Carbon monoxide poisoning in two workers using an LPG forklift truck within a coldstore

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Background
This report describes carbon monoxide (CO) poisoning in two workers using a hired forklift truck within a coldstore. The diagnosis was not considered until day 6 of the incident, and so measurements of blood or breath CO at the time of acute illness were unavailable.

Aims
To determine whether CO poisoning may be diagnosed retrospectively, where blood or breath CO measurements are unavailable, in the context of this particular incident.

Methods
Detailed clinical histories were obtained. Estimation of possible levels of CO exposure were made based on computer biokinetic modelling based on the Coburn–Foster–Kane equation.

Results
The combined method used supports the diagnosis of CO poisoning in these two cases.

Conclusions
Clinical assessment, in combination with mathematical exposure modelling, may lead to successful retrospective diagnosis of CO poisoning and identify putative work activities. CO poisoning should be suspected whenever internal combustion engines are used within buildings and workers complain of relevant symptoms. Hospital departments should maintain a high level of vigilance towards such incidents as this, and should routinely undertake a direct measure of the saturation of haemoglobin by CO, i.e. blood carboxyhaemoglobin or breath CO.

Key words
Carbon monoxide; coldstore; confined space; lift trucks; mathematical modelling.

Introduction
Carbon monoxide (CO) exposure remains a significant toxicological cause of morbidity and mortality [1–4]. Excessive levels of this gas can be encountered both in the workplace and in the home. Campaigns about the potential dangers from badly maintained or installed gas appliances in the home have not eliminated cases, which still arise in significant numbers. Likewise, the risk in the workplace has been recognized within the UK by a range of guidance [5–7], the recent review of the atmospheric exposure standard and the establishment of a biological monitoring guidance value using end-tidal breath measurements [8]. In the occupational and environmental fields, the role of the internal combustion engine as a source of CO has been highlighted as a potential risk, particularly when used in confined spaces. This includes the workplace use of internal combustion engine-powered forklift trucks within confined spaces [9,10]. Debate remains about the long-term health effects of low-level CO exposure, but there are still frequent accidental, acute exposures that cause death or serious clinical manifestations with possible long-term effects [11].

This report details an occupational incident involving two workers in a confined space using a liquid petroleum gas (LPG) forklift which was on-hire.
Case reports

A 50-year-old non-smoking male material handler (case 1), of previously good health, worked as a pair with a 45-year-old male colleague, also a non-smoker and of previous good health (case 2), transferring product in and out of a food company coldstore. This involved manual handling of goods, and use of an LPG forklift truck; the two workers shared these duties between them at their joint discretion. The mean coldstore temperature was maintained at +5°C. On day 1 of the incident, the pair began using an on-hire LPG powered forklift truck, their usual LPG powered truck being withdrawn for servicing. Predominantly, case 1 worked close to the truck, which was driven by case 2, with both workers entering the coldstore at intervals to transfer and move material.

Case 1

On day 1, case 1 noted unusual tiredness while at work. On day 2, over the first 3 h at work, while the pair were using the on-hire truck, case 1 developed a headache. Despite self-medicating with ibuprofen his headache increased, and was accompanied by mild dyspnoea. His wife was summoned to take him home and, on arrival at the workplace, found him acutely distressed. Within minutes of arrival she described witnessing a classic 'grand mal' seizure, there being no previous history of epilepsy. Paramedics remarked upon his high colour during transfer to the local casualty unit, from where he was transferred later the same day to the regional neurosurgical unit with a suspected subarachnoid haemorrhage and associated provoked seizure. No measurement of blood carboxyhaemoglobin was made. Pulse oximetry showed a normal $pO_2$ on admission to the local casualty unit. The diagnosis of probable CO poisoning was not made until day 6 (see below), when the investigating Health & Safety Executive (HSE) doctor contacted the neurosurgical unit having suspected it on receiving the incident report. The patient remaining under neurosurgical observation until that point in time. Following discharge from hospital, the patient gradually improved over several weeks, though he suffered with general exhaustion. Substantial anxiety affected his family at the time of his admission in view of the poor prognosis of subarachnoid haemorrhage. His driving licence was suspended for one year following the incident in view of the occurrence of a grand mal seizure.

Case 2

Case 2 predominantly drove the on-hire forklift truck. He experienced no symptoms on day 1 of the incident. On day 2, he experienced headache at work, which persisted on returning home and for which he self-medicated with ibuprofen. He reported a friend observing him to be ‘spaced-out’ on the evening of day 2. On day 3, his headache, which had not fully disappeared, increased upon return to work following use of the same forklift truck. He observed his handwriting to be irregular during paperwork. Eventually, he became tremulous and nauseated. His wife was summoned; by the time of her arrival, he was drowsy, and reports momentarily losing consciousness during this period. He did not attend hospital at any stage of his illness, although he did receive a domestic visit by his family doctor on the afternoon of day 3. Subsequently, his condition improved, although he had persistent tiredness, headache and gastrointestinal upset over the following 2 weeks.

Description of the coldstore and workpractices

The coldstore is a space of 1688 m$^3$, maintained at +5°C by a refrigeration system and using eight roof-mounted fans to ensure mixing of the cold air within the store. The forklift truck and staff enter the coldstore via a 19 m$^2$ opening at one end of the coldstore that is curtained by plastic strip to reduce loss of chilled air to the external atmosphere. Other entrances to the coldstore were not open. The management of the company were unable to give any information on the level of air-changes to the coldstore within this set-up. At the time of the incident, there were no CO monitors or alarms within it. Discussion with the firm suggested that duration of spells of work within the coldstore, while using the forklift truck, could be quite variable. Thus it proved difficult to be exact about work patterns during the incident days.

Subsequent investigations

The diagnosis of CO poisoning was not considered until day 6 of the incident, a Monday, when the production manager contacted HSE for advice and reported that two workers (cases 1 and 2) had become ill in relation to the same work process. Carboxyhaemoglobin measurements were not obtained in either worker due to the delay between the incidents and suspicion of CO poisoning. Subsequent analysis of exhaust from the on-hire forklift truck showed considerable elevation of CO emissions. Table 1 compares emissions from forklift trucks used normally at the company and the hired truck associated with the incident. In view of the lack of biological measurement in support of the suspected diagnosis of CO poisoning, mathematical modelling was used to estimate the likely atmospheric CO and blood carboxyhaemoglobin levels during use of the faulty vehicle in the coldstore.

Further enquiry amongst workers suggested that several other workers had experienced headaches that
could have been related to operation of the hired forklift truck.

Mathematical modelling of possible blood carboxyhaemoglobin levels

The use of models describing the levels of blood carboxyhaemoglobin in relation to atmospheric levels of CO are well established [12,13] and models of varying complexity have been used by a number of agencies, such as the US military and US Environmental Protection Agency (EPA), as part of risk assessment strategies for CO exposure [12,14,15]. Most of these models are based on the Coburn–Foster–Kane equation, which essentially describes the relative affinity of haemoglobin for CO compared to oxygen. The Health & Safety Laboratory (HSL) has developed a relatively simple computer model which uses the Coburn–Foster–Kane equation in a differential form coupled to other important physiological factors that influence the model outcome by making the model more representative of the subject in question. These include blood volume, derived from subject height and weight, blood haemoglobin concentration, the volume of respired air per unit of time reaching the gas-exchange areas of the lungs (which also depends on the work activity of the subject over time) and the individual’s diffusing capability of gases across the lung epithelium. The model can also take account of differences in atmospheric pressure and oxygen content in respired air. For varying levels of respired CO over time, the model reflects subsequent changes in blood carboxyhaemoglobin levels for the individual. This model has been validated against a range of published data [16–18], and used in the recent UK review of the occupational atmospheric exposure standard and the establishment of a biological monitoring guidance value for CO [8]. It has been increasingly used in forensic investigation of CO incidents and in running risk assessment scenarios. In the forensic investigation of CO exposures, HSL has used the model both in deriving the likely blood carboxyhaemoglobin profile from complex CO exposure patterns and the likely exposure pattern that led to a measured blood carboxyhaemoglobin level. The model is also capable of taking account of the influence of concomitant carbon dioxide exposure via a simple effect on the respiratory ventilation rate.

In this case, we have assumed that the respiration rate of the material handler (case 1) should reflect his undertaking light-to-medium work, while the forklift truck driver (case 2) would be closer to a sedentary work rate. This implies that blood carboxyhaemoglobin builds up faster towards any steady-state value in the material handler compared with the driver.

The model can be run using simple numerical descriptions of atmospheric CO levels over time (per minute) or can use more complex environmental compartmentalization of CO sources. For example, in this case, we have modelled a range of atmospheric exposure scenarios that are used as the respired CO input into the biological part of the model. The exposure scenarios were based on the forklift truck entering the enclosure of fixed volume a number of times over the working day with a varying split in the engine working underload or idling. Thus, the forklift truck is considered a point source of CO using the measured exhaust concentration of CO, its cubic capacity and varying engine speed.

A good approximation for the production of CO from the forklift truck is given by:

\[
\text{engine CO production in m}^3/\text{min} = (\text{engine r.p.m.}) \times (1400/2) \times (10^{-3}) \times (10^{-3}) \times (\%\text{CO exhaust gas/100})
\]

Respired gas concentrations within the biological model are calculated at body temperature and pressure, saturated (BTPS), even though produced at the low temperature of the coldstore, based on the assumption that respired gases equilibrate rapidly to body temperature within the alveolar region.

The atmosphere in the coldstore has been assumed as the default position to be produced by instantaneous mixing of exhaust gases by the ceiling mounted fans. This condition is more realistic for CO, which has almost the same relative density as air, compared to carbon dioxide which is heavier than air and will tend to accumulate at lower levels. Further modification to reflect the number of likely atmospheric changes per hour in the coldstore is appropriate. Some international regulatory bodies have recommended levels of atmospheric changes per hour for indoor facilities where LPG trucks are needed to be used. For example, the Ontario Ministry of Labour and American Conference of Governmental Industrial Hygienists (ACGIH) recommend a ventilation rate of 5000 cubic feet/min of fresh air for each LPG forklift truck in operation; this corresponds to ~5.2 air changes/h in the coldstore in question. Since it was not possible to calculate a reliable precise value for the number of atmospheric changes, we explored the influence of using 7.7, 5.2 and 2.6 coldstore air changes/h in this particular case.

The model demonstrates how running the hired forklift

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**Table 1.** Measured exhaust gas emissions in the normal and hired LPG forklift trucks

<table>
<thead>
<tr>
<th>Description</th>
<th>% carbon dioxide</th>
<th>% oxygen</th>
<th>% CO</th>
<th>p.p.m. CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal truck</td>
<td>9.7</td>
<td>6.7</td>
<td>0.074</td>
<td>737</td>
</tr>
<tr>
<td>Hired truck</td>
<td>5.4</td>
<td>10.0</td>
<td>4.25</td>
<td>42 250</td>
</tr>
</tbody>
</table>

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**Table 2.** Measured exhaust gas emissions in the normal and hired LPG forklift trucks

<table>
<thead>
<tr>
<th>Description</th>
<th>% carbon dioxide</th>
<th>% oxygen</th>
<th>% CO</th>
<th>p.p.m. CO</th>
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</thead>
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</tr>
</tbody>
</table>
truck within the coldstore continuously for some period of time could lead to significant build-up of CO. After 30 min of continuous running at working speeds, the CO levels in the coldstore would be close to equilibrium, at 400, 580 and 900 p.p.m. for the different suggested room air changes of 7.7, 5.2 and 2.6 changes/h, respectively; at 60 min, the CO levels are 420, 620 and 1150 p.p.m., respectively. After 60 min of continuous working within the coldstore using the forklift truck, the computed blood carboxyhaemoglobin level in the material handler would be 17.8, 24 and 38.5% for the three levels of room air changes, whereas blood carboxyhaemoglobin levels would be 8.8, 14.8 and 19.5%, respectively, for the forklift truck driver. Such data highlight the likelihood of more severe symptoms in the material handler compared with the sedentary truck driver, paralleling the symptomatology found in the incident.

Figures 1 and 2 show the computed blood carboxyhaemoglobin and atmospheric CO levels for a possible scenario of the forklift truck and two workers entering the coldstore for 30 min every hour, where 20 min is spent with the truck idling and 10 min with the truck working under load. The company disputes this as a likely exposure scenario, although the two workers’ account of the incident suggests it is plausible. The figures highlight that although the CO levels in the coldstore may fluctuate in a regular pattern depending on the truck being in or out of the coldstore, the blood carboxyhaemoglobin levels show a relative cumulative build-up with little beneficial influence of being outside where the CO exposure would be negligible. After 3–4 h of this work pattern, and with the lower coldstore ventilation rate of 2.6 room air changes/h, it may be expected that case 1 would suffer a strong headache, nausea and reduced discernment (Table 2), with case 2 (predominantly truck-driving) suffering lesser symptoms.

Discussion

The risk of using internal combustion engine powered forklift trucks in enclosed spaces has been highlighted in a number of published papers and reports [9,10,19,20]. Lofgren’s review [9] of 5 years’ of data from a US state found that the major source of occupational CO poisoning was the use of forklift trucks in enclosed spaces, especially in cold stores. Fawcett et al. [10] reported in depth on the 8% of the reviewed 220 cases of CO poisoning that were due to the indoor use of propane-fuelled forklift trucks. All these cases presented with neurological symptoms or persistent headache and, unlike our cases, were treated with hyperbaric oxygen therapy. Fawcett also found that in a survey of 12 local propane-fuelled forklifts, the average exhaust gas CO concentrations were 3.6% during idling and 3.0% at

Table 2. Table describing the relationship between blood carboxyhaemoglobin levels and presentation of symptoms

<table>
<thead>
<tr>
<th>Blood carboxyhaemoglobin (%)</th>
<th>Signs and symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5</td>
<td>No clinical signs or symptoms in healthy individuals</td>
</tr>
<tr>
<td>5–10</td>
<td>Compensatory increase in blood flow to brain and other vital organs</td>
</tr>
<tr>
<td>10–20</td>
<td>Headache, difficulty breathing on exertion.</td>
</tr>
<tr>
<td>20–30</td>
<td>Throbbing headache, nausea, loss of fine manual dexterity and reduced mental capacity for discernment</td>
</tr>
<tr>
<td>30–40</td>
<td>Very severe headache, dizziness, vomiting, fatigue and visual disturbances</td>
</tr>
<tr>
<td>40–50</td>
<td>Rapid heart rate and breathing, fainting</td>
</tr>
<tr>
<td>50–60</td>
<td>Coma and convulsions</td>
</tr>
<tr>
<td>&gt;60</td>
<td>Respiratory failure and death</td>
</tr>
</tbody>
</table>
working rate of 5000 cubic feet/min or 166 m$^3$/min for the enclosed space and the fitting of CO alarms. The carbon dioxide, ensuring an adequate level of air changes other specific devices that convert any exhaust CO to forklift trucks, ensuring that internal combustion spaces. Measures include the use of electrically powered eliminating the risk of using forklift trucks in enclosed this may be a simplification.

There have been several approaches to reducing or eliminating the risk of using forklift trucks in enclosed spaces. Measures include the use of electrically powered forklift trucks, ensuring that internal combustion powered trucks are fitted with catalytic converters or other specific devices that convert any exhaust CO to carbon dioxide, ensuring an adequate level of air changes in the enclosed space and the fitting of CO alarms. The ACGIH and Ontario Ministry of Labour recommends a ventilation rate of 5000 cubic feet/min or 166 m$^3$/min for each propane-powered forklift truck used in an enclosed space. However, our calculations suggest that even such a ventilation rate would not protect against substantial CO build-up in the coldstore well above the current HSE atmospheric exposure standard when using the faulty hired forklift truck. Also, any such increased ventilation rates would have to be matched against larger refrigeration running costs.

While regular maintenance can help to reduce toxic exhaust emissions in forklift trucks, the fitting of catalytic converters substantially reduces CO emissions. However, catalytic converters are only efficient at normal engine operating temperatures, so reductions in CO emission may depend on usage of the forklift truck. Therefore, the safest approach would be to use only electric-powered forklift trucks in enclosed spaces, although such trucks may have power limitations and need charging facilities.

The delay in diagnosing CO poisoning, as in this case, is not uncommon [21]. This is largely due to the non-specific symptoms that are presented; often CO poisoning is described as a 'flu-like viral illness [5]. Table 2 details the usual symptoms which occur at varying levels of blood carboxyhaemoglobin, although there may be some individual variation in their presentation. In the cases described in this report, both workers showed many of the signs and symptoms that are associated with CO poisoning [3,22,23]. The persistent exhaustion and chronic nervous disability felt by case 1 are consistent with the neurological and psychiatric sequelae often found after acute CO poisoning [3]. The isolated epileptiform seizure suffered by case 1 used to be generally regarded as a manifestation of extreme CO poisoning [24,25], but Herman [25] has suggested that this may be a simplification.

A putative diagnosis of CO poisoning based on non-specific symptoms can be substantiated by measuring blood carboxyhaemoglobin or the non-invasive measurement of breath CO; both tests are widely available at hospitals and even in primary healthcare. (Appropriate and portable breath CO analysers are available due to their use in smoking cessation programmes.) It should be noted that some symptoms may persist after the return of blood carboxyhaemoglobin or breath CO to normal levels. However, in a group of US workers, an episode of headaches, dizziness, weakness and nausea related to the indoor use of forklift trucks was misdiagnosed in a hospital emergency department due to their use of pulse oximetry readings as a measure of tissue hypoxia rather than reliance on blood carboxyhaemoglobin measurements [19]. The error in reliance on pulse oximetry as a measure of arterial oxygenation in CO poisoning has been noted elsewhere [26]. We recommend that specific carboxyhaemoglobin estimations, in addition to blood gas analyses of oxygen saturation or other haemoglobin derivatives, be used to investigate such cases referred to hospital emergency departments. We also re-emphasize that specific consideration should be given to the possible diagnosis of CO poisoning in the workplace where persistent work-related headaches are reported, especially with any suggestion of dizziness or weakness, and particularly where there is evidence of altered consciousness. The proximity of any internal combustion engines (especially petrol or LPG) should be investigated, and breath CO or blood carboxyhaemoglobin measurements should be urgently sought. Such blood or breath measurements need to be interpreted in the light of the likely cessation of CO exposure and the half-life of blood carboxyhaemoglobin, rather than in corroborating any currently presenting symptoms in the patient.

In conclusion, the cases described in this report highlight how staff, works management, and primary and emergency healthcare services need to be aware of the potentially life-threatening CO risk from internal combustion engines being run in enclosed spaces, and to be aware of the symptoms and signs that may be presented. The provision of appropriate control measures by those who have responsibility for such work activities may be life-saving.

References