
Resources, data curation: Aleksandra Kossakowska, Jakub Leicht
Investigation: Klaudia Konieczna, Sara Hassan
Writing – original draft: Wafa Al-Batool

Writing – review & editing: Wafa Al-Batool, Hiba Al-Batool
All authors have read and agreed with the final, published version of the manuscript.

Ethical approval
Not applicable.

Informed consent
Not applicable.

Funding
This study has not received any external funding.

Conflict of interest
The authors declare that there is no conflict of interests.

Data and materials availability
All data sets collected during this study are available upon reasonable request from the corresponding author.

REFERENCES

1. Akcan YL, Gultekingil A, Kesici S, Bayrakci B, Teksam O. Predictors of Severe Clinical Course in Children with Carbon Monoxide Poisoning. Pediatr Emerg Care 2021; 37(6):308-311. doi: 10.1097/PEC.0000000000001580
2. Aronow WS, Isbell MW. Carbon monoxide effect on exercise-induced angina pectoris. Ann Intern Med 1973; 79(3):392-5. doi: 10.7326/0003-4819-79-3-392
3. Aubard Y, Magne I. Carbon monoxide poisoning in pregnancy. BJOG 2000; 107(7):833-8. doi: 10.1111/j.1471-0528.2000.tb11078.x
4. Becker LC, Haak ED Jr. Augmentation of myocardial ischemia by low level carbon monoxide exposure in dogs. Arch Environ Health 1979; 34(4):274-9. doi: 10.1080/00039896.1979.10667413
5. Buboltz JB, Robins M. Hyperbaric Treatment of Carbon Monoxide Toxicity. 2023 Apr 24. In: StatPearls [Internet] Treasure Island (FL): StatPearls Publishing; 2024 Jan–
6. Buckley RG, Aks SE, Eshom JL, Rydman R, Schaider J, Shayne P. The pulse oximetry gap in carbon monoxide intoxication. Ann Emerg Med 1994; 24(2):252-5. doi: 10.1016/s0196-0644(94)70137-7
7. Can G, Sayılı U, Sayman ÖA, Kuyumcu ÖF, Yılmaz D, Esen E, Yurtseven E, Erginöz E. Mapping of carbon monoxide related death risk in Turkey: a ten-year analysis based on news agency records. BMC Public Health 2019; 19(1):9. doi: 10.1186/s12889-018-6342-4
8. Choi IS. Delayed neurologic sequelae in carbon monoxide intoxication. Arch Neurol 1983; 40(7):433-5. doi: 10.1001/archneur.1983.04050070063016
9. Coppens MJ, Versichelen LF, Rolly G, Mortier EP, Struys MM. The mechanisms of carbon monoxide production by inhalational agents. Anaesthesia 2006; 61(5):462-8. doi: 10.1111/j.1365-2044.2006.04536.x
10. Cronje FJ, Carraway MS, Freiberger JJ, Suliman HB, Piantadosi CA. Carbon monoxide actuates O(2)-limited heme degradation in the rat brain. Free Radic Biol Med 2004; 37(11):1802-12. doi: 10.1016/j.freeradbiomed.2004.08.022
11. DeBias DA, Banerjee CM, Birkhead NC, Greene CH, Scott SD, Harrer WV. Effects of carbon monoxide inhalation on ventricular fibrillation. Arch Environ Health 1976; 31(1):42-6. doi: 10.1080/00039896.1976.10667188
12. Drinhaus H, Nüsgen S, Hinkelbein J. Leitlinie zur Behandlung von Kohlenmonoxidvergiftungen wünschenswert [Guidelines desirable for treatment of carbon monoxide poisoning]. Anaesthesist 2016; 65(4):301-2. German. doi: 10.1007/s00101-016-0145-8
13. Eichhorn L, Thudium M, Jüttner B. The Diagnosis and Treatment of Carbon Monoxide Poisoning. Dtsch Arztebl Int 2018; 115(51-52):863-870. doi: 10.3238/arztebl.2018.0863
14. Ekblom B, Huot R. Response to submaximal and maximal exercise at different levels of carboxyhemoglobin. Acta Physiol Scand 1972; 86(4):474-82. doi: 10.1111/j.1748-1716.1972.tb05350.x

15. Ernst A, Zibrak JD. Carbon monoxide poisoning. N Engl J Med 1998; 339(22):1603-8. doi: 10.1056/NEJM199811263392206
16. Fagin J, Bradley J, Williams D. Carbon monoxide poisoning secondary to inhaling methylene chloride. Br Med J 1980; 281 (6253):1461. doi: 10.1136/bmj.281.6253.1461
17. Hart IK, Kennedy PG, Adams JH, Cunningham NE. Neurological manifestation of carbon monoxide poisoning. Postgrad Med J 1988; 64(749):213-6. doi: 10.1136/pgmj.64.749.213
18. Hasan S, Anis T, Malik BMA, Arshad A, Khadarkhan FE, Azeem S. Effect of Whole-Body Vibration Training on Glycaemic Control in Type 2 Diabetic Patients: A Randomized Control Trial. J Health Rehabil Res 2024; 4(3):1–9. doi: 10.61919/jhrr.v4i3.1185
19. Ilano AL, Raffin TA. Management of carbon monoxide poisoning. Chest 1990; 97(1):165-9. doi: 10.1378/chest.97.1.165
20. Kanburoglu MK, Cizmeci MN, Akelma AZ. A Rare Cause of Chronic Headache that May Be Misdiagnosed as Migraine: Chronic Carbon Monoxide Poisoning. Turk J Emerg Med 2016; 14(3):132-4. doi: 10.5505/1304.7361.2014.00868
21. Kano M. Pharmacology of the smoking. Diagn Treat 2009; 97: 1327–1331. doi: 10.48165/jiafm.2024.46.2.10
22. Kuo SC, Hsu CK, Tsai CT, Chieh MJ. Hyperbaric Oxygen Therapy and Acute Carbon Monoxide Poisoning. Hu Li Za Zhi 2018; 65(4):11-17.
23. Lettow I, Hoffmann A, Burmeister HP, Toepper R. Verzögerte Kohlenmonoxidenzephalopathie [Delayed neuro psychologyical sequelae after carbon monoxide poisoning]. Fortschr Neurol Psychiatr 2018; 86(6):342-347. German. doi: 10.1055/a-0599-0737. Erratum in: Fortschr Neurol Psychiatr 2018; 86(6):342-347. doi: 10.1055/a-0653-9348. Erratum in: Fortschr Neurol Psychiatr 2018; 86(6):342-347. doi: 10.1055/a-0653-9348
24. Messier LD, Myers RA. A neuropsychological screening battery for emergency assessment of carbon-monoxide-poisoned patients. J Clin Psychol 1991; 47(5):675-84. doi: 10.1002/1097-4679(199109)47:5<675::aid-jclp2270470508>3.0.co;2-h
25. Min SK. A brain syndrome associated with delayed neuropsychiatric sequelae following acute carbon monoxide intoxication. Acta Psychiatr Scand 1986; 73(1):80-6. doi: 10.1111/j.1600-0447.1986.tb02671.x
26. Penney DG. Chronic carbon monoxide poisoning: a case series. Boca Raton, FL: CRC Press, 2008; 551-67.
27. Powers RH, Dean DE. Forensic Toxicology: Mechanisms and Pathology (1st ed.). CRC Press 2016. doi: 10.1201/b19459
28. Ratney RS, Wegman DH, Elkins HB. In vivo conversion of methylene chloride to carbon monoxide. Arch Environ Health 1974; 28(4):223-6. doi: 10.1080/00039896.1974.10666472
29. Roughton FJW, Root WS. The fate of CO in the body during recovery from mild carbon monoxide poisoning in man. Am J Physiol 1945; 145:239-52. doi: 10.1152/ajplegacy.1945.145.2.239
30. Sawa GM, Watson CP, Terbrugge K, Chiu M. Delayed encephalopathy following carbon monoxide intoxication. Can J Neurol Sci 1981; 8(1):77-9. doi: 10.1017/s031716710004289x
31. Thom SR, Bhopale VM, Han ST, Clark JM, Hardy KR. Intravascular neutrophil activation due to carbon monoxide poisoning. Am J Respir Crit Care Med 2006; 174(11):1239-48. doi: 10.1164/rccm.200604-557OC
32. Thom SR. Carbon monoxide pathophysiology and treatment. In: Neuman TS, Thom SR, eds. Physiology and Medicine of Hyperbaric Oxygen Therapy. Philadelphia: Saunders Elsevier, 2008; 21-47.
33. Thomas GR. Ellenhorn's Medical Toxicology: Diagnosis and Treatment of Human Poisoning, 2nd ed. Matthew J. Ellenhorn, Seth Schonwald, Gary Ordog, and Jonathan Wasserberger. Baltimore, MD: Williams and Wilkins, 1997, 2047 pp., $199, ISBN 0–683-30031–8., Clin Chem 1998; 44(2):366. doi: 10.1093/clinchem/44.2.366
34. Thomsen HK. Carbon monoxide-induced atherosclerosis in primates. An electron-microscopic study on the coronary arteries of Macaca trus monkeys. Atherosclerosis 1974; 20(2):233-40. doi: 10.1016/0021-9150(74)90008-2
35. Tomaszewski C. Carbon monoxide. In: Nelson L.S., editor. Goldfrank's Toxicologic Emergencies. 9th ed. McGraw-Hill; New York, Chicago: 2011; 1658–1670.
36. Torne R, Soyer HP, Leb G, Kerl H. Skin lesions in carbon monoxide intoxication. Dermatologica 1991; 183(3):212-5. doi: 10.1159/000247672
37. Touger M, Gallagher EJ, Tyrell J. Relationship between venous and arterial carboxyhemoglobin levels in patients with suspected carbon monoxide poisoning. Ann Emerg Med 1995; 25(4):481-3. doi: 10.1016/s0196-0644(95)70262-8
38. Turino GM. Effect of carbon monoxide on the cardiorespiratory system. Carbon monoxide toxicity: physiology and biochemistry. Circulation 1981; 63(1):253A-259A.
39. Vegfors M, Lennmarken C. Carboxyhaemoglobinaemia and pulse oximetry. Br J Anaesth 1991; 66(5):625-6. doi: 10.1093/bja/66.5.625
40. Weaver LK. Clinical practice. Carbon monoxide poisoning. N Engl J Med 2009; 360(12):1217-25. doi: 10.1056/NEJMcp0808891
41. Wesley EE, Moorehead B, Haponik EF. Warehouse workers' headache: emergency evaluation and management of 30

patients with carbon monoxide poisoning. Am J Med 1995; 98 (2):145-55. doi: 10.1016/s0002-9343(99)80398-2

42. Williams J, Lewis RW 2nd, Kealey GP. Carbon monoxide poisoning and myocardial ischemia in patients with burns. J Burn Care Rehabil 1992; 13(2 Pt 1):210-3. doi: 10.1097/00004630-199203000-00006
43. Wong CS, Lin YC, Hong LY, Chen TT, Ma HP, Hsu YH, Tsai SH, Lin YF, Wu MY. Increased Long-Term Risk of Dementia in Patients with Carbon Monoxide Poisoning: A Population-Based Study. Medicine (Baltimore) 2016; 95(3):e2549. doi: 10.1097/MD.0000000000002549
44. WHO. Environmental Health Criteria 213, Carbon Monoxide. 2nd ed. Geneva: World Health Organization, 1999.