CBRN Equipment and the Wearer

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Introduction

A good part of this handbook is devoted to equipment and programs. These are necessary to provide and maintain the protection needed to survive emergency disasters when toxic materials are involved. CBRN respirators and protective clothing are designed, assembled, and tested to assure that they are capable of the level of protection that first responders and ancillary personnel require in order to be able to respond appropriately to the emergency and to do so without damage to them selves in the process. There is, however, another critical element is this response, and that is the responder him or her self. The protection afforded by the equipment does not come without price; for each additional piece of protective equipment worn to separate the wearer from the hazard, there is a performance penalty. Once adequate protection has been afforded, wearers must still cope with the burdens of protective equipment that affect their abilities to perform assigned tasks. An understanding of normal physiological adjustments to exertion and the alterations imposed by protective equipment can help the individual responder to form more realistic self-expectations in an emergency, help the supervisor or crew chief to have realistic expectations of his/her responders, and help emergency management personnel plan realistically for means to deal with emergencies. Thus, the emphasis of this chapter is on the wearers of protective equipment and how their abilities are affected by the equipment that keeps them alive.

Physiological Reponses to Work Activity

Before a brief discussion of ergonomics and work physiology, there are two things to keep in mind about heavy exertion while wearing respirators and protective clothing:

1. Work cannot usually be performed as long or as hard while wearing a respirator compared to when respirators are not worn. Wearing protective clothing plus respirators makes this situation even worse. Either more time must be allowed for a particular task or more responders must be assigned to the same task.
2. There is a great deal of wearer variability. Some wearers can tolerate respirator high inspiratory or expiratory resistance or pressure levels, while others cannot. Some wearers are much more anxious about wearing respirators than others. Some wearers can tolerate hot, humid conditions inside protective clothing, whereas others cannot. Even with the stringent selection process for many emergency personnel, this variability persists. And, one must also recognize that emergencies sometimes require people to respond who haven't been through the selection process. Because of this variability, each responder must be treated as an individual.

1. Work/performance time tradeoff

Very hard work cannot be performed for as long a time as work of lesser intensity (Figure 1). This is true even when unencumbered by CBRN equipment.. In the Figure, it can be seen that, for different activity levels, there are corresponding physiological limitations consisting of a cardiovascular limitation for very intense work, respiratory limitation for intense work, thermal limitation for moderate work, and what is generally called irritation limits for low-level activity. Protective masks and clothing generally shorten the time that a particular activity level can be sustained.

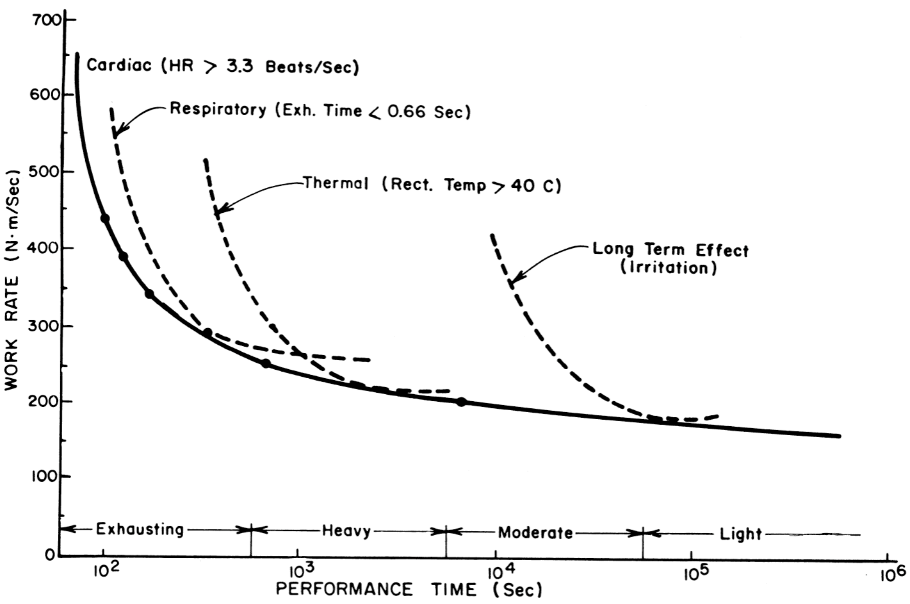

Figure 1. Schematic representation of performance time while exercising wearing a protective mask.

2. Physiological adjustments

The human body is attuned to performing physical labor. What follows the start of muscular activity is a coordinated series of adjustments involving all parts of the body, including the heart, blood vessels, the lungs, digestive system, nervous system, and the kidneys. The ones with most direct bearing on exercise adjustments are described below.

a. metabolism (3)

Muscular movement requires energy. This energy comes from an energy storage molecule called ATP. When the supply of ATP is exhausted, muscle activity ceases. It is important, therefore, to replenish the ATP supply as quickly as possible in order to maintain muscular work. There is also another energy-rich compound in the muscles called creatine phosphate that can act to replenish the ATP supply extremely quickly. When the muscle starts working there is enough ATP in the muscles to sustain the work for 0.5 sec. There is enough creatine phosphate present to keep the muscle working for up to 2 minutes. After that, other energy- forming mechanisms are necessary to replenish the ATP supply.

This other energy comes from stores of glucose in the blood, glycogen (an animal form of starch) in the muscles and liver, fats in the form of triglycerides in fat tissue, and body proteins. In order to extract the energy from these compounds, they must be respired, and there are two kinds of glucose respiration: anaerobic and aerobic. The difference between the two is that aerobic respiration requires oxygen and anaerobic respiration does not. Oxygen delivery to the muscles begins in the lungs, continues in the blood, and is finally delivered to the muscles (Figure 2). If enough oxygen can be delivered to the tissues, then aerobic respiration can keep up with the energy demands of the muscles. However, there are limits to the rate that oxygen can be supplied, called the maximum oxygen uptake, and, once the maximum oxygen uptake is reached, additional muscular energy must come from anaerobic respiration.

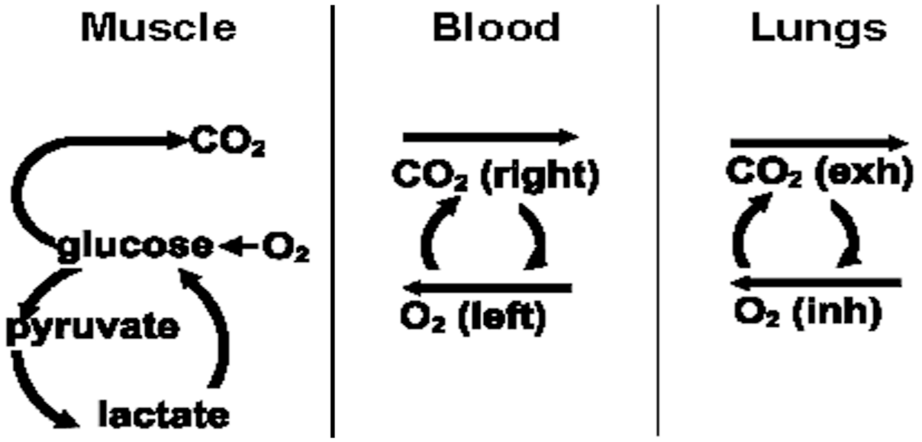

Figure 2. Oxygen delivery to the muscles is a multistep process, beginning with gas exchange in the lungs, being transported in the blood, and finally being used in the muscles.

Very heavy exertion requires at least some anaerobic respiration because oxygen demand exceeds the maximum oxygen uptake. This is called the anaerobic threshold. Anaerobic respiration yields 18 times fewer ATP molecules than does aerobic respiration, and so is not nearly as efficient. However, it does allow movement to continue, at least for a while.

One of the end products of aerobic respiration is carbon dioxide, which can be removed during exhalation. Carbon dioxide levels in the exhaled breath rarely reach more than 4-5% even at the extreme, but, if it did climb much higher, carbon dioxide can cause disorientation, confusion, and even death.

The main end product of anaerobic respiration is lactic acid that is dumped from the muscles into the blood. There are buffering mechanisms in the body that tolerate lactic acid additions, but these mechanisms have limited capacity. Once this capacity is reached, there is no other source of energy for the muscles and all muscular activity must cease. Period. This capacity to tolerate lactate is called the maximum oxygen debt because all the lactic acid must be reformulated into glucose at the end of exercise, and this requires oxygen.

Buffering the blood against lactic acid formation during anaerobic respiration produces extra carbon dioxide that can be exhaled. This extra carbon dioxide acts as a respiratory stimulant that leads to hyperventilation, or harder and deeper breathing.

All these processes proceed each time a person moves actively. They are much more efficient for younger people than for older people. Maximum oxygen uptake for 20 year olds is about 2.5 liters per minute, but declines nearly linearly to about 1.7 liters per minute at age 65. Well-trained individuals can have maximum oxygen uptakes up to twice these values. In addition, the maximum oxygen debt that can be incurred by an individual declines with age and is affected by training.

Metabolic responses during exercise, and especially during emergencies, are modified by the release of the adrenal hormones adrenalin (epinephrine) and cortisol. These hormones increase metabolic rate, increase the rate and force of heart contractions, enhance the availability of blood glucose, reroute blood from the gut to the muscles, and mobilize the nervous system. The combined actions of these hormones can affect physical, emotional, and cognitive functions.

Muscular strength declines with age, making task performance less efficient when more muscles must be recruited to perform a task. Muscular power can be restored relatively rapidly with strength training.

Drugs and medicines can also affect body metabolism, as can illness.

b. cardiovascular adjustments (3)

The heart adjusts to the physical demands of exertion by increasing its cardiac output, or the volume rate of blood flow through the arteries, capillaries, and veins. This is done to increase the rate of glucose and oxygen supplied to, and removal of lactate and carbon dioxide from, the muscles. The heart rate increases nearly linearly with work rate, beginning to increase nearly as soon as work rate increases. This is due to kinesthetic neural sensors in the muscles and joints that signal the fact that increased oxygen demand is on its way, despite the fact that there is as yet no reduction in blood oxygen concentration or rise in carbon dioxide concentration. Once the concentrations of these gases change, then control of heart response is determined by chemical sensors in the aorta, in the carotid arteries in the neck, and in the brain.

The stroke volume of the heart, the amount pumped for each heart beat, increases initially at the start of exercise, but soon reaches its maximum amount. Thereafter, cardiac output is determined only by heart rate. Cardiac output at rest is about 5 or 6 liters per minute; cardiac output can rise to 25 liters per minute during strenuous activity. Blood volume in a somewhat smallish 150 pound (70 kg) person is about 5.6 liters. Hence, it takes about 1 minute at rest and 12 seconds during exercise for blood to make the loop of the whole circulatory system.

Larger people generally have larger hearts and larger stroke volumes. Well-trained individuals have lower resting heart rates and higher resting stroke volumes. Older individuals can have somewhat lower cardiac efficiencies than younger individuals.

If body temperature rises due to overheating, then there is a secondary rise in heart rate, which puts additional stress on the heart. The water from sweat is derived from the blood plasma, causing the blood to thicken somewhat during prolonged exercise. This also increases stress on the heart, but is alleviated by drinking sufficient amounts of liquid, some of which can be drunk before the responder answers the emergency.

Cardiovascular adjustments also include shunting the blood from maintenance activities, such as digestion and kidney function, to working muscles where it is needed. Much of the blood in the circulatory system at rest is located in the leg veins; during exercise, most of the blood is shifted to the arteries. These changes occur very quickly after activity begins. Release of the hormones epinephrine and cortisol in an emergency speeds the heart and constricts some blood vessels to shunt blood to the arms and legs.

Oxygen delivery to the working muscles can be limited by the maximum cardiac output, given as the maximum heart rate times the maximum stroke volume. Once this maximum has been reached, metabolism continues anaerobically. Depending on the muscles being used and the vascular structure serving those muscles, there may be local regions of anaerobic metabolism occurring while the muscles as a whole are still aerobic.

c. respiration (3)

Respiration also increases as exercise progresses, but respiratory responses lag activity level changes by about 45 seconds. There are many respiratory responses that occur: the respiration rate increases, the tidal volume (or the amount of air breathed during each breath) increases up to a maximum amount, the respiratory waveform changes, there are adjustments to the airways, and lung volumes change. Many of these changes appear to be stimulated by carbon dioxide concentration of the blood, but initial respiratory adjustments occur too quickly for that to be the only determinant; kinesthetic sensors may also be important for initial respiratory adjustments.

Respiration is a multistep process, whereby air is breathed in, travels through the airways, reaches the alveoli (the sacs at the end of the lung where gas exchange takes place), diffuses across the alveolar membrane, dissolves in the blood, and is absorbed by the hemoglobin in the red blood cells. Carbon dioxide diffuses rapidly into the blood, so the concentration of carbon dioxide in the alveoli and the blood are always equal, even during the most intense activity level. Oxygen, on the other hand diffuses more slowly than carbon dioxide, so its concentration in the blood is lower than in alveolar air during inhalation. Diffusion rates of both gases change somewhat with activity level, with those for men being somewhat higher than those for women.

Inhaled air is oxygen rich and carbon dioxide poor. Exhaled air is oxygen poor and carbon dioxide rich. Because air flow in the airways is bidirectional, the first air that reaches the alveoli is the same as the last air that was exhaled during the previous exhalation. This is an indication of the dead volume of the lung, or that volume that stores carbon dioxide from the previous breath. Dead volume for average adults is about 180 milliliters, but dead volume of respirators can add to the effective dead volume of the respiratory system and affect performance.

Carbon dioxide is a very powerful respiratory stimulant. Increasing the concentration of inhaled carbon dioxide increases lung ventilation much more than does oxygen deficiency. Metabolically-produced carbon dioxide is even more effective than inhaled carbon dioxide at stimulating respiration. This is critical for additions of external dead volume, which transforms exhaled metabolic carbon dioxide into carbon dioxide inhaled during the next breath. Once the anaerobic threshold is reached, metabolic carbon dioxide appears to increase, and respiration is stimulated so much that lung ventilation increases dramatically as work rate intensifies.

Working muscles change their efficiencies over time as they heat and tire. Oxygen demands of muscles that have been worked for several minutes increase, thus increasing the need for the respiratory system to respond. This leads to a secondary rise in lung ventilation that continues well into the exercise duration.

Moving the chest wall, lung tissue, and air in the airways requires energy. This energy is equivalent to about 1-2% of the total body oxygen consumption at rest, but increases during intense activity to 8-10%. For people with obstructive pulmonary disease, the percentage at rest can be 18-20%. These people cannot perform strenuous exercise. Adding external resistance or dead volume from a respirator (APR), or external pressure (SCBA or PAPR), increases the amount of work that must be supplied to breathe. Oxygen to supply the needs of the respiratory system cannot be used to supply the working muscles, so respiratory demands can definitely limit the rate of work that can be expected of a responder.

The work of respiration is supplied by the respiratory muscles. These include the diaphragm, the intercostals, and the abdominals. Inhalation is caused mainly due to the straightening of the diaphragm in the chest. Exhalation at rest is passive; that is, the force to propel the air to leave the lung comes from the elasticity of the stretched lung. Exhalation during exercise needs to happen a lot faster than during rest, so becomes active when the abdominal muscles push air out of the lung. Due to this difference, it is much easier and comfortable to breathe against PAPR or SCBA positive pressure during exertion than during rest.

The airways are reactive, and change during exercise. They can constrict somewhat to reduce dead volume, and thus lower wasted breathing effort, but, as they constrict, they resist air flow and increase the work of breathing, so there is a dynamic level of airway tone that is achieved. These same airways may constrict to protect against respiratory irritants reaching the lung, and cause the same symptoms as a severe asthma attack.

d. thermal responses (3)

The large skeletal muscles are only about 20% efficient. Of the energy supplied to the muscles, approximately 80% ends up as heat. Thus, heat loss mechanisms are necessary to maintain thermal equilibrium of the human body.

These mechanisms include vascular adjustments, sweating, and voluntary responses. Voluntary responses include moving to cooler locales, stretching out to lose more heat, drinking cool liquids, or removing heavy clothing. These responses will generally be unavailable to emergency responders.

There is a thermal mass to the body that requires some time for heat to build up and cause dangerous body temperatures. There is a normal 6-10 minutes of activity that can occur before deep body temperature rises significantly. Skin temperature probably increases during this time. If sufficient heat cannot be lost to the environment, then body temperature will continue to rise until it reaches dangerous levels. A body temperature of 104º F (40º C) is expected to give a 50% casualty rate. This condition is characterized by disorientation, loss of body temperature control, and death.

Heat can be lost from the body by convection (usually, air movement), radiation (as to a cold clear sky), or evaporation. Convection and radiation heat loss depends on the difference in temperature between the surface losing heat and the surrounding fluid (usually air, but, in a pool, water). Thus, one adjustment the body makes during thermal stress is to warm the skin surface. It does this by shunting blood from deep veins into surface veins. This is why veins on the surface of the hands seem to stand out more in hot weather than in the cold. There is also a small, but significant, amount of convective heat loss from the respiratory system as air is breathed.

Evaporating water absorbs a large amount of heat, thus making sweating effective as a heat loss mechanism. Sweating heat loss on the surface of the skin is nearly 100% effective for losing heat. Sweating through clothing cools the clothing surface where the evaporation actually takes place, and only partially cools the skin. Sweat that drops from the skin is completely ineffective for heat removal. The amount of sweating depends on the cooling necessary, and different parts of the skin are recruited at different times to produce sweat. When fully recruited, the maximum cooling that can be obtained from sweating is equivalent to nearly 12 times the body heat production at rest (11.4 mets).

Women have higher percent body fat than do men. They use this body fat as insulation between their body cores and the outside environment. To lose heat, therefore, women depend more on vascular adjustments that do men. Men sweat more than women and lose a larger fraction of their heat in that way. Acclimation to hot environments can improve sweating efficiency by increasing both the rate of response and amount of sweat produced.

Some responders may not need to wear protective clothing with their respirators. However, covering up the entire body, and moving into a hot, burning environment eliminates nearly all possibility of heat loss natural to the human body. Other means must be provided, such as supply of cool air from an SCBA, or body temperatures must be closely monitored. An alternative is to limit heat exposure time and to provide adequate rest cycles.

So far, attention has been placed on overheating. Some emergencies may require response in very cold temperatures. At the beginning, cold temperatures may limit movement and dexterity. However, heat produced during activity and the extra insulation afforded by protective clothing and respirators soon overcome cold temperature effects on the body. Surface blood vessels in the head do not constrict in the cold, as do similar blood vessels in other parts of the body. Hence, nearly half of the body's heat loss in the cold comes from the head. Covering the head and face with protective equipment helps to insulate against this large amount of heat loss.

e. work/rest cycles (3)

As given in Figure 1, more intense work cannot be sustained as long as less intense work. If responders are expected to work very hard for a while, they must also be in a position to rest or, at least, slow down for a while. This can be a problem in dire emergencies, because anaerobic work continued for too long can result in the maximum oxygen debt being reached. Then the responder would not be able to work any more until he or she recovers sufficiently. Lives could be lost if it reaches this point.

The amount of time that a person can be expected to work is related to the fraction of the maximum oxygen uptake represented by the task being performed. Thus, performance time involves the size of the individual as well as age, sex, and physical conditioning. In general, men have higher maximum oxygen uptakes than women, but they have larger sized bodies that use more oxygen to move around. Older people have lower maximum oxygen uptakes than younger people. Responders in better physical condition have higher maximum oxygen uptakes, and, additionally, are abler to perform tasks with lower oxygen use than are less physically-able responders. This emphasizes the need for constant physical conditioning of those who are on call to deal with emergencies. Remember, however, that emergencies such as acts of terrorism are likely to occur almost anywhere and at any time. People may be pressed into service who are not physically conditioned or trained to respond properly. Thus, it is up to the supervisor to be aware of their limitations; emergency management personnel should include this contingency in their planning process.

Work performance times can range from forever at rest, to 4 hours walking at 3 miles per hour, to 23 minutes for cross-country running, to 10 minutes climbing stairs. These are typical times for an unencumbered 40 year old man. The addition of CBRN equipment can reduce these times to one-half or less of the values given, depending on the types of equipment worn.

Rest times are also dependent on the intensity of the task and the maximum oxygen uptake of the individual. In general, the more intense the work, the longer will be the recovery time, but the relationship is nonlinear. A task that can be performed for an hour requires at least a 10 minute rest period. More intense tasks (with shorter performance times) require longer rest times. One should be sure that rest can take place in a safe location.

Higher work rates are usually associated with higher lung ventilation (breathing harder). Harder breathing consumes air from the SCBA tank faster and can reduce protective capacity of PAPR and APR filters (although this would only be important in very extreme cases). These effects could be the most important determination of task performances times.

One mistake that can be made is to cool an overheated responder by stripping protective clothing and venting remaining clothing with cool or cold air. Sweat accumulated on the skin evaporates, overcooling the skin. This elicits a reflex that shunts blood from the skin to interior blood vessels in an effort to conserve heat. The result is that deep body temperature not only doesn’t cool very fast, but can actually increase by another degree as metabolism continues at a high level for a while after physical work ceases. To cool the overheated responder faster after intense work, open protective clothing only moderately to allow some of the accumulated sweat to evaporate slowly. Of course, venting protective clothing, removing gloves, and taking respirators off should only happen in a safe location.

f. prolonged activity (3)

Some responders will be assigned support tasks that are physically not very intense. These people will have no trouble with maximum oxygen debt, maximum oxygen uptake, or (most likely, unless the ambient temperature is extremely warm) excessive body temperature. Different challenges confront these responders. First of all, discomfort is felt more strongly when attention is not directed elsewhere. There can be a considerable amount of discomfort associated with wearing respirators, gloves, boots, and protective suits. These wearers will have to realize that these pieces of equipment are worn to protect them from contaminants that can shorten or reduce quality of their lives.

Those individuals prone to anxious feelings may have their anxieties made worse during periods of inactivity. Anxieties are the most important threat to protective equipment wear, and extremely anxious people should not be asked to wear CBRN equipment if possible.

For those who can tolerate the discomfort and claustrophobic feelings when wearing CBRN equipment, there will nonetheless be physical effects of prolonged wear. Many respirators require a tight face seal in order to assure adequate protection. The site of the face seal may produce rashes and edema in surrounding skin areas. These will disappear with time once the equipment is removed.

Vision can be important at low work rates. There may be tasks to be performed that require a broad visual field or fine discrimination among various lights, switches, or objects. Respirators interfere with vision in various ways, but visual acuity at low work rates can be compromised by lens fogging, dust or films on the lenses, or wearing of improper corrective lenses. Sweating people wearing respirators in cold drafts can easily incur moisture condensation inside the face piece. Dusts and precipitates that are of no respiratory consequence to the wearer can obscure vision if not able to be wiped from the lenses.

3. End points

Respirator masks may look like relatively simple devices. However, they are complex pieces of equipment. They can interfere with vision, speaking and hearing, respiration, heat loss, eating and drinking, sneezing, scratching one's face, other equipment, and a feeling of well-being. Interference with each of these functions can be the source of impaired performance when working while wearing a respirator. Both respirators and other protective clothing can be heavy, adding weight and bulk to make movements even harder than they would have been without them. Each protective component insulates not only against contaminants, but also against heat loss.

a. cardiovascular (3)

There is a maximum heart rate that can be achieved by an individual. This is age dependent, generally being able to be predicted as 220-(age of the individual). Younger people therefore have higher maximum heart rates. Once this maximum heart rate is reached, cardiac output no longer increases, and oxygen delivery to the muscles becomes static. Anaerobic metabolism is incurred, terminating when the maximum oxygen debt in reached. Cardiovascular-limited exercise normally terminates in 2 to 4 minutes.

b. respiratory (3)

The most important function of the respiratory system is the removal of carbon dioxide from the body. Adjustments during exercise increase depth and rate of breathing in order to expel this gaseous end-product of aerobic metabolism. Exercise exhalation becomes actively supported by the abdominal muscles, spewing carbon dioxide at faster rates as exercise intensifies. At some point, the rate at which air can be exhaled becomes limited by the distensible airways in the respiratory system. Any further increase in abdominal pressure cannot increase expiratory flow rate. Thus, for normal individuals, there is a limitation when exhalation time decreases to one-half second. Carbon dioxide cannot be expelled any faster than this minimum exhalation time allows. Respiration does not usually limit work performances of healthy individuals, but respiration can limit work time when respirators are worn. Respiratory-limited work usually lasts 5-20 minutes.

For those people with respiratory impairments, the maximum pressures that can be generated by the respiratory muscles can limit the rates at which they can breathe through external resistances or against external pressures. These people are not likely to be found as first responders, but may volunteer from on-site spectators.

c. thermal (3)

The most important work limitation associated with heat is deep body temperature. It must be prevented from reaching 40º C. A conservative limit might be 39.2º C (102.5º F). Beyond this, thermal discomfort becomes overwhelming and death may ensue. Muscular efficiency is reduced at high temperatures and judgment ability becomes impaired. Thus, the overheated individual cannot be expected to recognize his or her own dangerous situation.

Because of the thermal capacity of the body to store heat, it takes a while before body temperature rises to the point where it can become limiting. Heat-limited work usually occurs in the 10 minutes to 2 hour time range.

d. long term limits (3)

Physiological limits to long term exercise deal with limitations on blood glucose levels and muscle glycogen stores. Dehydration or electrolyte depletion may occur. These are difficult to quantify for any individual, but frequent eating and drinking can deter them from happening.

Psychological effects are also important. Feelings of fatigue are common, as are feelings of anxiety and discontent.

The Nature of the Threat to Health

Contaminants of many kinds may be present at the site of an emergency. As the name Chemical-Radiological-Biological-Nuclear suggests, contaminants may be any of these, each with its own particular threat to the health of the responder. There may be combustion and smoke at the emergency site; these can lead to toxic products of combustion with severe health consequences if inhaled. There may, instead, be a release of some chemical or biological toxin, again with possibly severe consequences. This section is meant to explain, in general, the health effects of some of the contaminants likely to be encountered so that the wearer understands the repercussions of improper protection. Respirator filter cartridges are constructed to remove each of these airborne contaminants from the air that is breathed.

a. gases/vapors (2-4)

Gases and vapors produced in a fire can be classified as those that asphyxiate and those that irritate. The asphyxiants are generally the more dangerous. Of these, carbon monoxide and hydrogen cyanide are the most common. Carbon monoxide, like oxygen, links to hemoglobin in the red blood cells, but, unlike oxygen, does not release easily. Carbon monoxide, a product of incomplete combustion of hydrocarbons, is 200 times more tightly bound to hemoglobin than is oxygen. Once all the hemoglobin sites for oxygen are filled with carbon monoxide, body cells can no longer be supplied with oxygen, and death is imminent. If exposure to carbon monoxide is nonlethal, then the victim must be placed in a hyperbaric oxygen chamber for a long time to force the carbon monoxide to leave the hemoglobin sites. Even then, some central nervous system damage may persist.

Hydrogen cyanide is equally dangerous. Cyanide irreversibly binds to an enzyme in cells critical for the last step in the metabolism of glucose to form energy. As a result, cells cannot use oxygen from the blood, and the person dies. Cyanide occurs naturally in plants as a defense against animal foraging, and animals, in turn, have developed the ability to tolerate a small amount of ingested cyanide. When produced in a fire, however, the concentration of cyanide is well beyond the tolerable limit.

Irritants may be either inorganic or organic, and are usually produced when organic materials in furniture, wallboard, resins, adhesives, paint, pesticides, petroleum, plastics, solvents, and other construction materials are burned. This class of contaminants causes immediate irritation of the respiratory tract. Those that are water soluble irritate the upper airways, whereas insoluble gases irritate the lower airways. Depending on the nature of the gas or vapor, irritation may range from mild to severe. The bronchial airways may constrict in response to serious irritation, cutting off air to the lungs.

Rescue workers and others exposed to the dusts, gases, and fumes at the World Trade Center site in New York were tested and found to lack the ability to detect odors and irritants years after they were removed from the area (6). This insidious property of irritating gases makes it unreliable to depend on responders to recognize the dangers they face.

Chemical agents may also be present at the site of a terrorist attack. These can either be extremely irritating, as is tear gas, or obstruct muscular action, as does the organophosphate Sarin. Sarin vapors were released in an attack in Tokyo in 1995 and killed 13 people. Sarin does not vaporize easily at ambient temperatures, but could be more of a threat at high combustion temperatures.

b. particulates/dusts (2,4)

There are many particulates formed in fires. These can range in size from nanoparticles (on the order of 10^{-9} meters) to 50-100 microns (10^{-6} meters). Larger particles require the turbulence of flame and smoke convection in order to remain buoyed in the atmosphere. Inhaled particles larger than 5-10 microns are deposited on the walls of the respiratory system, where short hairs, called cilia, catch them and propel them toward the throat; when at the throat, they can be swallowed or expelled, if no respirator is being worn. Smoking cigarettes can impair cilia function.

Inhaled particles smaller in size than 10 microns are called “respirable dust”. These particles may not impact the airway walls, and so reach the alveolar level of the lung. There they stay and cause lung damage. If the particles are in the nanometer range, they can move through the lining of the lungs and into cells in the body. Even chemically inert substances such as gold or titanium dioxide can become toxic in these small sizes. These have been shown to be carcinogenic in animals.

The dusts and other contaminants to which emergency workers were exposed at the World Trade Center site were particularly dangerous (6). Nearly 70% of those at the site suffer respiratory problems at a rate of twice the general population. Asbestos fibers were present there and posed a particular problem. Asbestos fibers appear under a microscope as sharply-pointed needles with hooks that can catch on lung tissue (Figure 3). Asbestos fibers cannot be removed by natural means. They can cause a respiratory disease called asbestosis, in which the lung tissue becomes fibrous, and difficult to expand. Breathing becomes difficult, and may become cancerous (called mesothelioma). It is suspected that some nanoparticles can cause similar symptoms.

Particulates can also cause a condition known as chronic obstructive pulmonary disease (COPD) in which the tissue structure of the lung breaks down until it becomes difficult to exhale. If the symptoms include shortness of breath, then the disease is called emphysema; if symptoms are cough and mucus formation then it is called chronic bronchitis. COPD is the fourth leading cause of death in the US.

Figure 3. Asbestos fibers are small and can easily penetrate lung tissues.

c. radiological products

The danger posed by radiological products depends on the type of radiation emitted by the product. The least energetic emission is the alpha particle, essentially a helium nucleus; it does not have the ability to penetrate deep into tissue, and so has limited danger as long as it is not inhaled or ingested. The more energetic particle is a beta particle, an electron; it can penetrate tissue and damage cellular DNA, causing mutations or even death. The most energetic is gamma radiation, a very energetic wave capable of ionizing chemicals within a cell and causing genetic damage; it can also burn tissues and is especially dangerous when a gamma-emitter is inhaled.

Plutonium is often mentioned as a terrorist threat (7). Inhaled plutonium is much more dangerous than is ingested plutonium because small particles of respirable size can penetrate the lung and enter body cells via the blood stream. However, plutonium is an alpha particle emitter, and only mildly dangerous. A typically respirable plutonium particle 3 microns in size has a mass of about 1.4×10^{-10} grams and has a risk of increasing cancer in the person inhaling the particle of only 0.00017%.

d. biological agents (4)

Almost any bacterium, virus, or prion that causes human disease can be used by terrorists to provoke panic in the population. Unless respiratory protection is unavailable or unused, sufficient protection is available to stop the threat.

The most notorious bacterial agent used in the recent past is anthrax, a bacterium belonging to a class of toxin-producing microbes. Others, in this class, such as *Salmonella, Listeria,* and *Clostridium,* produce food poisonings of various kinds.

Anthrax is particularly dangerous because it can exist in durable alternate forms called endospores, 1-5 microns in diameter. These can cause the anthrax disease if they contact the skin or if they are inhaled. They are much more dangerous if inhaled. It takes an inhalation of 8000-10,000 endospores to kill an average person. As few as 100 endospores may kill those most susceptible. As with all biological agents, these bacteria need time to grow to dangerous populations within the body, and, therefore, are not immediately lethal.

Another biological agent of interest is Ricin, a toxic material derived from caster beans. Ricin interferes with cellular metabolism, and can be particularly dangerous if swallowed or inhaled as a dust or mist. Respirator filters can easily removed these particles from the air.

e. heat

Heat can dry and burn unprotected skin. It can also damage lung tissue to the point that oxygen and carbon dioxide can no longer be exchanged.

How CBRN Equipment Affects the Cardiovascular System (5)

Data from multiple studies have shown that the use of respirators by themselves have no effect on heart rates of the wearers. From this, it appears that respirators do not impose additional stress on the heart. However, for respirators and protective clothing with significant weight, the additional weight can impose an ergonomic burden that translates into cardiac stress. This additional weight acts equivalently to body weight as long as it is carried close to the body. Each kilogram (2.2 pounds) of extra weight can be expected to reduce the work performance time by 2.5 minutes if walking at a high rate of speed.

If extra weight is carried awkwardly away from the body, then the energetic penalty can be an additional 50-60% of the energetic cost of carrying the load next to the body. Extra heavy loads add, as well, to the nonproportional energy cost of carrying them. Loads carried by the hands are less burdensome than loads carried on the feet. Heavy protective clothing carries with it a higher energy penalty than can be accounted for by its weight alone. Apparently, bulk and friction of the clothes is also an important factor.

Translating the energy requirement of wearing protective clothing and carrying (or dragging) extra weight into cardiac burden is not a straightforward procedure. A lot depends on whether climbing up stairs, down stairs, or walking on the level; the texture and compositions of walking surfaces; the speed of movement; and the body temperature of the wearer. Under relatively easy walking conditions, the increase in heart rate while carrying an extra 60 pounds (27 kilograms) of weight is a heart rate increase of 10% of the maximum.

How Respirators Affect Respiration (5)

Air-purifying respirators have inspiratory resistances dominated by filter resistances, with a typical value of 3.5 centimeters of water-seconds per liter (or 50 mm H_2O at 85 L/min flow rate). Exhalation resistances of the exhalation valves may be somewhat less than 1.5 cm H_2O-sec/L. Powered air-purifying respirators (PAPRs) may have much lower inhalation resistance but the same exhalation resistance. Self-contained breathing apparatus (SCBA) may have zero or negative equivalent resistance, but very high pressures to exhale against. Although exhaling against high pressures is uncomfortable at rest, when respiration usually includes passive exhalation, high-exhalation pressures can be tolerated better during exercise when the respiratory muscles for exhalation contract actively. Previous work seems to indicate that inspiratory and expiratory resistance effects are equivalent, although a test using very high expiratory resistance indicated exhalation resistance can severely degrade performance.

The effects of inspiratory resistance on performance are felt most at very intense exercise (80-85% maximum oxygen consumption). Performance time decreases linearly with increased inspiratory resistance at this exercise intensity. A resistance level of 3.5 cm H_2O-sec/L is expected to result in a 30% performance decrement. Because of this, one might expect performance with PAPR's to be better than with air-purifying respirators, but this has yet to be definitively answered, and the extra weight of the blower and tubing may counteract any advantage of lower resistance.

Extreme environmental conditions may drastically shorten PAPR battery capacity. If the battery fails to provide sufficient current to power the blower motor, the filtration capacity of the device would still be present. However, it would become an unpowered air purifying respirator (APR) with significant inspiratory resistance and dead volume. Breathing under this circumstance may become more of a burden, but the respirator must continue to be worn to provide respiratory protection.

Extra inspiratory resistance promotes hypoventilation of the wearer (lower minute volumes and oxygen uptake). This can result in an earlier transition from aerobic to anaerobic respiration, and faster progress toward the maximum oxygen debt. Also, lower resistance filters can be expected to need greater filtering capacity because of the extra air breathed through them.

Facepiece dead volume accumulates exhaled carbon dioxide and returns it to the respiratory system during the next inspiration. A typical value for respirator dead volume is 350 mL. Such a dead volume is expected to reduce performance time by 19% at 80 to 85% of maximum oxygen uptake. Dead volume may be reduced by choosing a PAPR over an air-purifying respirator. Because carbon dioxide is a psychoactive gas, dead volume may also produce discomfort and performance decrement at low-intensity work.

Intense exercise uses more air than does moderate exercise, and because very intense exercise metabolism has a higher anaerobic component than does moderate exercise, the air that is used is not consumed as efficiently as it is at lower intensity. Some SCBAs recycle spent air, but there is still some air blown off through exhalation valves. No closed circuit SCBAs have been approved for CBRN use as of this writing. The net result of spent air expulsion is that tank air gets depleted much more rapidly at high work rates than at moderate work rates. This can severely limit the time spent immersed in the conflagration.

Heat and Cold and CBRN Equipment (3, 5)

Use of respirators in nontemperate conditions can lead to special problems. Cold conditions can cause fogging of full face piece respirators, which leads to severe dissatisfaction with respirator use. Nose cups inside the face piece are designed to eliminate fogging, but are not always effective. Fog-proof lenses are available on some models. Fog-proofing solutions that can be applied to the face shield are also available. Cold can also cause valve sticking and stiffen the rubber face piece material to the point that it prevents a good facial seal. Cold rubber has a higher thermal conductivity than does still air, so in still, cold air the face may be cooled by the respirator. In a cold wind, however, the face piece may add a small amount of insulation to the face.

Use of respirators in hot conditions leads to several difficulties:

1. Discomfort has been related to facial temperatures inside the face piece. Facial skin temperatures are more important for comfort than skin temperatures in other parts of the body. PAPR blowers send filtered air over the face that evaporates sweat and cools the face. SCBA air expands and cools when released from the tank; this cool air can also help to alleviate facial discomfort. APRs, however, have been found to be uncomfortable in the heat because they do not supply cool air.

2. At moderate work rates (50 to 70% of maximum oxygen uptake), respirators impede the loss of heat from the face and can result in hyperthermia occurring sooner than it otherwise would. This is not usually a problem except when the rest of the body is sealed in protective clothing. With no easy means to lose heat, the body can overheat, especially in hot and active conditions.

3. Sweat produced inside the face piece can accumulate and cause discomfort, interfere with breathing, and cause exhalation valve sticking.

There is also an effect of heat on the ability to recognize dangers, make coordinated movements, and perform manual tasks. As deep body temperature increases, dexterity, cognition, and motor skills degrade significantly (Figure 4).

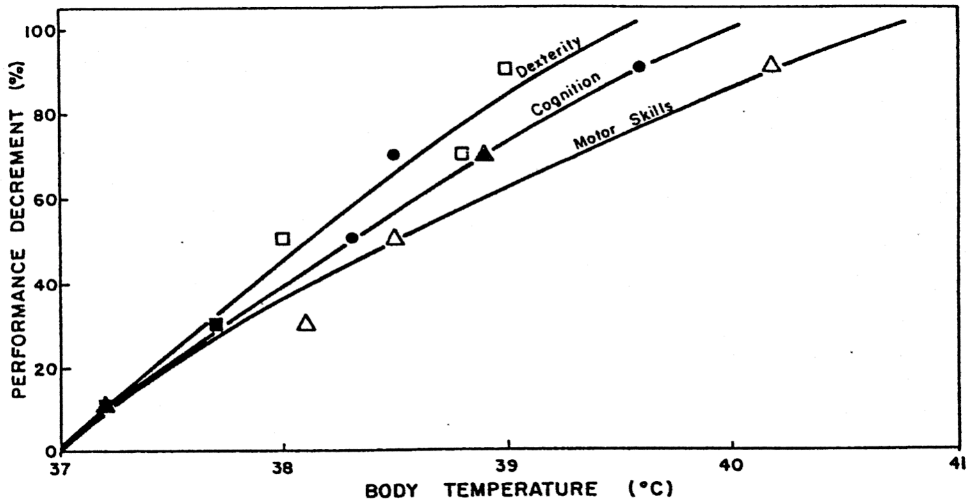

Figure 4. Effect of body temperature on dexterity, cognition, and motor skills.

Humidity in the air has a profound effect on the ability of the body to lose heat when there is exposed skin or the respiratory system breathes ambient air directly. When humidity tends toward saturation (100% relative humidity), there is less ability to evaporate moisture into the air. Sweating heat loss and respiratory moisture loss is directly related to the amount of moisture in the air.

When fully encapsulated in CBRN protective gear, however, the likelihood that there will be areas of exposed skin is small. In that case, the effect of ambient relative humidity on heat loss is small to none. APR and PAPR filters remove at least some of the humidity from the air that is inhaled by the wearer. High humidity conditions may promote respirator lens fogging.

Intense Activity with CBRN Equipment

First responders can never be sure what conditions await them when called to an emergency. In at least some of these incidents, there will be need for urgency and extraordinary measures. High exertion would be appropriate until the situation can be controlled. Under these extreme haste conditions, several problems may occur: protective equipment may not be put on correctly, exertion may reach levels that cannot be sustained, body overheating may occur, and respirators may slip on the sweaty face.

The responder should be careful with his or her equipment, because it stands between the wearer and either loss of life or a remaining life of disability. Some respirator leakage is expected to occur, especially as sweat builds up on the face and the respirator does not exactly follow sudden head movements. Some leakage can take place through the exhalation valve, especially when it becomes wet from sweat. Both SCBAs and PAPRs are positive pressure devices, but just because they are positive pressure does not mean that they cannot leak at local spots around the peripheral face seal. Respirator leakages have been measured in the workplace, but they have not been found to significantly affect the overall protection given. This issue may become a little more critical in situations where the contaminant is more dangerous than those in industrial environments. Of particular interest is the leakage from the face seal of oxygen-enriched gases in SCBAs into combustible atmospheres. Although SCBA gases are kept to an oxygen concentration that does not promote fire, the emergency responder should be aware of the possibility that a dangerous condition could suddenly arise.

Communications with Respirators (5)

Full face piece respirators interfere with visual cues during speaking and listening. It thus becomes more difficult not only to recognize what is said, but also who is saying it. Distance and intelligibility are interrelated; longer distances between communicating individuals result in less intelligibility. Speakers and listeners should talk in sentences where the message can be conveyed by context as well as by word recognition. Sentence context allows speakers and listeners to be separated by 10 times the distance compared to communicating by single words. Simple words and phrases are unable to be understood 27% of the time at distances as close as 2 feet.

When telephones or radios are used for long-distance communication, expect a 10% error rate in recognition of words and a 50% increase in the time required to recognize the words. Because standard telephone and radio equipment dimensions are not entirely compatible with respirator face pieces, protocols should be established to let the user know when to move the earpiece from the ear and to move the mouthpiece in front of the speech diaphragm. Training in the use of these protocols is essential.

Special communication equipment is available from some manufacturers and some respirators have speech diaphragms or are made of materials that enhance speech transmission.

If responders are close enough to be able to see each other, a lot of communication can take place with hand signals. There are some generally-accepted hand signals that denote easily-understood simple messages (examples of these are thumbs up for agreement, a finger across the throat for danger, an upright palm to indicate "stop", and pointing to indicate direction). These will be harder to see in a smoky environment and with gloves on, so there is a distance penalty even with hand signals.

One of the most difficult impediments to clear communication is speech accents. If speech cannot be clearly transmitted without a respirator, it will be nearly impossible with a respirator. Hand signals may serve to overcome speech understanding, but different cultures may also have different interpretations of hand signals.

Vision and Respirators (5)

Sharp vision is important for some of the tasks required during an emergency. There is a natural tunneling of vision that occurs during intense exertion: attention is focused on objects straight ahead. Consequently, degradation of vision due to respirator use during high exertion has little effect on the ability to complete the required task. Under normal conditions, this might be advantageous to task performance. In a situation where dangers can come flying from all directions, there may be difficulty recognizing peripheral threats.

Vision is extremely important for performing low-physical intensity tasks, such as computer work, console monitoring, and reading. There are many aspects of vision, including visual acuity, peripheral vision, and color detection, and some or all of these may be needed. Respirators should be selected to accommodate requirements for peripheral vision, acuity, and color recognition.

Responders requiring corrective lenses while wearing respirators must not wear spectacles with temple bars or straps that come between the sealing surface of the respirator and the face. Instead, special corrective lens mounting kits may be used with full face piece respirators. These may not be entirely satisfactory for some wearers. Those who can wear contact lenses can usually do so while wearing a respirator mask. As long as the insides of respirators are kept clean, dust particles will not be present to cause difficulties with contact lenses.

Dust, mist, smoke, condensation, or water flowing down over the face piece lenses can degrade visual acuity during an emergency. Under such conditions, task performance can be expected to be seriously degraded (Figure 5), and extra training under these conditions might be warranted. Disorientation in a low-visibility environment is common, and may make it difficult to know how to move or which is the safest direction to go.

Although visual acuity has little to no effect on performance of intense physical activity, wearing a full face piece respirator while walking, running, or driving can erode visual acuity somewhat, probably due to the pull of the face piece on the face. Recognition of objects or signs while wearing a respirator and walking or driving cannot be expected to happen as quickly as without a respirator.

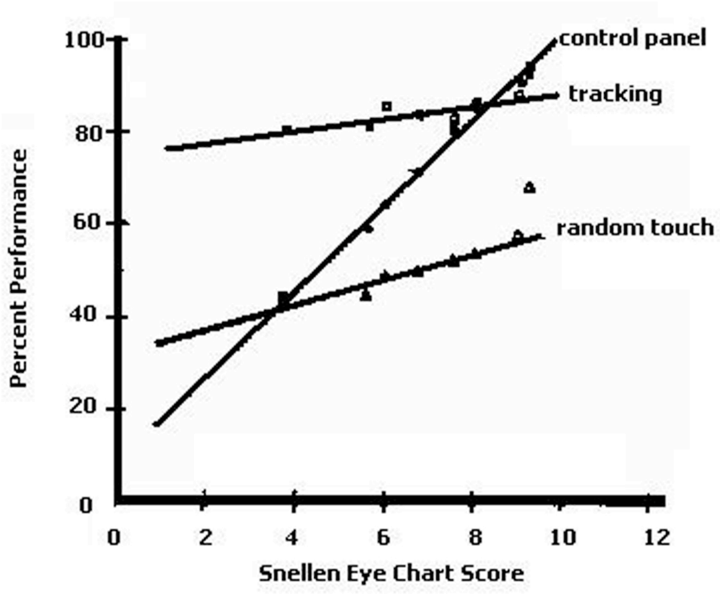

Figure 5. Performance for several tasks as visual acuity varies while wearing respirators. The Snellen eye chart denotes better vision for higher line numbers. Control panel recognition and performance ability is particularly sensitive to visual acuity.

Other Equipment and CBRN Gear (5)

Respirators can interfere with responder activities because of their bulk or weight. Use of respirators in tight places is difficult and can temporarily disrupt facial seals when bumping against other objects. Respirators may interfere with sighting equipment or with other measuring devices. Contrarily, the impact resistance of the lenses of many full face piece respirators can be a positive attribute in situations where objects or debris may fall to the face.

CBRN protective clothing is also bulky and heavy, and can impede responder progress. Small spaces must be larger for a protected responder to fit through. Gloves make fine hand or finger movements nearly impossible.

Anxieties (5)

Anxious individuals should not be asked to wear respirators. Studies have shown that anxiety level is a very reliable indicator of difficulty encountered while wearing a respirator. Extremely anxious individuals do not perform for as long or at the same work rate as low-anxiety wearers. A supervisor, therefore, should probably avoid these problems by allowing their anxious employees to perform jobs that do not require respirators to be worn.

Personal Procedures (5)

The facial area inside a respirator is usually not accessible from the outside unless the face seal is broken. Thus, eating, drinking, scratching one's face, blowing one's nose, or rubbing an eye are not possible while wearing full face piece respirators. One exception to this is certain military respirators that have a drinking tube incorporated into their designs.

As long as periodic breaks are allowed, respirators should not add to the fatigue that accompanies long term work. Food or drink can be ingested during those breaks, and energy levels maintained.

The inaccessibility of the face may generate considerable tension in the mind of the wearer, especially if the reason to access the face is due to some particular sensitive need. Dust or dryness in the eyes of contact lens wearers, runny noses, or unbearable pressure to parts of the face can be particularly distressing. If the situation does not allow the wearer to leave the hazardous environment to take care of the problem, then considerable anxiety may develop.

Another personal issue that generates much controversy is the presence of facial hair (e.g., beards or goatees) on a person who must wear a respirator. Every respirator use regulation or standard prohibits use of tight-fitting respirators with facial hair that comes between the sealing surface of the face piece and the face or that interferes with valve function. Many experimental studies with negative-pressure respirators (including air-purifying and atmosphere-supplying respirators) show the protection provided by the respirator is reduced when facial hair is lying between the sealing surface of the respirator face piece and the wearer's skin. Some studies have found that when pressure inside the face piece was positive, there was no degradation of the protection provided. However, not all positive-pressure respirators can actually maintain positive pressure inside the face piece during the entire breathing cycle and at all work rates. For this reason, use of tight-fitting, positive-pressure respirators by people with facial hair is unacceptable. The protection provided by respirators with hoods and helmet is not affected by facial hair.

Control and Training Issues (6)

The special nature of total protection required by CBRN emergencies adds additional burdens on the responders and on those who are managing the effort. Full CBRN protective gear makes activities by the wearers much more burdensome than if the gear was not worn. Training in the fully-protected mode can familiarize the responder with this burden so that it does not come as a surprise during an actual emergency. Similarly, line supervisors and emergency managers must take special care to protect those who are placing themselves at risk. Additional manpower is required to assure that each individual is not overwhelmed by difficulties. Every effort must be made to remain in contact with each responder under the supervisor’s responsibility.

According to the RAND Report in the aftermath of the World Trade Center attacks, communications among firefighters and to and from control centers was one of the biggest issues needing improvement. As mentioned before, communications while wearing respirators is difficult at best, and, unless first responder training includes communications training, this issue could repeat in the next general emergency.

The uncontrolled nature of extreme emergencies and terrorist actions makes precise planning and training very difficult. CBRN equipment is only one element to be taken into account. Maintaining some semblance of order and situational control can be challenging. Understanding the limitations imposed by normal physiological adjustments to exercise, as modified by CBRN equipment use, can help planning and training programs.

Physical stress in the World Trade Center conflagration accounted for one-quarter of the firefighter injuries and one-half of their immediate deaths. At this point, there are no good solutions to this problem; CBRN equipment, as has been said, is heavy and hot, and not likely any time soon to become less so. The immediate problem is protection. The equipment provides that. Training and responder tactics must be used as much as possible to overcome the limitations imposed by the equipment. It cannot be expected that first responders operate as if they did not wear the equipment. Without the equipment, they could lose their lives; with the equipment, they must act smart.

For Further Reading

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