SYSTEMATIC REVIEW

Mass Casualty Incidents in the Underground Mining Industry: Applying the Haddon Matrix on an Integrative Literature Review

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ABSTRACT

Objective: Underground mining is associated with obvious risks that can lead to mass casualty incidents. Information about such incidents was analyzed in an integrated literature review.

Methods: A literature search (1980-2015) identified 564 modern-era underground mining reports from countries sharing similar occupational health legislation. These reports were condensed to 31 reports after consideration of quality grading and appropriateness to the aim. The Haddon matrix was used for structure, separating human factors from technical and environmental details, and timing.

Results: Most of the reports were descriptive regarding injury-creating technical and environmental factors. The influence of rock characteristics was an important pre-event environmental factor. The organic nature of coal adds risks not shared in hard-rock mines. A sequence of mechanisms is commonly described, often initiated by a human factor in interaction with technology and step-wise escalation to involve environmental circumstances. Socioeconomic factors introduce heterogeneity. In the Haddon matrix, emergency medical services are mainly a post-event environmental issue, which were not well described in the available literature. The US Quecreek Coal Mine incident of 2002 stands out as a well-planned rescue mission.

Conclusion: Evaluation of the preparedness to handle underground mining incidents deserves further scientific attention. Preparedness must include the medical aspects of rescue operations. (*Disaster Med Public Health Preparedness*. 2018;12:138-146)

Key Words: underground mining, mass casualty incident, rescue, medical emergency, preparedness

Underground mining is considered one of the most hazardous industrial occupations.[1-3] Worldwide each year, thousands of fatalities occur in coal, hard-rock, and metal mines.[4] These incidents deserve attention. In 1898 an underground mining disaster occurred on the Isle of Man; approximately 20 workers died because of smoke inhalation. This is the earliest report found with a scientific approach to a mass casualty incident (MCI) in the mining industry.[5] In 1907, 2 mining disasters were reported, one in the United States[6,7] and the other in Australia.[8] In 1909, emergency medical services (EMS) were addressed, suggesting the use of supplementary oxygen by the rescue crew at a coal pit incident.[9] Moreover, experimental studies were conducted in the mid-20th century regarding the tolerance of rescue personnel to heat and moisture.[10,11] These studies gave rise to modern safety management in the mining sector. A major catalyst for safety-management improvements was the passage of the US Occupational Health and Safety Act, which played a pivotal role in mining safety in North America.[4] Despite obvious progress in occupational-health legislation, there appears to be a gap between the understanding of and the need for an acute medical response when mining incidents occur. This gap scaled up to an MCI becomes even more evident, in particular concerning EMS capability. Recently, EMS personnel in Sweden were addressed in a survey regarding underground mining, and the survey confirmed a low preparedness level among the EMS personnel for handling mining incidents. The survey suggested a need for additional education and training.[12] Furthermore, the level of EMS infrastructure and preparedness varies substantially among countries. Also, mining conditions show variability in technology and rock characteristics, as well as occupational health legislation and traditions. This variability adds complexity to this review about strategies to handle MCIs occurring in the mining industry.

This integrative literature review explored details from MCIs occurring in the underground mining industry to identify morbidity and mortality and the EMS response to the events and the impact of EMS on victim health outcomes. Details about injury-creating mechanisms were also collected. The information was structured by using the Haddon matrix[13] for comparing human, technical, and environmental factors.

METHODS AND MATERIALS

Literature Search

Scientific reports were systematically selected, according to principles outlined in the guide "Assessing Health Care Interventions."[14] The guidelines come from the Swedish Agency for Health Technology Assessment and Assessment of Social Services and share essential elements with the PRISMA-P protocol. This approach provided relevance to the aim. Quality aspects were considered[14] and randomized controlled studies were given the highest rank. Nevertheless, randomized studies are not applicable to MCIs occurring in the mining industry as these are primarily descriptive. To gather information relevant to MCIs and EMS, the literature search had to be widened to consider incidental-type studies.

Inclusion and Exclusion Criteria

The primary inclusion encountered a "MCI" occurring in the "underground mining industry" with an incident either primarily described or secondarily interpreted from available data. Unfortunately, reports addressing medical aspects of MCIs were few and consequently the search was widened to include safety aspects and occupational health. This widening of scope did not affect the process, which followed the same formalized routine described in Table 1.

Reports older than 1980 were excluded. This was justified given modern safety improvements and legislation in occupational health medicine that have introduced important changes. For the same reason, our review was restrained to countries within the European community, the United States, Canada, Australia, and Turkey. Non-English-language reports were excluded.

The literature search was conducted within PubMed (National Library of Medicine, Bethesda, MD). The search was supplemented with a free-text search within PubMed resulting in 4 additional studies; one additional report was found by using the EBSCOHost search engine (EBSCO, Ipswich, MA). The extraction was further supplemented with 2 studies found by using backward searches from lists of references of published reports and one PhD thesis with relevance to the field.

Structure of Event Mechanisms

In this study, we applied the Haddon matrix[13] to the complexity of MCIs occurring in the underground mining industry with the ambition to form a structure for review (Figure 1). This matrix provides a structure for describing injury-creating mechanisms and is a well-known and commonly used framework for systematic analyses of various incidents, including car-crash events.[13] According to the Haddon matrix, the mechanisms are sequentially separated over time versus their contributing factors, ie, human, technical, and environmental. Environmental factors may be further separated into physical and socioeconomic details. The Haddon matrix reveals how a small incident may become amplified and how it can escalate into an MCI if unfavorable factors interact and accumulate over time. Figure 1 shows the matrix and how it was applied to MCIs in the mining industry. For example, prior to an MCI, an individual miner may have a substantial knowledge base regarding safety rules and methods and have a positive attitude toward following these rules. The miner may also be experienced in working underground and have a high stress resistance to hazardous situations. These factors are addressed as A1 conditions. Once an MCI has occurred, EMS and hospital performance are examples of environmental and organizational details in the post-event phase, which are addressed here as C3 conditions.

RESULTS AND DISCUSSION

Screening for Relevance and Quality

Overall, 564 published studies were identified in the literature search. The number of reports was condensed by using a screening process that evaluated the appropriateness to the aim and grading for scientific quality, respectively. The authors conducted the screening and grading independently and thereafter collectively discussed the findings. Thirty-one reports remained for detailed analysis. The screening array is shown in Figure 2. The list of selected references is shown in Table 2.[15-45] The review focused on information relevant to the topic of MCIs occurring in the underground mining industry, EMS, and information interpretable by the Haddon matrix.

The Haddon Matrix

The scientific reports were reviewed and structured according to the Haddon matrix.[13] Rock characteristics will be referred to repeatedly because incidents in the mining industry are often influenced by the type of rock being excavated. In the Haddon matrix, rock characteristics are addressed as a

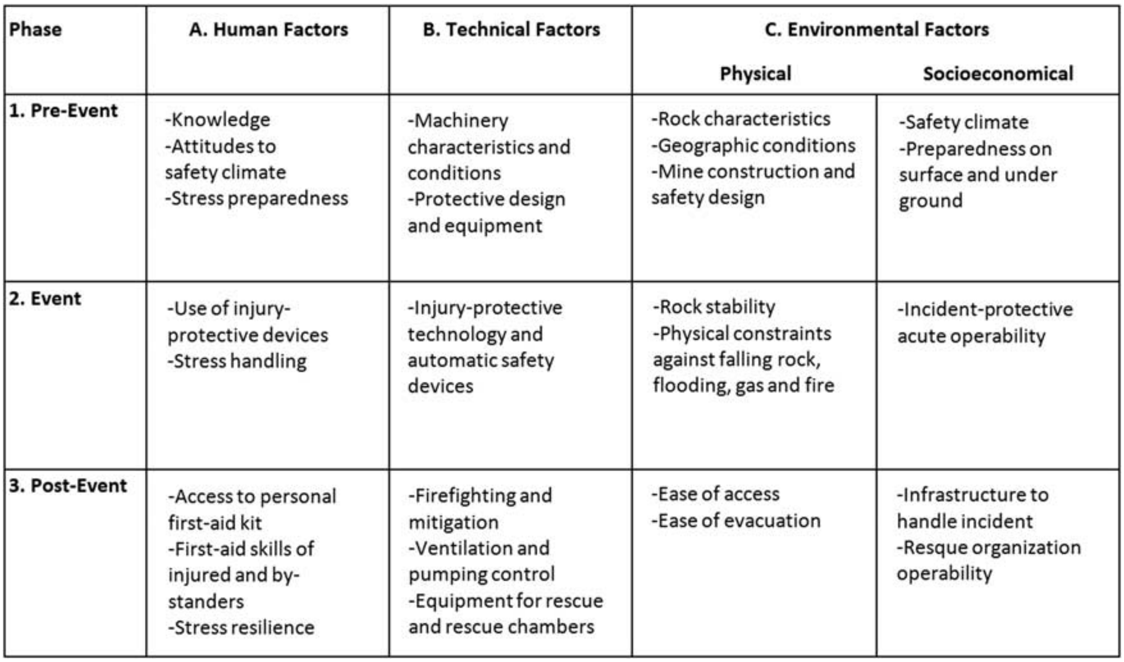
TABLE 1

Combination of Terms for the PubMed Search

Category 1	Category 2	Category 3	Category 4	Category 5	Exclusion Filter
Mining Mines	Disaster Accident Catastrophe Incident Injury/Incident	Mass casualty Trauma/Injury Hazard(s)	Rescue	Safety work Safety management Safety measures Accident prevention	Post-traumatic/Psychology Data-mining Radiation/Nuclear Genome/Disease/Cancer

FIGURE 1

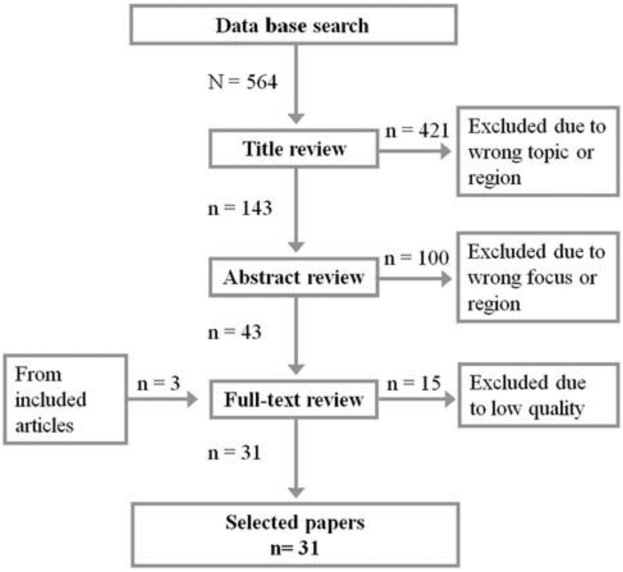
The Haddon Matrix Applied on Mass Casualty Incidents in the Underground Mining Industry.



Phase	A. Human Factors	B. Technical Factors	C. Environmental Factors	
			Physical	Socioeconomical
1. Pre-Event	-Knowledge -Attitudes to safety climate -Stress preparedness	-Machinery characteristics and conditions -Protective design and equipment	-Rock characteristics -Geographic conditions -Mine construction and safety design	-Safety climate -Preparedness on surface and under ground
2. Event	-Use of injury-protective devices -Stress handling	-Injury-protective technology and automatic safety devices	-Rock stability -Physical constraints against falling rock, flooding, gas and fire	-Incident-protective acute operability
3. Post-Event	-Access to personal first-aid kit -First-aid skills of injured and by-standers -Stress resilience	-Firefighting and mitigation -Ventilation and pumping control -Equipment for rescue and rescue chambers	-Ease of access -Ease of evacuation	-Infrastructure to handle incident -Resque organization operability

FIGURE 2

Flow Chart of the Literature Search.



C1 condition. The most obvious difference is seen between soft-rock mining of sedimentary coal versus solid hard-rock mining, typically metal core. The geomechanical characteristics introduce a technical variability exemplified from risks associated with roof scaling, strain, and collapsing rock. Also, the organic nature of coal sediments amplifies risks from gas poisoning, explosion, and fire; these risks are not present in the solid-rock mining industry. This report addressed both soft-rock and hard-rock mining. The rock is an environmental physical characteristic that affects how the mine is constructed; consequently, this environmental factor interacts with technical B1 conditions. Additionally, this environmental and technical interaction may influence the decision to excavate via an open-pit rather than underground.

Injury-Creating Mechanisms Related to Fire and Explosions

A common denominator in many reports was to describe an injury-creating mechanism of which fire, explosion, and toxic gas share the same context and deserve special attention. During 7 years in the 1990s, 47 US miners died from thermal burn injuries in mining incidents.[15] Many of these incidents occurred in coal mines, again exemplifying a C1 factor of rock characteristics (Figure 1). Explosions in these mines remain a frequent cause of fatalities, having killed hundreds of miners in both Europe[16-18] and the United States[19] over the last 30 years. Methane gas explosion triggered the mass-burn incident in the Cardowan coal mine in Scotland 1982. Approximately 200 people were underground at the time of the explosion, and of these, 40 miners were injured with burns predominating in 36 workers, whereas 6 suffered

TABLE 2

Results of the Literature Review[a]

Reference	Author, Year, Country, and Journal	Title	Method	PICO, Cohort, and Participants
[15]	Quinney et al, 2002, USA, *Journal of Burn Care & Rehabilitation*	Thermal burn fatalities in the workplace, United States, 1992 to 1999.	Statistical analysis	Thermal burn fatalities (n = 1189) investigated between 1992 and 1999 in Washington, DC, US
[16]	Onder et al, 2010, Turkey, *Industrial Health*	Evaluation of occupational fatalities among underground coal mine workers through hierarchical log linear models.	Statistical analysis	Fatal incidents (n = 830) investigated between 1980 and 2004 in Turkish coal mines
[17]	Dubaniewicz, 2007, USA, *Proceedings of the IEEE Industry Applications Society Annual Meeting*	The Brookwood disaster and electrical requirements for hazardous (classified) locations.	Technical report on electrical defects	Search for topic in the Mine Safety and Health Administration (US) database
[18]	Stojadinovic et al, 2012, Serbia, *Injury*	Mining injuries in Serbian underground coal mines – A 10-year study.	Statistical analysis	Injuries (n = 5850) investigated between 2000 and 2009 in 9 Serbian coal mines
[19]	Dubaniewicz, 2009, USA, *Journal of Loss Prevention in the Process Industries*	From Scotia to Brookwood, fatal US underground coal mine explosions ignited in intake air courses.	Documental review and statistical analysis	Fatal outcome after explosions, identified and described since 1976 in the Mine Safety and Health Administration (US) database
[20]	Allister et al, 1983, Scotland, *British Medical Journal*	Cardowan coal mine explosion: experience of a mass burns incident.	Case report	Descriptive report of burn victims in coal mine incident (n = 40), 1982, in Scotland
[21]	Hansen, 2015, Sweden, Mälardalen University, PhD dissertations, no. 178	Study of heat release rates of mining vehicles in underground hard rock mines.	Technical report on heat distribution	Experimental setting in underground conditions
[22]	Hansen, 2009, Sweden, Fourth International Symposium on Tunnel Safety and Security	Literature survey - fire and smoke spread in underground mines.	Literature review	Search of topic, mainly literature from the US, Canada, South Africa, Australia, Sweden, India, China, Russia, and United Kingdom
[23]	Kucuker, 2006, Turkey, *Occupational Medicine*	Occupational fatalities among coal mine workers in Zonguldak, Turkey, 1994–2003.	Statistical analysis	Underground coal mine fatalities (n = 164) investigated between 1994 and 2003 in Zonguldak, Turkey
[24]	Roberts et al, 2008, USA, *Journal of the American College of Surgeons*	Surviving a mine explosion.	Case report	Descriptive, of 1 survivor, 2006, Virginia, US
[25]	Rabinovitch et al, 1989, USA, *American Review of Respiratory Disease*	Clinical and laboratory features of acute sulphur dioxide inhalation poisoning: Two-year follow-up.	Case report with laboratory findings	Two-year follow-up of 2 miners surviving severe sulphur dioxide inhalation
[26]	Probst et al, 2013, USA, *Accident Analysis and Prevention*	Pressure to produce = pressure to reduce accident reporting?	Statistical analysis	Investigation of copper-mine workers (n = 212), versus productivity, in the Southwest US
[27]	Lenné et al, 2012, Australia, *Accident Analysis and Prevention*	A systems approach to accident causation in mining: an application of the HFACS method.	Statistical analysis	Incidents at mining operations (n = 263) investigated between 2007 and 2008 in Australia
[28]	Laflamme et al, 1996, Sweden, *American Journal of Industrial Medicine*	Age-related accident risks: Longitudinal study of Swedish iron ore miners.	Statistical analysis	Review of accident-reporting forms from underground mine workers (n = 524) between 1980 and 1993 in Sweden
[29]	Muzaffar et al, 2013, USA, *Journal of Occupational and Environmental Medicine*	Factors associated with fatal mining injuries among contractors and operators.	Statistical analysis	Review of fatal injuries occurring among employed operators or contractors in the mining industry (n = 157410) between 1998 and 2007 in the US
[30]	Sanmiquel et al, 2012, Spain, *International Journal of Occupational Safety and Ergonomics*	Exploratory analysis of Spanish energetic mining accidents.	Statistical analysis	Analysis of work-related accidents, stratified by workers' age, experience, and size of mine (n = not given) between 1999 and 2008 in the Spanish energetic mining sector

TABLE 2

(continued)

Reference	Author, Year, Country, and Journal	Title	Method	PICO, Cohort, and Participants
[31]	Groves et al, 2007, USA, *Journal of Safety Research*	Analysis of fatalities and injuries involving mining equipment.	Statistical analysis	Review of cohort (n = 190940) between 1995 and 2004 regarding accidents relating to mining equipment, reported in the Mine Safety and Health Administration (US) database
[32]	Ruffe et al, 2011, USA, *International Journal of Injury Control and Safety Promotion*	Machine-related injuries in the US mining industry and priorities for safety research.	Statistical analysis	Review of identified accidents involving machinery and haulage (n = 562) between 2000 and 2007, reported in the Mine Safety and Health Administration (US) database
[33]	Kecojevic et al, 2007, USA, *Safety Science*	An analysis of equipment-related fatal accidents in U.S. mining operations: 1995–2005.	Statistical analysis	Evaluation of fatalities, reported by the mining industry, involving equipment (n = 483) between 1995 and 2005 in the US
[34]	Sanmiquel et al, 2010, Spain, *Journal of Safety Research*	Analysis of work related accidents in the Spanish mining sector from 1982-2006	Statistical analysis	Serious and fatal mining accidents (n = 212) investigated between 1982 and 2006 in Spain
[35]	Patterson et al, 2010, Australia, *Accident Analysis and Prevention*	Operator error and system deficiencies: Analysis of 508 mining incidents and accidents from Queensland, Australia using HFACS.	Statistical analysis	Review of mining incidents and injuries (n = 508) between 2004 and 2008 in Queensland, Australia
[36]	Ozer et al, 2014, Turkey, *Medical Science Monitor*	Autopsy evaluation of coal mining deaths in the city of Zonguldak, Turkey.	Review of autopsy results and statistical analysis	Review of forensic records of mining-industry fatalities (n = 42) between 2005 and 2008 in Zonguldak, Turkey
[37]	Tapia, 2002, USA, *Journal of Emergency Medical Services*	Choreographed Care at Queqreek Mine Rescue.	Case report	Descriptive report, based on an incident with trapped miners (n = 9) in 2002, Pennsylvania USA
[38]	Frank, 2002, USA, *Journal of Emergency Nursing*	Miracle of the miners: the Quecreek rescue from an ED perspective.	Case report	Descriptive report, based on an incident with trapped miners (n = 9) in 2002, Pennsylvania USA
[39]	Asfaw et al, 2013, USA, *Accident Analysis and Prevention*	Profitability and occupational injuries in U.S. underground coal mines.	Statistical analysis	Analysis of incidents in the mining industry, stratified by revenue (n = 5669 “mines*year”) between 1992 and 2008, reported in the Mine Safety and Health Administration (US) database
[40]	Poplin et al, 2013, USA, *Journal of Safety Research*	Enhancing severe injury surveillance: The association between severe injury incidents and fatalities in US coal mines.	Statistical analysis	Analysis of injuries in coal mines stratified by severity according to the Abbreviated Injury Scale (AIS) in a cohort (n = 56526) between 1996 and 2006 in the US
[41]	Page, 2009, USA, *Journal of Safety Research*	Blood on the coal: The effect of organizational size and differentiation on coal mine accidents.	Statistical analysis	Review of incidents in underground coal mines stratified by organizational size (n = 4649) between 1983 and 1999 in the US
[42]	Blank et al, 1996, Sweden, *Accident Analysis and Prevention*	The impact of major transformations of a production process on age-related accident risks: a study of an iron-ore mine.	Statistical analysis	Review of accident reports (n = 359) investigated between 1980 and 1993 in Swedish iron-ore mines
[43]	Monforton et al, 2010, USA, *American Journal of Public Health*	An impact evaluation of a federal mine safety training regulation on injury rates among U.S. stone, sand, and gravel mine workers: an interrupted time-series analysis.	Statistical analysis	Effect of safety training on nonfatal injuries (n = 7998) investigated between 1995 and 2006 in US open-pit mines
[44]	Passmore et al, 1990, USA, *American Journal of Public Health*	Tailored safety training for miners in small Pennsylvania surface coal mines.	Protocol	Descriptive
[45]	Schüffel, 1993, Germany, *Journal of the Royal Society of Medicine*	The mining disaster of Borken, the implementation of a 3-year support programme and the help through EuroActDIS.	Case report	Descriptive, interviewing of family members after a fatal mining incident (n = 50) in 1988 Germany

[a] PICO, Patient/Problem, Intervention, Comparison, and Outcome.

mechanical injuries from the explosion. The burn injuries were treated conventionally on site, illustrating adequate post-incident managing (A3 factor). Six workers later required advanced treatment at a specialized hospital. In terms of EMS, this Scottish report clearly illustrates the difficulty of caring for multiple burn victims in remote areas,[20] which refers to C3 conditions in the Haddon matrix.

In Sweden, vehicle fires have been shown to be the primary source of underground mine fires;[21] a typical B1 factor. Furthermore, fuel kept underground at "fuel islands" is an identified obvious risk.[22] The safety around fuel storage underground may be categorized as a C1 factor and the consequences, in the case of fire, become a B3 problem. Hot and toxic smoke is regarded as a significant threat and may heavily restrict visibility (B3) and interfere with an evacuation.[21] Smoke elimination by ventilation may be regarded as both a B3 and a C3 factor and the preparedness to do so a C1 detail. The consequences of smoke are clearly illustrated at a fire in a Swedish mine in 2008 where it trapped 8 miners. The rescue personnel could not descend to the victims because of heavy smoke. The trapped miners took shelter in a rescue chamber supplied with compressed air. Despite the chamber being designed for only 6 people, with inadequate air supply for the 8 miners, they were rescued after 3 attempts over a 6-hour period once the fire had been extinguished.[21,22] The issue around rescue chambers for underground fires relates to both technical and environmental details. Their chosen capacity, for example, number, size, air supply, and location, becomes a C1 factor; their pre-incident technical condition a B1 factor; and their function during the incident and rescue operation become B3 and C3 details, respectively. The awareness of workers knowing where the nearest chamber is located, and their subsequent decision to use the chamber, are also relevant as A1, A2, and A3 conditions.

Injury-Creating Mechanism Related to Toxic Gas

There are various toxic gases to consider at MCIs in the mining industry. Again, a clear distinction is noted between organic gases in coal mines versus gases of inorganic character, a discrepancy related to C1 in the matrix. Methane is an organically generated gas of low endogenous toxicity. Methane gas threats are associated with asphyxia due to accumulated concentrations, but more importantly from explosion and fire[19] as outlined above. It has been reported from Turkish coal mines, analyzing a 9-year period of incidents, that 11% of all fatalities (n = 164) were associated with different forms of gas poisoning.[23]

Sulfur dioxide is a well-known inorganic gas in the mining industry. The gas may slowly asphyxiate[24] and is a prominent and feared airway irritant. Respiratory damage due to sulfur dioxide inhalation was reported in 1985 when 3 miners were exposed and injured.[25] The same survey described sulfur dioxide in a Canadian copper mine that was responsible for 1 miner's death.[25] Of interest at that incident, 2 survivors covered their heads with rubber pants combined with emergency oxygen for inhalation. They effectively improvised simple escape hoods, illustrating an outstanding A3 factor. They were rescued after 3.5 hours, but despite their innovative action, they suffered severe airway damage and long-term impairment.[25]

Toxic gas may also form at combustion with carbon monoxide forming at oxygen shortness and hydrogen cyanide from burning plastic materials. At the methane gas explosion and fire in the US Sago mine in 2006, 14 miners remained trapped and exposed to gas and smoke for 41 hours. All but 1 miner died from airway distress after toxic gas inhalation.[24] This incident highlights the need for B3 preventive strategies and further described a negative C3 consequence associated with a prolonged rescue operation.

Human Factors

It has been suggested that injuries occurring in the US mining industry are underreported.[26] Human factors, such as skilled-based errors, incorrect decision-making, supervision failure, and violations of rules are some root factors of such mining incidents. These human pre-event factors (A1) may interact with technical (B1) details to cause incidents involving machinery, scaffolding, and electrical equipment.[27]

Age of the miner is a human factor of particular interest. It was found in 2 separate studies that young miners between 18 and 29 years of age were those most frequently injured in Swedish[28] and Turkish[23] mining industries. It was further proposed that young miners were more likely assigned to higher-risk tasks, which combined with a lack of experience, may exacerbate the risk of injuries. From the perspective of the Haddon matrix, these circumstances reflect young miners' attitudes toward safety and match their self-judged experience to acquired skills (A1) and how these interact with the environmental safety climate within the mining company (C1). Nevertheless, these results do not find support in a US study, contradicting the assumption that lower age equals higher risk. In that study of the US mining industry, the most frequent age of fatal events occurred in the age span of 35 to 43 years for contractors and operators.[29] Moreover, a Spanish study concluded that older age groups were more frequently involved in injury events and were more prone to suffer severe injuries than were younger individuals.[30]

Technical Factors

Three US studies were found, describing injuries relating to machinery and equipment,[31-33] all illustrating B1 mechanisms (Figure 1). Of impact, 41% of all severe injuries (n = 562) involved different types of machinery. This was exemplified by conveyor belts, bolting machines, and haulage equipment.[32] In one study, underground ore haulage machinery was associated with the highest rate of fatalities.[31] In another report, covering a 10-year period in the US mining industry, machinery and technical equipment contributed to fatal outcomes in between 37% and 88% of incidents among annually reported injuries (n = 483). The highest rate (22.3%) was seen for haul truck incidents.[33] Similarly, a Spanish study indicated that 14% of all serious or fatal injuries (n = 212) related to being run over or hit by moving machinery.[34] In Turkey, 20% of all injuries (n = 164) involved interaction with underground railway traffic.[23]

Ventilation and control of air flow and air quality are of mandatory importance in an underground mine; all depend on technical equipment and their function. The igniting mechanisms of explosions have been investigated in US coal mines, indicating ventilation systems to be a source of ignition.[19] One example described an accumulation of coal dust particles in an air inlet shaft that was ignited by a faulty electric cable.[19] This illustrates a typical B1 factor. However, in this particular case, the primary explosion was followed by a secondary explosion that killed all of the rescue personnel.[19] The secondary explosion exemplifies a B3 sequence that may have been preventable, which instead contributed to negative consequences in terms of C3.

Environmental Physical Factors

In an Australian report, environmental factors of subsidence and entrapment were identified as the most important precondition variable for unsafe actions.[35] This observation of typical C1 mechanisms finds support in a Turkish study.[23] During a 15-year period, 50% to 60% of all reported mining fatalities were due to subsidence, mostly rock falls of different proportions.[23,36] Moreover, a similar conclusion was described from the Spanish underground mining industry, covering a 25-year period, showing subsidence and falling objects responsible for 48% (n = 212) of serious and fatal injuries. In 16% of these events, the victim was trapped between or behind objects.[34]

Environmental conditions may interact with technical details, as described for the MCI occurring in the US Quecreek mine in 2002. In that incident, methane gas was ignited and exploded, causing subsidence and flooding in parts of the mine. Nine miners were trapped in an obviously life-threatening situation but were rescued after 3 days.[37,38] The event exemplifies a sequence of a technical B1 factor that escalated into an environmental disaster (C1). However, the accumulation of methane gas may also be considered a C1 factor expected to occur in a coal mine; granted, safety equipment may have helped (B1) to prevent the incident.

Subsidence is a reported catalyst for other hazards. When trapped by rock falls, toxic gases became more difficult to avoid and the combination of these circumstances may be lethal.[24] The US Quecreek mine incident is an illustrative and well-described MCI in these aspects.[37,38] The explosion and subsidence caused massive amounts of cold (13 °C) water to flood the mine. Pumping of 230,000 m^3 of water helped to drain the shaft. However, the miners were assumed to be chest deep in the water and to suffer from severe hypothermia. Therefore, heated air (37 °C) was pumped down to the miners via a 6.5-inch diameter communication shaft that was rapidly drilled to access the entrapment. The EMS team also raised concerns that flooding may have created a water-lock entrapment deep underground with overpressure in relation to the atmospheric surface. A pressure differential of this kind has been reported to compromise the safety of the surviving miners.[37,38] This mechanism, a C1 condition, has similarities with decompression sickness of deep-water diving. Consequently, the EMS team proposed a cap be installed at the shaft opening to regulate the pressure change during the rescue operation. Also, decompression chambers were prepared. However, only one miner needed decompression treatment. All of the trapped miners were rescued after 72 hours via another drilled 30-inch wide rescue shaft. The miners were transferred for care at hospitals in the area that had been prepared for optimal treatment of the expected medical conditions.[37,38] The US Quecreek mine incident illustrates several good examples of preparedness (C1), technical operability at rescue (B3), and EMS abilities (C3).

Environmental Socioeconomic Factors

Several studies have investigated how socioeconomic factors such as organizational size and profit-seeking affect injury prevalence. These factors address the safety climate (C1) in Figure 1, but also involve attitudes among the miners to adapt to this climate (A1). Conclusions may be drawn in this context by considering the effects of injuries of annual working hours per miner, geographic location, and other criteria. It was observed that a mine subject to high production demands reported a somewhat decreased rate of injuries. This observation was surprising.[39] These mines were instead found to have a higher occurrence of non-injury events.[40] It has been shown that smaller mines (by organizational size) had a higher injury rate than larger ventures, probably as a result of a lower ability or interest to invest in the mine infrastructure, safety equipment, and safety activities,[26,30] all C1 preventive measures. It was noted that the size of the mother company was an important factor that needs consideration.[41] A larger venture may allocate more resources toward safety investments.[26] Subcontractors in the US mining industry were found to have a 3 times higher risk of being involved in a fatal injury event compared with full-time mining employees.[29] The subcontractors' lack of safety education and experience in working underground was proposed as an explanation for this difference,[28] which may be addressed as an A1 factor in the Haddon matrix. A Swedish study concluded that technology investments with the aim of reducing the number of employees did not have any direct effect on the rate of injured personnel.[42] It may be interpreted that a presumed negative influence on safety from a higher production rate per miner (A1) may be counterbalanced by more efficient and safer machinery with less required manual interaction (B1).

We found no evidence in the literature confirming or rejecting the notion that governmental regulations (C1) on safety training (A1) for mining personnel have had an impact on the number of injuries.[36,43] If the provided training only followed federal laws, the training would often miss important specific safety issues of specific mines. In one US study, tailored programs of training were regarded as having a greater reducing effect on injuries than national or federal regulations.[44]

Emergency Medical Services at MCIs in Underground Mining

The US Quecreek mine incident was mentioned above but deserves further attention regarding EMS capability. At this incident, 9 miners were trapped as an effect of a methane gas explosion, subsidence, and flooding. A 24-member Special Medical Response Team was formed early to include paramedics, emergency medical technicians, physicians, assistants, and supporting staff.[37] The individual team members and their knowledge had a direct influence on the rescue operation, illustrating both a pre-event preparedness (C1) and an obvious post-event operability (C3). This was further exemplified by the drilling of a delivery shaft to the entrapped miners for oxygen, heating, and radio communication.[37] In doing so, the risk associated with air decompression (C2) was also considered. The US Navy prepared 9 mobile hyperbaric chambers (C3) in the event of such treatment.[37,38] Moreover, the 9 miners were suspected to be contaminated with fuel; consequently, decontamination equipment was prepared (C3). An unknown detail at the rescue operation concerned the miner's physical condition; the miners could have been unconscious or disabled and unable to enter the rescue capsule. The drilled ventilation shaft gave necessary and positive information in these respects (C3). Radio contact further allowed the miners to be remotely triaged and prepare an order of evacuation (C3). On the surface, a heated tent was erected for casualty clearing, emergency treatment, and secondary triage. The miners were then transported to the nearby trauma hospital.[37] The hospital had been prepared in advance by personnel reinforcement and equipment.[38] All these details had relevance to C1 and C3 factors in the Haddon matrix (Figure 1).

Apart from the US Quecreek mine incident, EMS was briefly referred to in the report following the US Sago mine explosion. Of 14 entrapped miners, only 1 survived after a prolonged rescue operation. Nevertheless, a post-event effort (C3) was described to organize air transport of victims to specialized burn centers.[24]

The need for psychological support in both short- and long-term post-incident perspectives (C3) is acknowledged in the literature.[45] It is further emphasized that this support needs to include not only the survivors but also the victims' families, working colleagues, and rescue personnel.[45]

Limitations

Our study had the ambition to explore information about EMS at incidents in the mining industry. However, the scrutinized literature presented few such examples. In our search, only one MCI, the US Quecreek mine incident in 2002, analyzed the EMS perspective, which was summarized into 2 separate reports,[37,38] both in line with our primary aim. The search was limited to the PubMed database, addressing EMS and MCI in the context of underground mining, which may have restrained the perspectives of this study. Moreover, there was a risk of bias that incidents not resulting in injuries or death are not being reported by the mining industry, or if reported, were not accessible by the described search procedure. Furthermore, underground mining is by tradition considered to be a hazardous occupation which may add a bias of normality.

CONCLUSIONS

Our literature review, which focused on MCIs in the underground mining industry, identified a diversity of reports, whereas only very few had relevance to our primary aim of EMS. This negative observation suggests a need for future studies that highlight EMS perspectives in particular. Underground rock excavation is obviously a dangerous environment associated with many unpredictable risks of major impact. The environmental difference between soft-rock coal and hard-rock mining adds a disparity to injuries and their mechanisms. Nevertheless, the Haddon matrix identified several pre-event and post-event actions of great importance for injury prevention and mitigation and rescue preparedness.

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