Chapter 36

PROTECTIVE UNIFORMS FOR NUCLEAR, BIOLOGICAL, AND CHEMICAL WARFARE: METABOLIC, THERMAL, RESPIRATORY, AND PSYCHOLOGICAL ISSUES

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INTRODUCTION

Protective uniforms, in the broadest definition, describes every item of clothing or equipment worn by humans for protection from natural and man-made environments. Although clothing is an essential item for everyday human survival, the term protective uniform is usually reserved to describe individually worn garments and equipment designed to protect the wearer from extraordinary natural or man-made environmental extremes. In both military and civilian occupations, protective uniforms are routinely used to sustain the health and well-being of personnel performing activities in environments that pose hazards to human health. Protective uniforms fall into the following six general categories, each characterized by the nature of the hazard the uniform protects against:

1. cold weather (extreme cold weather clothing systems),
2. thermal, heat, and open flame (firefighting),
3. hazardous chemical agents, biological agents, or both (chemical–biological warfare, hazardous material cleanup),
4. ionizing radiation (nuclear power facilities, nuclear weapon fallout),
5. low-oxygen environments (aircrews, astronauts), and
6. ballistic projectiles (military operations, explosive ordinance disposal, law enforcement).

In each application, the protective uniform is designed to shield or isolate the user from specific hazards in the environment. Protective uniforms frequently encapsulate the wearer, creating a microenvironment within the uniform. Consequently, when wearing a protective uniform, the external environment, the nature of the barrier produced by the protective uniform, and the microenvironment within the uniform all contribute to the individual's physiological and psychological responses.

From the earliest days of warfare, combatants have used chemical and biological weapons against their opponents.[1] On the modern battlefield a soldier may be confronted with a wide array of chemical and biological weapons, as well as residual radioactivity from the detonation of nuclear weapons. Personal protection from these weapons requires that the soldier be isolated from the contaminated environment. This can be in the form of sealed shelters providing collective protection for small military units or via use of individual protective uniforms. Because the most widely used protective uniform in the military is for protection against nuclear, chemical, and biological weapons, this chapter focuses on that category of protective uniforms. Additional information about and illustrations of many of the protective items mentioned here are found in Chapter 16, Chemical Defense Equipment, and in particular its attachment, Psychological Problems Associated With Wearing Mission-Oriented Protective Posture Gear, in *Medical Aspects of Chemical and Biological Warfare,* another volume in the *Textbook of Military Medicine* series.[2]

The US Army refers to fighting on a battlefield on which nuclear–biological–chemical (NBC) hazards are present as *NBC operations*. To protect against these hazards, NBC protective garments (clothing, gloves, boots) and equipment (the mask) form a barrier between the user and the contaminated environment. However, the wearing of NBC protective clothing is accompanied by degradation in the performance of military operations.[3,4] The magnitude of the performance decrement depends on a complex interaction of human, mission (eg, uniform, equipment, and task), and environmental factors. In general, all protective uniforms increase the energy costs of performing work and impair the following human functions: biomechanics, thermal regulation, respiration, sensory perception, communications, eating and drinking, elimination of body wastes, and sleep. In concert, these stresses on physiological and psychological function degrade work performance and mission effectiveness. This chapter reviews these factors and discusses how they can impair the soldier's ability to perform military tasks and possible countermeasures to sustain performance.

PROTECTIVE UNIFORMS

Most modern NBC protective uniforms for combatants comprise five items:

1. a one- or two-piece overgarment that covers the torso and extremities,
2. overboots,
3. rubber gloves,
4. hood, and
5. a full-facial respiratory protective device, usually called a chemical–biological (CB) mask.

Depending on the environmental and operational situations, NBC overgarments may or may not be worn over the standard issue military utility uniform (ie, the combat fatigue, also called the battledress uniform, BDU) or other specialized uniforms (eg, flight suits). Protection against ballistic weapons or blunt impact is afforded by various styles of body armor and helmets. Although not considered part of the NBC protective uniform ensemble, body armor interacts with the protective uniform in a manner that may impair work performance. In the US military, the various levels of protection afforded by the NBC protective uniform are referred to as mission-oriented protective posture (MOPP), which has seven commonly encountered levels (Table 36-1). The concept behind MOPP levels is that the degree of NBC protection can be adjusted to the type and magnitude of the NBC threat. Furthermore, because the impairment of work performance increases with the degree of encapsulation, working in an intermediate MOPP level affords some NBC protection with less impairment of work performance.[5]

The current NBC protective uniform system provided to US military personnel is the battledress overgarment (BDO) with CB mask.[6] The BDO is a camouflaged, two-piece garment made with a nylon-and-cotton shell and an inner layer of charcoal-impregnated polyurethane foam. Drawstrings seal the BDO coat over the waist of the BDO trousers (Figure 36-1). The wearer's feet are protected by vinyl overboots, the hands by butyl rubber gloves with cotton liners; the face is covered by the CB mask, and the scalp and neck by an attached butyl rubber hood. The BDO is engineered to protect the user from field concentrations of liquid, aerosol, and vapor chemical–biological warfare agents. The BDO protects through a combination of repelling an agent at the garment's surface, and absorbing and encapsulating the agent in an activated charcoal barrier. In environments where chemical or biological agents may exceed field concentrations, specialized protective uniforms, such as the Self-Contained Toxicological Protective Outfit (STEPO), which provides greater protection, may be used. The STEPO is a completely encapsulating, one-piece, protective garment, which can be worn for toxic chemical cleanup or by explosive ordnance disposal teams when chemical munitions are present. In situations where the NBC threat is low but still present, a chemical protective undergarment containing a charcoal layer worn under the BDU may provide a limited level of protection.[7–9]

Because the respiratory system's airways and lungs present the largest surface area of the body to the environment, inhalation is the most advantageous route for introducing NBC agents into the body. The CB mask is designed to protect the respiratory system, eyes, and face from NBC threats. In combination with a hood, it also protects the scalp, ears, and neck. Externally, a CB mask consists of a

TABLE 36-1

US ARMY CLASSIFICATION OF NUCLEAR–BIOLOGICAL–CHEMICAL PROTECTIVE UNIFORM ENSEMBLES*

NBC Protective Uniform Components	MOPP Ready	MOPP 0	MOPP 1	MOPP 2	MOPP 3	MOPP 4	Mask Only
CB Mask	Carried	Carried	Carried	Carried	Worn†	Worn	Worn
Overgarment	Ready	Available	Worn†	Worn†	Worn†	Worn	—
Vinyl Overboots	Ready	Available	Available	Worn	Worn	Worn	—
Gloves	Ready	Available	Available	Available	Available	Worn	—
Helmet Protective Cover	Ready	Available	Available	Worn	Worn	Worn	—
Chemical Protective Undergarment	Ready	Available	Worn‡	Worn‡	Worn‡	Worn‡	—

CB: chemical–biological; MOPP: mission-oriented protective posture

*Based on level of threat and degree of MOPP gear required

†In hot weather, coat or hood can be left open for ventilation

‡Chemical protective undergarment is worn under the battledress uniform, coveralls, and flight suit

Reproduced from US Department of the Army. *NBC Protection*. Washington, DC: DA; 1992: 2-4. Army Field Manual 3-4.

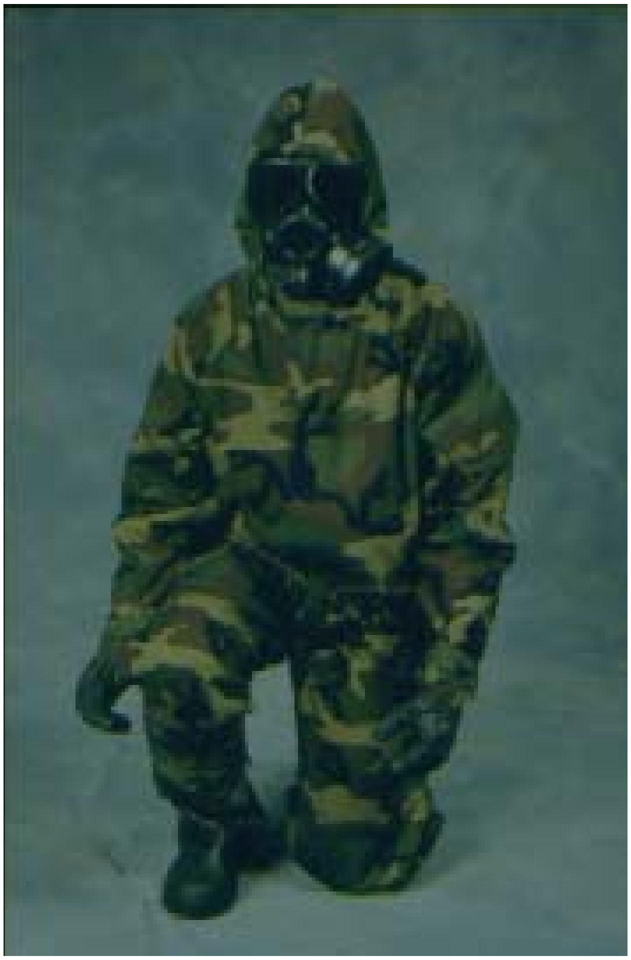

Fig. 36-1. A modern military nuclear, biological, and chemical (NBC) protective uniform (US Military Joint Service Lightweight Integrated Suit Technology Program, called the JSLIST). Note the total encapsulation of the individual at MOPP 4 (mission-oriented protective posture, level 4). From top to bottom, the NBC uniform components are the hood, US Army M40 Field Chemical–Biological (CB) protective mask, overgarment coat, overgarment trousers, rubber gloves, and vinyl overboots. Photograph: Courtesy of US Army Soldiers System Center, Natick, Mass.

facepiece and head harness, usually constructed of silicone rubber; transparent eyelenses; one or more voicemitters for transmitting the user's voice; one or more filter cartridges or a hose supplying filtered air; and a drinking tube, which allows the soldier to drink while wearing the mask (Figure 36-2). Internally, the CB mask is fitted with a nosecup, which isolates the oral and nasal openings from the eyes and eyelenses. Inlet and outlet valves on the nosecup direct filtered air into the respiratory system and prevent moist, exhaled air from flowing across the eyelenses and fogging them in cold weather.[10]

The standard NBC filter canister is designed to protect the user from field concentrations of CB agents and radioactive particles. The filter canister contains materials that capture and hold airborne particles, aerosols, and vapors. The filter does not alter the concentration of the atmospheric gases (oxygen, carbon dioxide, nitrogen) and does not absorb carbon monoxide gas. Thus, the standard military CB mask does not provide supplemental oxygen to sustain life in low-oxygen environments or protect against carbon monoxide poisoning. Typical construction materials include a high-efficiency particulate air (HEPA) filter made of either paper or glass wool, or both, to capture aerosols and particles, and activated (Whetlerized) charcoal to absorb organic compounds. With this filtering type of CB mask, soldiers must increase their breathing efforts to inhale air through the CB mask's filters and inspiratory ports.

In crew-served vehicles, a similar CB mask is frequently used, one that is supplied by a vehicle-powered blower with filtered air, thus alleviating the need for the wearer to generate airflow across the NBC filter. Vehicle-powered air blowers generally provide approximately 3 cu ft/min of filtered air to each crew member and are usually part of a vehicle-supplied microclimate cooling system, which also alleviates heat stress. Air-supplied CB masks may also be used aboard naval vessels, aircraft, and by ground-support vehicles that service civil engineering units that are performing repairs to airfield runways, roads, and bridges. The major limitation to the use of air-supplied CB masks is the availability of power for the blower motor; the uncertain power requirements limits the portability of air blowers and constrains the excursions of service personnel using such systems to the length of the umbilical line from the power source.

The NBC filters used in most current military CB masks present some potential problems to the user. Added resistance to airflow is the most significant problem, requiring increased breathing effort and producing various adverse respiratory sensations (ie, breathlessness). These filters occasionally produce ammonia, particularly in humid environments, which causes stinging, burning, and tightness of the chest that is only relieved when the wearer removes the CB mask. Also, inhalaion of the friable carbon is a possibility. Inhalation may produce deleterious health effects because Whetlerized carbon may contain copper, chromium, and silver, in addition to CB agent–contaminated carbon. Future NBC filters may avoid these potential problems by using zeolites and clathrate-like sorbents, which would capture organic agents by forming a cage around the toxic molecule.

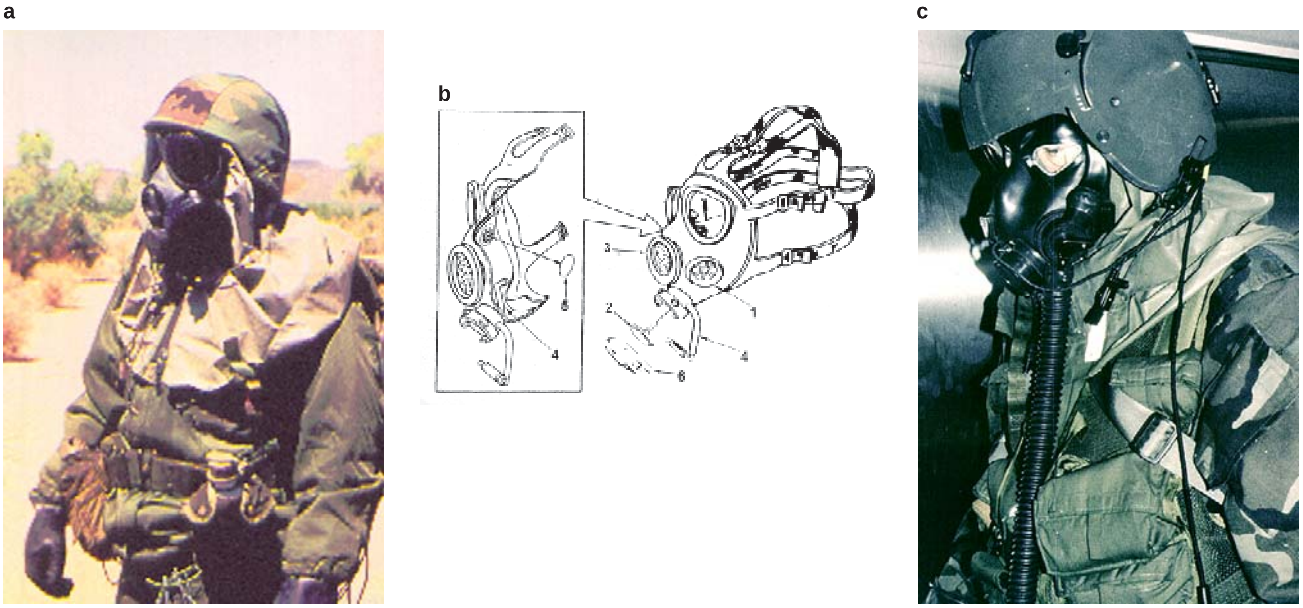

Fig. 36-2. (**a**) The soldier is wearing a US Army M40 Field Chemical–Biological (CB) protective mask with hood. (**b**) Mounted into the interior and exterior of the CB mask facepiece are (1) the inlet valve and filter canister connection, (2) the outlet valve, (3) the voicemitter, (4) the drinking tube, (5) the nosecup inlet valve, and (6) the outlet valve cover. (**c**) The pilot is wearing a US Army M43 Chemical–Biological (CB) mask and hood under the HGU-56p aviator helmet. The nuclear–biological–chemical (NBC) filter assembly is located near the pilot's waist. Note that the mask and eyepieces are contoured to interface with helmet-mounted heads-up displays. Photograph a: Courtesy of US Army Research Institute of Environmental Medicine, Natick, Mass. Drawing b: Department of the Army. *Operator's Manual for Chemical–Biological Mask: Field, M40*. Washington, DC: Headquarters, DA; June 1988: 2-2. Photograph c: Courtesy of US Army Aeromedical Research Laboratory, Fort Rucker, Ala.

BIOMEDICAL ASPECTS

Metabolic and Biomechanical Responses

Military occupational tasks can require a wide range of metabolic intensities, from slightly greater than rest to near maximal exercise. Many military tasks are physically demanding (see the Department of the Army's *Soldier's Manual of Common Tasks*[11] and *Military Occupational Specialties*,[12] both of which contain the Physical Task List). The wear and carriage of clothing, load carriage devices, and personal mission-related equipment all contribute to increasing the metabolic requirements of a work task. Several studies[13–16] have addressed the metabolic responses to multilayered garments. Routinely, NBC uniforms are worn over the service member's standard work uniform (ie, utility fatigue, BDU, aviator flight suit, or armored vehicle crew jumpsuit), creating a multilayered uniform.

Metabolic Rate Responses

Early studies of multilayered uniforms focused on cold weather garments. These studies found that the increase in metabolic rate for a given task was greater than would be predicted by the added weight of the garments alone, for which three possible explanations were proposed: increased weight on the extremities, hobbling, and friction between clothing layers.[13,14] It is well known that carrying a given weight on the hands or feet increases metabolic rate more than carrying that same weight on the torso.[17] However, only a small portion of the increased energy cost associated with wearing multilayer clothing is attributed to additional weight on the extremities.[13] This leaves hobbling and friction between clothing layers as the most likely explanations for increased metabolic rate when wearing multilayer clothing systems. Hobbling is the interference with joint movement caused by the bulkiness of the multilayer uniform. The friction produced between the clothing layers, which restricts body motion and increases the muscular force needed to accomplish a given body motion, contributes to the hobbling effect.[13,14] The change in center of gravity caused by the weight of the uniform may also contribute to the hobbling effect.[14]

Although early studies identified and measured the effect that multilayer arctic clothing ensembles have on energy costs, in general, extrapolation of these findings to all multilayer clothing ensembles is limited because only the bulkiest uniforms—arctic clothing—were studied, and energy costs were measured over a relatively narrow speed range of treadmill walking.

Two studies[15,16] evaluated the effect of NBC uniforms on energy costs of various tasks. One study[15] reported that wearing an NBC uniform (in the United Kingdom) increased the energy cost of a simple stepping task by approximately 9%. The authors estimated that each layer of clothing contributed 3% to 4% to the increased metabolic cost of the stepping task, even after they had accounted for the increased weight of the clothing.[15] A comprehensive study of the energy costs associated with performing a wide range of military occupational tasks in an NBC uniform was reported by Patton and associates.[16] Forty-two physical tasks were selected from the US Army's *Soldier's Manual of Common Tasks*[11] and the Physical Task List contained in AR 611-201, *Military Occupational Specialties*.[12] The physiological and perceptual responses of the test volunteers who performed each task were compared between the BDU and an NBC uniform (the BDO worn over the BDU; see Table 36-1). This study also evaluated the effects of gender on the physiological and perceptual responses on task performance in 36 of 42 tasks while wearing the NBC uniform.[16] The key findings of this study relating to energy expenditure are summarized in Table 36-2.

Patton and associates[16] found that wearing the NBC uniform over the BDU increased metabolic energy costs by more than 5% in 69% of the tasks performed by men and in 64% of the tasks performed by women. As the metabolic cost of a task increased (light to moderate to heavy), the effect of the NBC uniform on energy expenditure was greater. Furthermore, the effect of the NBC uniform on energy costs was larger in tasks requiring greater mobility (ie, load carriage). Although women worked at a greater percentage of their maximal oxygen uptakes ($\dot{V}O_2max$), the effect of the NBC uniform on energy cost was generally similar in men and women. The only gender difference noted was that women demonstrated a greater increase in metabolic costs in NBC uniforms in tasks requiring continuous mobility. The authors speculated that the hobbling effect of the NBC uniform may be greater in women than men due to women's smaller stature and weight. Consequently, the additional weight of the NBC uniform seems to impose a greater strain on women compared with men. A further possible explanation, not presented by the authors, is that the NBC uniforms may not have been sized and fitted appropriately to the female body.

TABLE 36-2

EFFECT OF WEARING THE NUCLEAR-BIOLOGICAL-CHEMICAL PROTECTIVE UNIFORM ON ENERGY COSTS OF VARIOUS MILITARY TASKS

Task Category	Men		Women	
	$\Delta\dot{V}O_2$	Δ%	$\Delta\dot{V}O_2$	Δ%
Light (< 325 W)	0.055 ± 0.011	8.1	0.041 ± 0.008	8.7
Moderate (325–500 W)	0.134 ± 0.022	12.6	0.145 ± 0.021	16.0
Heavy (> 500 W)	0.215 ± 0.019	11.3	0.183 ± 0.029	12.7
Stationary	0.051 ± 0.017	6.8	0.048 ± 0.011	7.8
Intermittent	0.108 ± 0.024	9.0	0.089 ± 0.015	10.1
Continuous	0.218 ± 0.017	14.3	0.202 ± 0.026	17.0

Mean ± SD increase in $\dot{V}O_2$ (L/min and percentage) between basic US Army battledress uniform, BDU (MOPP 0) and complete nuclear–biological–chemical (NBC) protective ensemble worn over the BDU (MOPP 4), by task category.

Task categories Stationary, Intermittent, and Continuous are based on the degree of whole-body mobility over a distance. Stationary: lift/lower tasks; Intermittent: lift/carry tasks; Continuous: load carriage tasks.

Adapted from Patton JF, Murphy M, Bidwell T, Mello R, Harp M. *Metabolic Cost of Military Physical Tasks in MOPP 0 and MOPP 4.* Natick, Mass: US Army Research Institute of Environmental Medicine; 1995: 21, 23. USARIEM Technical Report T95-9.

No study to date has attempted to address the contribution of each NBC uniform component (eg, gloves, overboots, overgarments) to the overall increase in energy cost. The finding that the NBC uniforms' greatest effect on metabolic cost was on tasks requiring mobility suggests that motion of the lower extremities was most hindered by the NBC uniform. Casual observations by various investigators suggest that loose-fitting overboots may be a significant source of increased energy cost with NBC uniforms. Without significantly altering the weight on the feet, an inappropriately large overboot may reduce traction, alter gait, or both, thus exacerbating the hobbling effect of the uniform.

Biomechanical Effects of NBC Uniforms

In addition to the increased energy costs of performing various tasks, the NBC protective uniform generally restricts the range of motion of the torso, head, and extremities.[18] Activities such as walking, running, dodging, and jumping are perceived to be more cumbersome in the NBC protective uniform. The US military NBC protective uniform can restrict head flexion as much as 20% in the ventral–dorsal plane and lateral rotation of the head by as much as 40% to 50%.[18,19] Such restrictions of head movements, caused principally by the CB mask, limit a soldier's normal visual scan; hence, more pronounced head movements are required to view the environment and to localize sound.[20]

Unfortunately, NBC protective uniforms also degrade manual dexterity, psychomotor coordination, and performance of many activities accomplished with the hands.[21] The rubber gloves distort the tactile sensations of various tools, equipment controls, keysets, and grip handles. Finger dexterity can be affected by as much as 30%, depending on the thickness of the gloves. Soldiers wearing thicker (0.44-mm) gloves required more time to accomplish simple keying tasks accurately.[22] Finger dexterity and visual–motor coordination degrade slightly by wearing the rubber handwear and mask.[18,23] Military pilots, keenly aware of the importance of tactile sensations from flight controls, are reluctant to wear the bulky gloves when flying an aircraft.[20]

In summary, several studies indicate that wearing NBC uniforms over a standard work uniform increases the metabolic cost of performing physical tasks, and that the increased energy costs are greatest in tasks requiring mobility. The potential for the hobbling effect and friction between clothing layers of NBC uniforms to increase metabolic costs of military tasks underscores the importance of fitting service members with properly sized NBC garments and boots to minimize the increased energy costs associated with wearing these uniforms.

Thermoregulatory Responses

Heat stress is a major limitation to work performance and tolerance in NBC uniforms.[24–30] Aside from the fact that the protective uniform is significantly responsible for the thermal load on the wearer, the subsequent thermoregulatory responses and consequences of the heat strain are not unique to protective uniforms. Therefore, only aspects of managing heat stress directly attributable to work in NBC protective uniforms are addressed here.

As described earlier, to protect the wearer from a contaminated environment, the NBC protective uniform must provide a barrier between the wearer and that environment. This barrier creates a microclimate around the surface of the individual encapsulated in the NBC protective uniform. NBC protective uniforms have high insulating and low moisture permeability properties (Figure 36-3). The insulating property of a garment is measured by the *resistance* (Rc) to dry heat flow (conduction, convection, radiation), expressed in clo units (Equation 1):

$$(1) \qquad 1 \text{ clo} = 0.155°\text{C} \bullet \text{m}^2/\text{W}$$

The moisture permeability of a garment, also called the *evaporative resistance* (Re), is expressed as a ratio of the permeability index (Im) to the insulation (clo). The higher the evaporative resistance (Im/clo), the more potential a garment has for evaporative heat loss. When fully encapsulated in the US Army BDO, this NBC protective uniform has particularly low moisture permeability. Of particular note are the additive properties of an NBC uniform worn over the BDU, probably due to the air layers trapped between the garments. For example, compared with the complete NBC ensemble worn over a standard BDU, wearing the NBC uniform over only cotton underwear reduces the Rc by approximately 30% and increases the Re by approximately 3-fold. Several studies[7–9] have shown that wearing close-fitting NBC overgarments, thereby eliminating multiple air layers, would lower thermal insulation and increase moisture permeability, thus reducing heat strain.

The degree of thermal stress experienced when wearing an NBC protective uniform depends on the

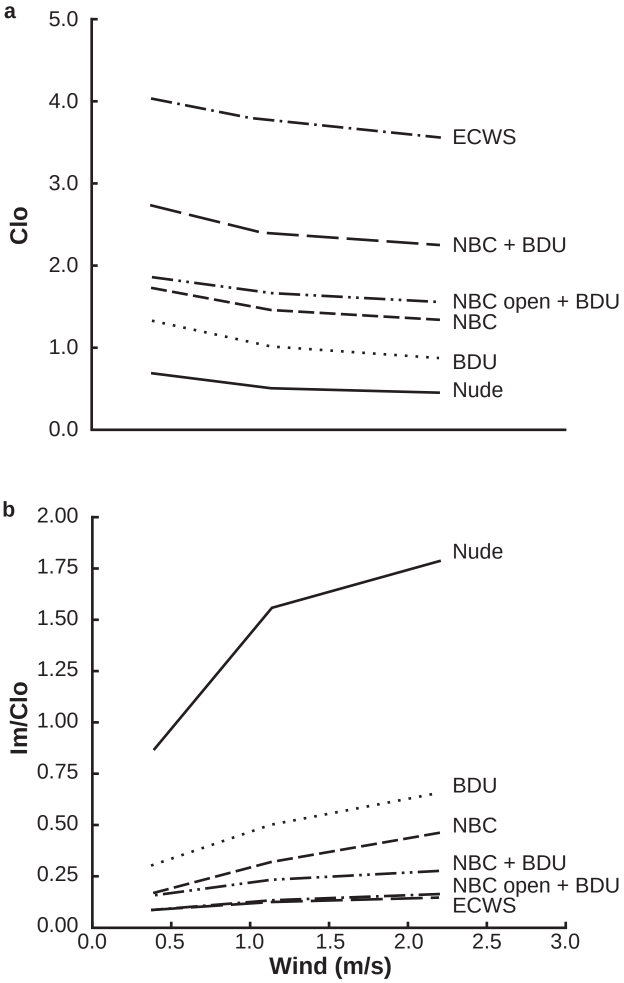

Fig. 36-3. Insulative (**a**) and moisture permeability (**b**) characteristics of a typical nuclear–biological–chemical (NBC) protective uniform and several representative military clothing ensembles. BDU: US Army battledress uniform; NBC open (ie, jacket unbuttoned) + BDU: open NBC overgarment worn over BDU; NBC + BDU: closed (ie, jacket buttoned) NBC uniform worn over BDU; ECWCS: extreme cold weather clothing system. Data sources: (1) Gonzales RR, Endrusick TL, Santee WR. Thermoregulatory responses to cold: Effects of handwear with multi-layer clothing. J Appl Physiol. 1998;69:1076–1082. (2) Gonzalez RR, Levell CA, Stroschein LA, Gonzalez JA, Pandolf KB. *Copper Manikin and Heat Strain Model Evaluations of Chemical Protective Ensembles for the Technical Cooperation Program*. Natick, Mass: US Army Research Institute of Environmental Medicine; 1993. USARIEM Technical Report T94-4.

environmental conditions (air temperature, humidity, radiant energy, and air velocity) and the rate of metabolic heat production. However, given the NBC uniform's resistance to heat dissipation, the most significant factor determining the microclimate environment, and thus the thermal load on the service member, is the rate of metabolic heat production.[24,30] When the rate of metabolic heat production exceeds the rate of heat dissipation, metabolic heat is stored and body temperature rises (Figure 36-4). Generally, a cool, dry, ambient environment will facilitate metabolic heat dissipation at light physical work rates, and to a lesser degree as metabolic rate increases.[30] A simple way to assess the impact of ambient thermal conditions on physical activity in NBC uniforms is to use the wet bulb globe temperature (WBGT) index.[31] As a rule of thumb, wearing NBC protective uniforms adds approximately 10°F to the measured WBGT.[31] However, this recommended adjustment is based on field observations of physical work performance, not body heat storage.[32] Thus, adjusting the WBGT when wearing NBC uniforms should be done cautiously: although Technical Bulletin, Medical 507[31] states that the same approximately 10°F adjustment to the measured WBGT is applicable when wearing body armor, the actual adjustment is approximately 5°F.[32]

Because of the low moisture permeability of the NBC uniform, vapor loss from the skin (sweating) condenses on the skin and the internal surfaces of the protective uniform. Consequently, evaporative heat loss is greatly reduced, resulting in uncompensable heat stress.[28] Several options for reducing heat stress, and subsequently heat illness, in NBC protective uniforms have been suggested,[5,33] including (1) reduce the barrier by wearing the minimal level of protective clothing appropriate to the NBC threat, (2) reduce metabolic heat production, and (3) cool the microclimate by mechanical means. Owing to the power requirements of microclimate cooling systems, this manner of heat stress reduction is currently limited to crew-served vehicles and aircraft.

Military doctrine[5] provides commanders with methods for assessing the degree of NBC threat and determining the appropriate levels of protection. Minimizing the number of uniform layers or allowing service personnel to wear NBC uniforms open, or both, significantly enhance heat dissipation, thus increasing work capacity (see Figure 36-3). If the NBC threat requires total encapsulation within an NBC uniform, commanders can reduce heat casualties by employing mission-compatible preventive measures and medical support.

Because metabolic heat production is the main source of thermal stress in NBC uniforms, reducing metabolic intensity is the single most effective way of reducing heat illness in protective uniforms. The options are to work at a given metabolic inten-

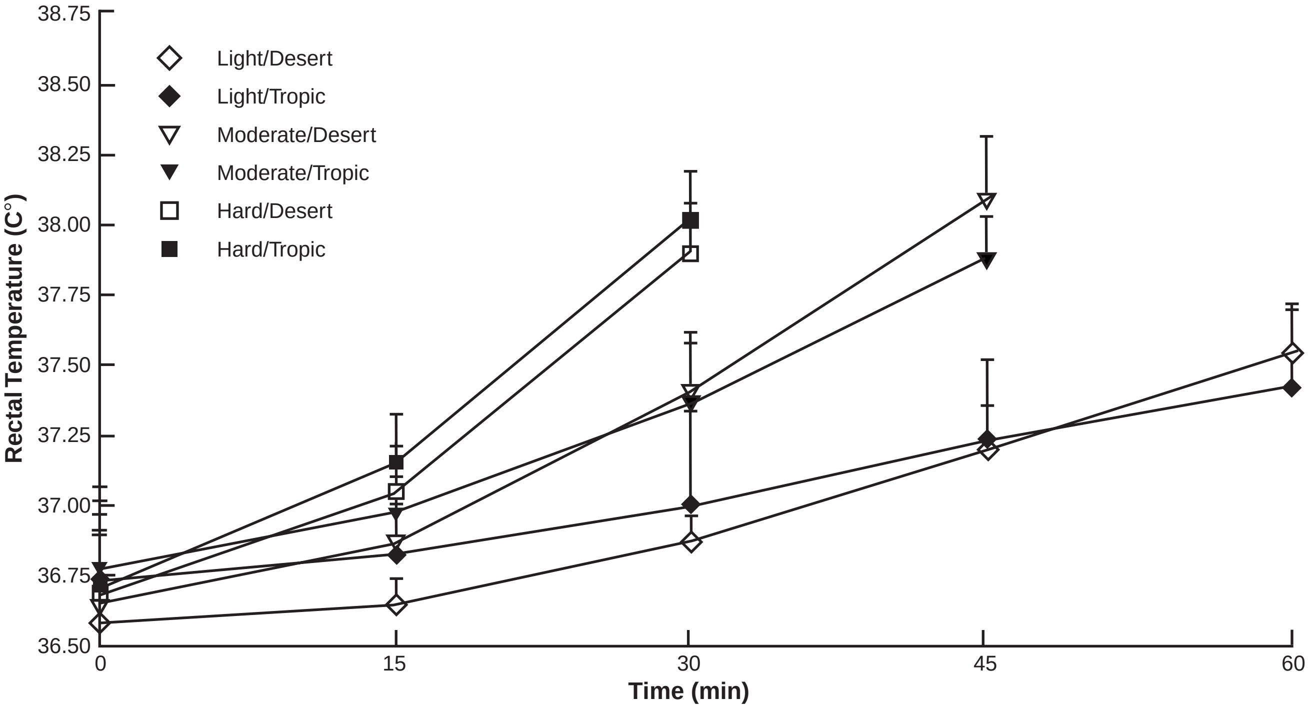

Fig. 36-4. Core body temperature response to physical work (light, ~ 300 W; moderate, ~ 430 W; and hard, ~ 600 W) in a nuclear–biological–chemical (NBC) protective uniform at MOPP 4 (mission-oriented protective posture, level 4) worn over cotton undergarments in desert (43°C, 20% rh) and tropic (35°C, 50% rh) environments. Note that when wearing the NBC protective uniform, core body temperature depends more on work rate than on ambient environmental conditions. Reproduced from Cadarette BS, Montain SJ, Kolka MA, Stroschein LA, Matthew WT, Sawka MN. *Evaluation of USARIEM Heat Strain Model: MOPP Level, Exercise Intensity in Desert and Tropic Climates.* Natick, Mass: US Army Research Institution of Environmental Medicine; 1996: 37. USARIEM Technical Report T96-4.

sity until exhaustion from heat strain occurs, or to decrease metabolic heat load by reducing work intensity and/or using rest periods to lower the time averaged metabolic rate. The use of work/rest cycles will increase tolerance times and decrease heat casualties, but the time required to perform a task will be increased. Using the prediction capability of the USARIEM Heat Strain Model,[34–36] the maximum single work period and work/rest cycle periods have been developed for a wide range of environmental conditions and work intensities. Tables 36-3 and 36-4[33] present maximum single work periods and work/rest cycles for a matrix of climatic conditions during daylight and nighttime operations.

The calculated work periods assume that the troops are fully hydrated, rested, and heat acclimatized, and that fewer than 5% heat casualties will result.[33] Adequate hydration is particularly difficult to achieve in NBC protective uniforms, given the barrier presented by the CB mask. Although most modern CB masks have drinking tubes, they are cumbersome to use, and taking a drink requires expenditure of energy and time. Thus, if hypohydration is suspected, the work periods given in Tables 36-3 and 36-4 should be reduced.

For aircrews and other manned vehicles with clear canopies that expose the crew compartment to high radiant heat loads (the greenhouse effect), heat dissipation may not be possible even when metabolic heat production is low. The thermal strain is greatest when the aircraft is motionless on the ground and its onboard environmental control systems are shut down or at lower efficiency.[37–39] Typically, aircraft cockpits become cooler as the aircraft ascends into the lower temperatures of higher altitudes or cockpit ventilation is improved by the aircraft's forward motion. However, when wearing an aviator NBC protective uniform, body temperature may remain elevated for a long time after takeoff. This may cause crew performance decrements as well as diminished acceleration (G) tolerance.[38–40]

TABLE 36-3

WORK TIMES IN NUCLEAR-CHEMICAL-BIOLOGICAL PROTECTIVE UNIFORMS DURING DAYLIGHT OPERATIONS[*]

		Maximum Single Work Period (minutes)								Work/Rest Cycle (minutes of work per hour)							
		NBC Uniform + Underwear				NBC Uniform + BDU				NBC Uniform + Underwear				NBC Uniform + BDU			
WBGT (°F)	Ta	VL	L	M	H	VL	L	M	H	VL	L	M	H	VL	L	M	H
78	82	NL	177	50	33	NL	155	49	32	NL	30	10	5	NL	25	10	5
80	84	NL	142	49	32	NL	131	48	32	NL	25	10	na	NL	20	10	na
82	87	NL	115	47	31	NL	110	46	30	NL	20	5	na	NL	15	na	na
84	89	NL	104	45	30	NL	100	45	30	NL	na	na	na	NL	na	na	na
86	91	NL	95	44	29	NL	93	44	29	NL	na	na	na	NL	na	na	na
88	94	NL	85	42	28	NL	83	42	27	NL	na	na	na	NL	na	na	na
90	96	NL	79	41	27	NL	78	41	27	NL	na	na	na	NL	na	na	na
92	98	NL	75	40	26	NL	74	40	26	NL	na	na	na	NL	na	na	na
94	100	NL	70	39	25	NL	70	39	25	NL	na	na	na	NL	na	na	na
96	103	203	65	37	23	194	65	37	23	na	na	na	na	na	na	na	na
98	105	141	62	36	22	140	62	36	22	na	na	na	na	na	na	na	na
100	107	118	59	35	21	118	59	35	21	na	na	na	na	na	na	na	na

[*] Assumptions used in generating this table: (1) service personnel are fully hydrated, rested, and acclimatized, (2) 50% relative humidity, (3) wind speed = 2 m/s, (4) clear skies, and (5) < 5% heat casualties.

BDU: battledress uniform
na: work/rest cycle not feasible
NL: no limit (continuous work possible)
Ta: ambient temperature (dry bulb, °F)
WBGT: wet bulb globe temperature (°F)

Work Intensities:
- H: heavy (> 500 W)
- M: moderate (325–500 W)
- L: light (172–325 W)
- VL: very light (105–175 W)

Adapted from Burr RE. *Heat Illness: A Handbook for Medical Officers*. Natick, Mass: US Army Research Institute of Environmental Medicine; 1991: 50, 54. USARIEM Technical Report T91-3.

TABLE 36-4

WORK TIMES IN NUCLEAR-CHEMICAL-BIOLOGICAL PROTECTIVE UNIFORMS DURING NIGHT OPERATIONS*

		Maximum Single Work Period (minutes)								Work/Rest Cycle (minutes of work per hour)							
		NBC Uniform + Underwear				NBC Uniform + BDU				NBC Uniform + Underwear				NBC Uniform + BDU			
WBGT(°F)	Ta	VL	L	M	H	VL	L	M	H	VL	L	M	H	VL	L	M	H
60	68	NL	NL	76	42	NL	NL	73	41	NL	NL	30	20	NL	NL	25	15
66	75	NL	NL	66	39	NL	NL	64	38	NL	NL	25	15	NL	NL	25	15
72	82	NL	NL	58	36	NL	NL	57	36	NL	NL	20	15	NL	NL	20	10
78	88	NL	NL	53	34	NL	NL	52	33	NL	NL	15	10	NL	NL	15	10
80	91	NL	NL	50	32	NL	NL	50	32	NL	NL	15	5	NL	NL	15	5
82	93	NL	206	49	32	NL	168	48	31	NL	30	10	5	NL	25	10	5
84	95	NL	144	47	31	NL	133	47	30	NL	25	10	na	NL	20	5	na
86	97	NL	121	46	30	NL	115	45	29	NL	15	5	na	NL	10	na	na
88	100	NL	100	44	28	NL	97	43	28	NL	na	na	na	NL	na	na	na
90	102	NL	91	43	27	NL	89	42	27	NL	na	na	na	NL	na	na	na
92	104	NL	83	41	26	NL	82	41	26	NL	na	na	na	NL	na	na	na
94	106	NL	77	40	25	NL	76	40	25	NL	na	na	na	NL	na	na	na

*Assumptions used in generating this table: (1) service personnel are fully hydrated, rested, and acclimatized, (2) 50% relative humidity, (3) wind speed = 2 m/s, (4) clear skies, and (5) < 5% heat casualties.

BDU: battledress uniform
na: work/rest cycle not feasible
NL: no limit (continuous work possible)
Ta: ambient temperature (dry bulb, °F)
WBGT: wet bulb globe temperature (°F)

Work Intensities:
- H: heavy (> 500 W)
- M: moderate (325–500 W)
- L: light (172–325 W)
- VL: very light (105–175 W)

Adapted from Burr RE. *Heat Illness: A Handbook for Medical Officers*. Natick, Mass: US Army Research Institute of Environmental Medicine; 1991: 58, 60. USARIEM Technical Report T91-3.

Paradoxically, G protection systems may contribute to the thermal strain by adding additional insulative layers to the aircrew uniform.[41]

Respiratory System Responses

Protective uniforms impede ventilation (ie, breathing) by adding three external loads to the respiratory system: (1) flow-dependent resistive loads, (2) volume-dependent elastic loads, and (3) dead space. Under normal conditions, breathing is opposed by two internal forces: *respiratory system resistance* and *elastance*. Respiratory system resistance is the sum of two internal resistive forces: airflow resistance and pulmonary tissue resistance, which is produced by the rubbing of the surfaces of the lung on the internal surface of the thorax. Airway resistance is the major contributor to total respiratory system resistance and is proportional to inspiratory and expiratory airflows. Airway resistance increases dramatically at the high airflow rates that are routinely obtained during moderate and higher intensity exercise. Resistance is expressed as a pressure drop (expressed in cm H_2O) per liter of airflow per second. The healthy adult has a total respiratory resistance of approximately 4 cm $H_2O/(L/s)$.[42]

Expansion of the thorax during inspiration is opposed by the elastic elements of the lung and the chest wall. Total respiratory system elastance is derived from the pressure–volume relaxation characteristics of the lung and the chest wall and is a measure of the "stiffness" of the respiratory system. Total respiratory system elastance increases as the volume of air inhaled increases. Total respiratory system elastance is expressed as the change in lung volume per change in pressure across the chest wall. A healthy adult has an average total respiratory system elastance, in the mid range of lung volume, of approximately 2% vital capacity (VC)/cm H_2O.[43]

Finally, although not a physical force opposing breathing, the respiratory system dead space (V_{DS}) is the volume of air within the upper and lower airways that does not contribute to pulmonary gas exchange in the alveoli. This anatomical V_{DS} is approximately 0.150 L in the adult. For effective gas exchange, the volume of air inhaled in each breath must be sufficiently large to fill the V_{DS}, as well as an appropriate alveolar volume for pulmonary gas exchange.

Of the aforementioned loads imposed on the respiratory system by the NBC uniform, the CB mask contributes added resistance to airflow and increased dead space. The CB mask uses filter elements to remove chemical and particulate contaminants from inhaled air. By their very design, these filters increase airflow resistance. To separate the inspired and expired air pathways, CB masks utilize one-way valves and internal channels, which also impede airflow. The space within the CB mask nosecup adds dead space, which forces the wearer to increase his or her breathing. Finally, the NBC uniform garments, load carriage equipment, and body armor produce an external constraint on the chest wall separate from that imposed by the CB mask. These factors act independently and in concert to impair breathing; consequently, they impair performance of military operations.

CB Mask Airflow Resistance

The CB mask opposes breathing by applying a nonlinear, phasic, flow-resistive load. It is further defined as a passive load, as the respiratory muscles must develop forces to overcome the load. Although an early recognized limitation of the CB mask was its inspiratory and expiratory airflow resistance, the development of standards for acceptable levels of breathing resistance for CB masks did not occur until World War II. Even though common sense dictates that the added resistance to breathing should be kept as low as possible, increasing the filtering material at the inlet increases the protection a CB mask provides. Thus, every respiratory protective device, including CB masks, has a direct correlation between the degree of protection against CB agent penetration and the magnitude of added resistive load.

Studies by Silverman and colleagues[44] investigated the effects of breathing against added resistance while working at various rates on a cycle ergometer. These studies produced two major findings. First, added inspiratory resistance greater than 4.52 cm $H_2O/(L/s)$, in combination with expiratory resistance exceeding 2.90 cm $H_2O/(L/s)$, resulted in decreased submaximal oxygen uptake, minute ventilation ($\dot{V}_E$) and physical endurance at work levels above 135 W. Second, they determined the mean airflow curves for external work rates up to 180 W, which they concluded probably represented the physiological limit for which respiratory protection should be provided. Their research also led to the standard practice of measuring CB mask airflow resistance at a steady state airflow rate of 85 L/min. These data provide the basis for most modern military CB mask design criteria and certification tests.

Subsequent studies sought to refine the maximum tolerable added resistance to breathing which a CB mask should impose on its wearer. Most notably, Bentley and colleagues[45] recognized that the peak negative intrathoracic pressure and respiratory work rate per liter of inhaled air were good predictors of subject discomfort (ie, dyspnea). Furthermore, they recognized that peak inspiratory airflows were approximately equal to 2.7 times the $\dot{V}_E$. (This latter finding is useful for estimating the appropriate steady state airflow rate of a blower-supplied CB mask system to match the ventilatory requirements of various physical activities). From these data, Bentley and colleagues[45] formulated a standard for acceptable CB mask resistance such that 90% of the population tested would not experience dyspnea. They determined that the pressure swing (peak exhalation pressure minus peak inhalation pressure) at the mouth should not exceed 17.0 cm H_2O.

A study by Lerman and colleagues[46] evaluated a range of inspiratory resistance from 0.3 to 4.6 cm $H_2O/(L/s)$ on physiological, psychological, and physical performance at a work rate equivalent to 80% of each subject's maximal oxygen uptake ($\dot{V}O_2$max). At this work rate, all levels of added inspiratory resistance decreased exercise $\dot{V}_E$ (Figure 36-5) and exercise endurance. Thus, at this high but not uncommon level of physical work, any increase in the inspiratory resistance will impair $\dot{V}_E$ and physical work performance. Most sustained, self-paced work is performed at approximately 40% of $\dot{V}O_2$max.[47] A study by Sulotto and colleagues[48] suggested that for prolonged work at this metabolic rate, the added resistance of the CB mask be such that maximal inspiratory pressures not exceed 2.0 cm H_2O. Assuming at approximately 40% $\dot{V}O_2$ max that $\dot{V}_E$ will be approximately 40 L/min, then the inspiratory resistance would not exceed approximately 1.2 cm $H_2O/(L/s)$, using Sulotto's recommended guidelines.

During development of the current US Army field CB mask, the M40,[49] maximum permissible inspiratory and expiratory resistances were 3.88 and 1.84 cm $H_2O/(L/s)$, respectively, at a constant airflow of 1.42 L/s (85 L/min). However, as seen in the pressure–flow relationship for this mask (Figure 36-6), the relationship is not linear, and the apparent inspiratory resistance is nearly doubled at inspiratory flow rates higher than 4 L/s. Numerous studies have investigated the effects of added resistance applied to inspiration, expiration, or both during rest and exercise at various metabolic intensities. Many of these studies employed much larger or smaller added resistance to breathing than is typical of CB masks [range: 2.5–6.0 cm $H_2O/(L/s)$]; thus, these studies are not directly relevant to ventilatory responses in NBC uniforms.

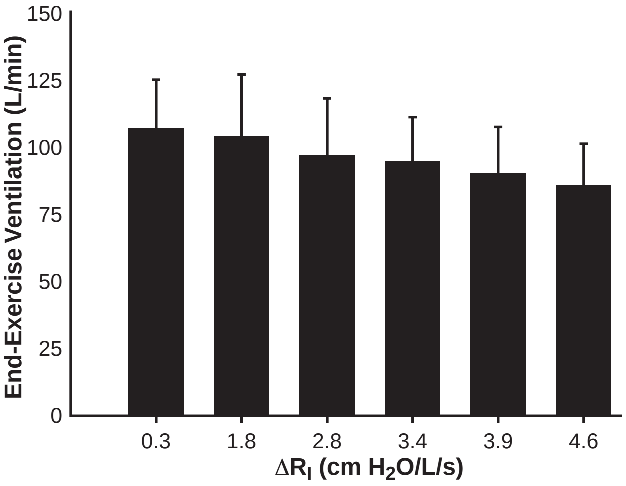

Fig. 36-5. The effect of increasing chemical–biological (CB) mask inspiratory resistance (ΔR_I) on exercise minute ventilation. In this experiment, the mask was commercially available respiratory protective device similar to a CB protective mask. Six filter canisters of varying airflow resistance were used. The exercise work rate (ie, level) was approximately 80% $\dot{V}O_2$max. The three largest ΔR_I, right, are representative of filters common to CB masks. Data source: Lerman Y, Shefer A, Epstein Y, Keren G. External inspiratory resistance of protective respiratory devices: Effects on physical performance and respiratory function. *Am J Ind Med.* 1983;4:736, Table 3.

The following sections review breathing responses to added resistive loads comparable to those imposed by CB masks: their effects on respiratory system ventilatory capacities, energy costs and the work of breathing, and the pattern of breathing; and respiratory system limits to exercise, adaptation to wearing the CB mask, dead space in the CB mask, and the effects of the NBC uniform and individual equipment on breathing.

Effect of Resistive Loads on Respiratory System Ventilatory Capacities

The ventilatory, or breathing, capacity of the respiratory system is measured during various clearly defined breathing maneuvers, usually of maximal effort or short duration.[50] In clinical practice, pulmonary function tests are capable of evaluating restrictive and obstructive patterns of ventilatory dysfunction associated with pathophysiological conditions. These

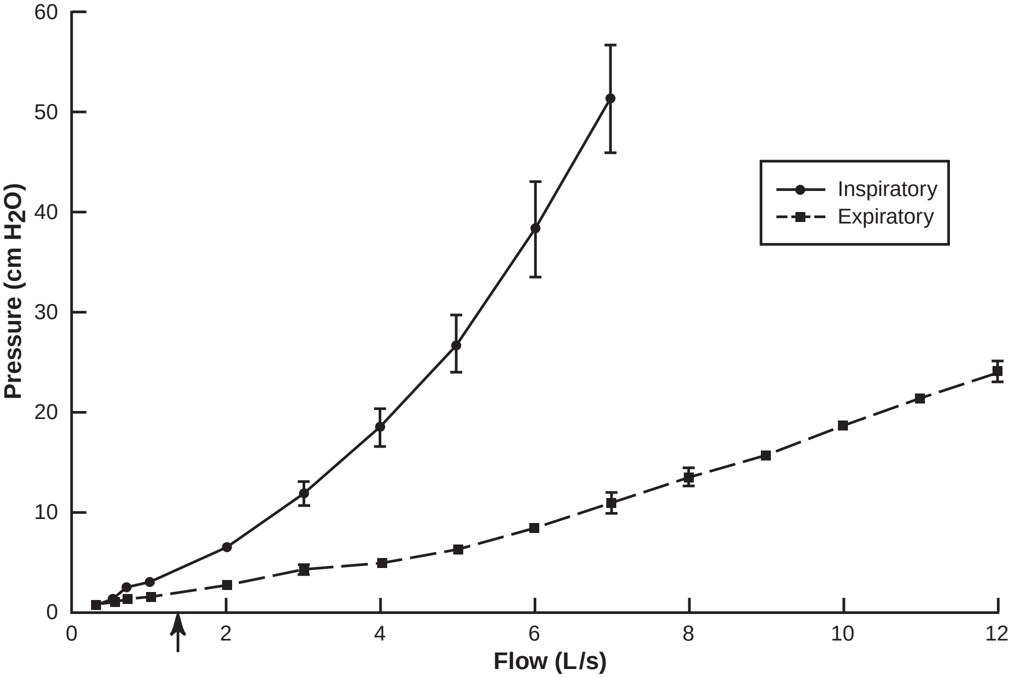

Fig. 36-6. Pressure-flow relationships of a US Army M40 Field Chemical–Biological (CB) protective mask with a C2 canister filter. All pressure drops were measured during steady state flows. The arrow indicates the standard flow rate (85 L/min) used to assess CB mask airflow resistance criteria. Note how the pressure drop across the inlet of the CB mask increases as a nonlinear function of flow.

same measures may be used to assess the impact of external loads imposed on the respiratory system. There are few published studies of the effects of a CB mask on maximal ventilatory capacities, as measured by standard pulmonary function tests.[51–53] The effects of a US Army M40 CB mask on pulmonary function of 15 healthy, male soldiers with normal pulmonary function is shown in Table 36-5.

In general, wearing a CB mask impairs an individual's normal pulmonary function. The pulmonary function tests that measure airflow characteristics, and are effort dependent, are more susceptible to reduction as a result of CB mask wear.[51] Furthermore, the inspiratory flows are impacted more than expiratory flows due to greater inspiratory verses expiratory resistance of the CB mask. Maximal lung volumes are not impacted by CB mask wear, because, in well-motivated subjects, maximum lung volumes are not flow-dependent. These effects on pulmonary function are visually apparent in the flow-volume loop of a healthy man with and without a CB mask (Figure 36-7). In this subject, the CB mask's impairment of inspiratory flows is clearly evident. On the other hand, the small added expiratory resistance may actually improve expiratory flow rates at the lower lung volumes (ie, $FEF_{25\%–75\%}$, or forced expired flow, midexpiratory phase) by reducing the magnitude of the dynamic airway compression during the forced expiration. The overall impact of the CB mask on maximal ventilatory capacity is seen in the measured maximal voluntary ventilation (MVV). The MVV is a measure of the maximal volume of air an individual could breathe during a short (~15-s) period. The MVV represents the upper limit for exercise $\dot{V}_E$. When wearing the CB mask, the MVV is decreased by approximately 22%, due to the effort and flow-dependence of this breathing-capacity measurement. These results are similar to those reported in an earlier study of the M17A2 CB mask[52] and of a commercially available respiratory protective device[54] similar to the military CB mask.

The three studies mentioned above[51,52,54] also shed light on the value of conventional pulmonary function tests in assessing individual capability to use protective respiratory devices. In the three studies, the traditional benchmarks of pulmonary function—forced vital capacity (FVC) and forced expired volume in 1 second (FEV_1)—were not significantly affected by wear of a CB mask due to the relatively small added expiratory-flow resistance (compared with normal resistance associated with breathing without a mask). Only pulmonary function mea-

TABLE 36-5

EFFECT OF THE US ARMY M40 FIELD CHEMICAL–BIOLOGICAL PROTECTIVE MASK ON RESTING PULMONARY FUNCTION

PFT Variable	Clinical Mouthpiece and Nose Clip (Mean ± SD)	M40 CB Mask and C2 Filter Canister (Mean ± SD)	%Δ
FVC (L)	5.73 ± 0.90	5.66 ± 0.91	–1
FEV$_1$ (L)	4.65 ± 0.67	4.45 ± 0.69	–5
FEV$_1$ /FVC	0.82 ± 0.07	0.79 ± 0.08	–3
FEF$_{50\%}$ (L/s)	5.95 ± 1.51	5.20 ± 1.76	–12
FIF$_{50\%}$ (L/s)	7.38 ± 1.89	5.39 ± 0.78*	–23
FEF$_{50\%}$/FIF$_{50\%}$	0.84 ± 0.24	0.95 ± 0.24	+19
PEF (L/s)	8.96 ± 1.30	7.86 ± 1.92*	–12
PIF (L/s)	7.91 ± 1.64	5.71 ± 0.73*	–26
MVV (L/min)	188.9 ± 26.0	147.5 ± 24.1*	–22
TLC (L)	7.66 ± 1.34	7.61 ± 1.23	0
RV (L)	1.93 ± 0.89	1.96 ± 0.73	+10
FRC (L)	2.96 ± 0.77	3.09 ± 0.65	+7

*Significant difference from baseline ($P < .05$)
N = 15 male soldiers, aged 24 ± 5 y

FEF$_{50\%}$: forced expiratory flow, 50%
FEV$_1$: forced expiratory volume in 1 sec
FIF$_{50\%}$: forced inspiratory flow, 50%
FRC: functional residual capacity
FVC: forced vital capacity
MVV: maximum voluntary ventilation
PEF: peak expiratory flow
PFT: pulmonary function test
PIF: peak inspiratory flow
RV: residual volume
TLC: total lung capacity

Adapted from Muza SR, Banderet LE, Forte VA. *The Impact of the NBC Clothing Ensemble on Respiratory Function and Capacities During Rest and Exercise.* Natick, Mass: US Army Research Institute of Environmental Medicine; 1995: 17. USARIEM Technical Report T95-12.

sures of *inspiratory* flows were significantly impaired by CB mask wear. However, using pulmonary function measures of inspiratory performance may not be practical because many simple pulmonary function test instruments cannot measure inspiratory flows, and given the effort-dependent nature of inspiratory maneuvers, these measures are prone to greater variability, which can hinder their interpretation. Raven and colleagues[54] evaluated the effects of a respiratory protective mask in a large population that included individuals with above- and below-normal pulmonary function. Of particular note was their observation that the decrement in MVV was directly related to the individual's pulmonary function capability (Figure 36-8). Thus, individuals with the highest 15-second MVV without the mask experienced the greatest decrement with the mask on. Raven and colleagues[54] concluded that measurement of an individual's 15-second MVV while he or she is wearing a respiratory protective mask can be used as a screening test for capability to perform work in a respiratory protective device.

Effect of Resistive Loads on Energy Costs and Work of Breathing

To breathe, the respiratory muscles must perform physical work. The total work of breathing is the sum of flow-resistive work, plus elastic work, plus chest wall deformation, plus gas compression, plus inertial work, plus negative work. At rest, during quiet breathing through the nose, the work of breathing is approximately 4 J/min ($\sim 0.5\ \text{J/L}_{\dot{V}_E}$).[55] As ventilation increases to meet the metabolic demands of exercise, the work of breathing progressively increases (Figure 36-9), approaching approximately 300 J/min at ventilations near 120 L/min ($\sim 2.5\ \text{J/L}_{\dot{V}_E}$). At rest, the oxygen cost of unobstructed breathing is approximately 1% to 2% of basal oxygen consumption (Table 36-6).[55] As ventilation increases to meet the metabolic demands of physical work, respiratory muscle oxygen consumption increases hyperbolically.[56] However, if the oxygen cost of breathing is expressed as a function of respiratory work (O_2/J), less oxygen is consumed per unit work of breathing at the highest exercise ventilations, but the latter expression does not account for all the work of breathing, and thus the value of O_2/J is probably lower than reported.[57]

What is fundamentally important here is that the oxygen cost of breathing per unit of ventilation increases by 5- to 10-fold during heavy exercise, compared with rest. The greater cost of breathing at high levels of exercise ventilation (O_2/min/$L_{\dot{V}_E}$) may be the result of many factors, including

- increased flow-resistance associated with turbulence and dynamic airway compression,[58]
- increased respiratory muscle velocity of shortening,[59]

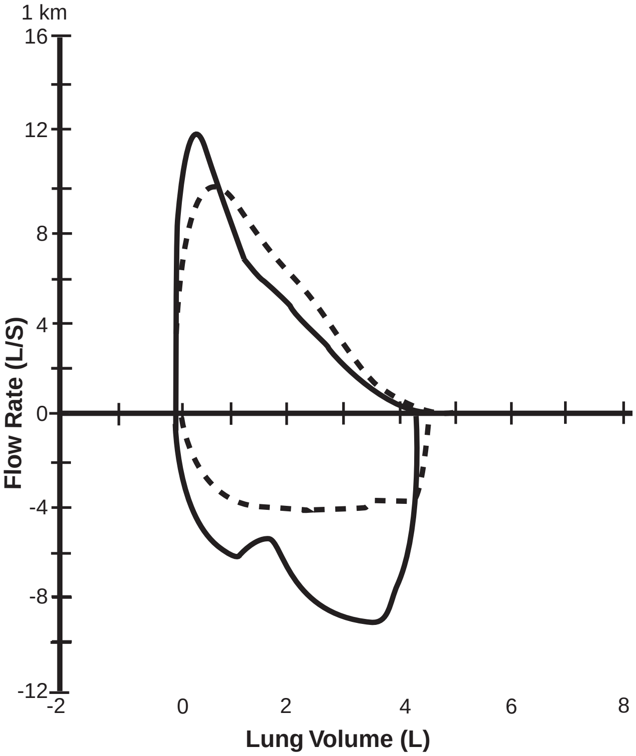

Fig. 36-7. Flow-volume loop of a healthy man with normal pulmonary function performed with standard clinical low resistance mouthpiece and nose clip (solid line) and the US Army M40 Field Chemical–Biological (CB) protective mask (dashed line). Data were obtained during single maximal effort forced expiratory and inspiratory efforts.

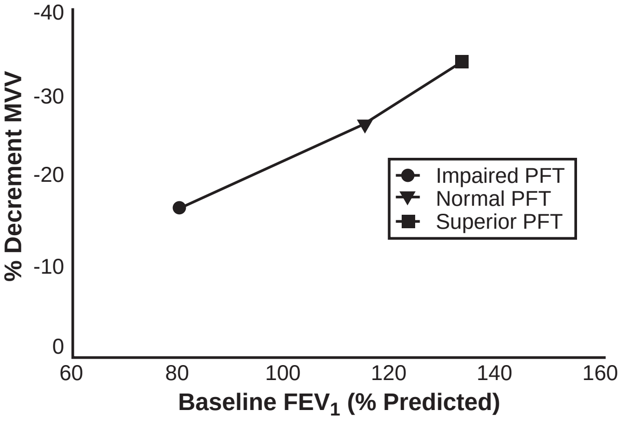

Fig. 36-8. Interaction between baseline pulmonary function (FEV$_1$) and decrement in maximal voluntary ventilation (MVV) induced by a commercially available respiratory protective device similar to a chemical–biological (CB) protective mask. PFT: pulmonary function test. Data source: Raven PB, Moss RF, Page K, Garmon R, Skaggs B. Clinical pulmonary function and industrial respirator wear. *Am Ind Hyg Assoc J.* 1981;42(12):899, Table 2.

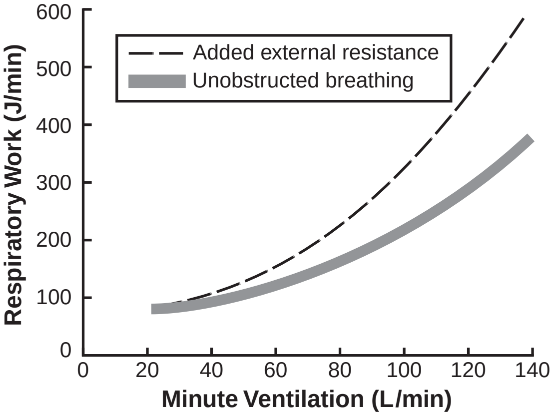

Fig. 36-9. Ventilatory work plotted as a function of minute ventilation. Unobstructed work of breathing[1,2,3] includes estimated work associated with chest wall distortion.[3] The estimated work of breathing with added resistance (~ 5.25 cm H_2O/L/s)[4] is calculated by adding the external work of the added resistance to the baseline unobstructed work of breathing. Thus, the estimated total work of breathing with the added resistance similar to that obtained from a typical chemical–biological (CB) protective mask does not include additional work caused by further chest wall distortion. Data sources: (1) Aaron EA, Johnson BD, Seow KC, Dempsey JA. Oxygen cost of exercise hyperpnea: Measurement. *J Appl Physiol.* 1992;72:1810–1817. (2) Johnson BD, Saupe KW, Dempsey JA. Mechanical constraints on exercise hyperpnea in endurance athletes. *J Appl Physiol.* 1992;73:874–886. (3) Goldman MD, Grimby G, Mead J. Mechanical work of breathing derived from rib cage and abdominal V-P partitioning. *J Appl Physiol.* 1976;41(5):752–763. (4) Demedts M, Anthonisen NR. Effects of increased external airway resistance during steady-state exercise. *J Appl Physiol.* 1973;35:361–366.

TABLE 36-6

THE OXYGEN COST OF UNOBSTRUCTED BREATHING FROM REST THROUGH MAXIMAL EXERCISE

Metabolic Rate	Rest	Mild to Moderate Exercise	Moderate to Heavy Exercise	Maximal Exercise
$\dot{V}_E$ (L/min)	< 20	63–79	79–117	117–147
mL O_2/min/$L_{\dot{V}_E}$	~ 0.25–0.5	~ 1.80	~ 2.10	~ 2.85
mL O_2/J	~ 0.75	~ 1.4	—	~ 1.1

—: value not available
Data sources: (1) Roussos C, Campbell EJM. Respiratory muscle energetics. In: Macklem PT; Mead J, eds. *The Respiratory System.* In: Part 2, *Mechanics of Breathing.* Section 3, Vol 3. In: American Physiological Society. *Handbook of Physiology.* Baltimore, Md: Williams & Wilkins for APS; 1986: 481–509. (2) Aaron EA, Seow KC, Johnson BD, Dempsey JA. Oxygen cost of exercise hyperpnea: Implications for performance. *J Appl Physiol.* 1992;72:1818–1825.

- work done on the chest wall, producing distortion with no net external airflow,[60] and
- work done to decompress alveolar gas.[59]

Furthermore, as ventilation increases, expiratory muscles are recruited, which increases the oxygen cost of breathing. There is evidence that the efficiency of the expiratory muscles is approximately half that of the inspiratory muscles.[61] Thus, the oxygen cost of expiratory work is greater than that of inspiratory work. In healthy, fit individuals, the oxygen cost of breathing accounts for approximately 6% to 10% of the total body oxygen at exercise intensities between 75% and 100% of maximum.[57]

The external added airflow resistance imposed by a CB mask increases the work of breathing proportionally as ventilation increases (see Figure 36-9). Using a "respirator-type load" of unspecified magnitude, Harber and colleagues[62] reported that during progressive intensity exercise (O_2 range: 0.5–2.5 L/min), the increase in peak external inspiratory work was approximately 1.7-fold greater than the increase in average inspiratory work. Not illustrated in Figure 36-9 but nonetheless significant is the impact of the added external resistance on work done on chest wall distortion and alveolar gas decompression that may be expected as both the respiratory muscle force and the pattern of activation change to overcome the external resistive loads.[63–65] Many studies have measured the oxygen cost of breathing with externally applied airflow resistance. However, most of these studies employed added resistances much larger than those commonly found in CB masks. In general, these studies report that the oxygen cost of breathing is much greater during resistive loading than unobstructed hyperpnea for the same amount of work done.[64,66,67] For example, Collett, Perry, and Engel[66] reported a linear relationship between respiratory muscle oxygen and external work of breathing (range: 10–137 J/min), with a slope of approximately 2.4 mL O_2/J across inspiratory resistance, ranging between 26 and 275 cm H_2O/(L/s) at inspiratory flow rates between 0.26 and 1.54 L/s. This study also found that the respiratory muscle oxygen consumption during inspiratory resistive loading is proportional to the inspiratory pressure generated against the load. Thus, given the typical pressure–flow characteristics of CB masks (see Figure 36-6), the oxygen cost of breathing will increase hyperbolically as minute ventilation increases.

Effect of Resistive Loads on Pattern of Breathing

When breathing is opposed by resistive loads, the ventilatory responses are regulated by the combined actions of mechanical load compensation intrinsic to the respiratory muscles (length–tension and force–velocity relationships) and neural reflexes.[68] In conscious humans, the ventilatory response to resistive loading is also modulated by neural responses mediated by conscious perception of the added load.[68,69] The literature is replete with reports of the effects of added flow-resistive loads on the pattern of breathing in normal healthy adults.[51,62,68,70–89] Four factors contribute to the subsequent ventilatory response:

1. the magnitude of the added resistive load;
2. whether the load is applied only to inspiration, expiration, or both;
3. the duration of the load; and

4. the background level of ventilation (ie, rest or exercise) when the load is presented.

Minute ventilation is commonly analyzed by its volume and timing components: tidal volume (V_T) and breathing frequency (f). However, this approach does not allow an analysis of the duration of the breath spent in inspiration (T_I) or expiration (T_E). A more informative approach is to partition $\dot{V}_E$ into its inspiratory flow rate and timing components. The mean inspiratory flow rate is the volume of inspiration divided by its time (V_I/T_I) and is a measure of inspiratory drive. The duty cycle is the ratio of time spent in inspiration to that of the total breathing cycle time (T_I/T_{TOT}) and represents the fraction of the respiratory cycle allocated to inspiration. During unobstructed breathing at rest, T_I/T_{TOT} is approximately 0.4, and V_I/T_I is proportional to the prevailing $\dot{V}_E$. With increasing $\dot{V}_E$ during exercise, the T_I/T_{TOT} increases to approximately 0.5, owing to the proportionally larger reduction in T_E than in T_I with increasing breathing frequency. The V_I/T_I increases in proportion to the exercise $\dot{V}_E$, consistent with the increased activity of the inspiratory muscles.[90] It is generally believed that both the pattern of breathing and the subsequent adjustments as $\dot{V}_E$ changes reflect an optimal adaptive regulation process by the *respiratory controller* (ie, the respiratory center in the brainstem) as it attempts to achieve some type of minimum work of breathing criterion.[91,92]

The typical ventilatory response to an added resistive load is to prolong the phase of the breath to which the load was applied.[82,87,93] Thus when a CB mask is worn, the pattern of breathing will reflect an increased T_I and T_I/T_{TOT}, a decreased V_I/T_I, and a possible decrease in T_E.[62,86,94,95] Depending on the prevailing $\dot{V}_E$ and the magnitude of the added resistive load, $\dot{V}_E$ may or may not be sustained at appropriate levels. This pattern of breathing reduces both the flow-resistive component of the work of breathing[86,91,92] and the adverse perception of the added load to breathing.[96,97] With the onset of exercise, the pattern of breathing during the ensuing hyperpnea—while wearing a CB mask or a comparable resistive load—does not demonstrate the usual adjustments observed during unobstructed breathing. Given the increased T_I/T_{TOT} due to the added inspiratory load, the usual increase in T_I/T_{TOT} as exercise $\dot{V}_E$ increases is diminished.[62,95] Likewise, the rise in the V_I/T_I is decreased when a CB mask is worn, particularly when the $\dot{V}_E$ exceeds approximately 40 L/min.[62,95] Thus, the added resistive load of a CB mask constrains the respiratory controller's adaptive regulation process.

Limits to Exercise When Using the CB Mask

Numerous studies have investigated the effects of added resistance applied to inspiration, expiration, or both, at various exercise intensities. A general finding of studies of added resistance to breathing, typical of many CB masks [range: 2.5–5.0 cm $H_2O/(L/s)$], is decreased exercise $\dot{V}_E$ and endurance time at metabolic rates greater than approximately 60% $\dot{V}O_2$max.[48,85,95,98–102] The reduction in $\dot{V}_E$ is usually directly proportional to the increase in resistance (see Figure 36-5). Usually the $\dot{V}O_2$max is reduced, but the relationship between oxygen uptake and submaximal workloads is not altered. The reduction in $\dot{V}O_2$max when breathing through the added resistance may be related to the increase of alveolar carbon dioxide subsequent to the relative hypoventilation.[46,98–100] At submaximal workloads, increased airflow resistance may decrease exercise endurance.[85,103,104] Even small increases in external airway resistance can negatively impact exercise endurance (Figure 36-10): simply *wearing* a CB mask—even with no filter elements—decreased exercise performance in healthy, fit soldiers during a high-intensity run.[85]

The physiological mechanisms by which added resistance to breathing impairs work performance are complex. Among the possible mechanisms are

- mechanical restrictions on ventilation,
- the increased metabolic cost of breathing,
- constraints on the pattern of breathing, and
- increased adverse respiratory load sensation.

Whatever the mechanism, ventilation may be sustained at adequate levels to meet metabolic demand right up to the premature cessation of the physical work task. Alternatively, hypoventilation may ensue, with consequent rise in partial pressure of arterial carbon dioxide (Pa_{CO_2}), which may contribute to subsequent task failure.[105]

In almost all healthy, fit individuals, unopposed breathing per se does not limit maximal aerobic exercise.[58,106] These individuals' maximal exercise $\dot{V}_E$ does not exceed their MVV, which represents the upper limit for exercise ventilation. The maximum sustained ventilatory capacity (MSVC) is the level of voluntary hyperpnea that could be maintained for prolonged (4–15 min) periods. The MSVC ranges from 55% to 80% of the MVV.[90,107] In normal adults, the maximal exercise $\dot{V}_E$ usually approaches only 70% to 80% of an individual's MVV,[108] a level corresponding to the MSVC. McCool and colleagues[109] observed that high rates of respiratory muscle oxy-

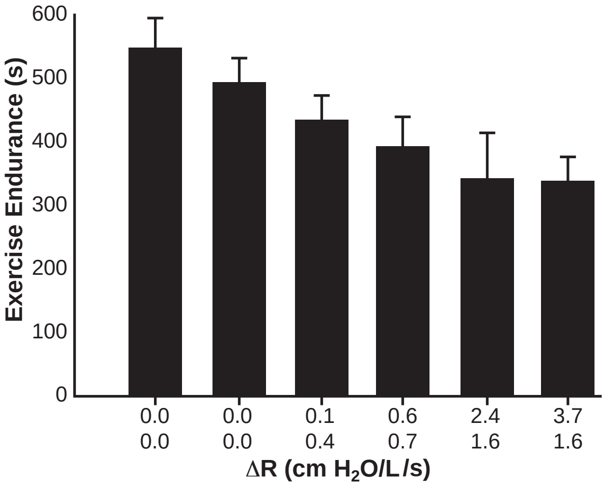

Fig. 36-10. Effect of US Army M9 and M17 Chemical–Biological (CB) protective masks with increasing inspiratory resistance on physical work endurance (running time); (~ 11 km/h at 0% to 6% grade. Each CB mask was modified to alter the magnitude of inspiratory resistance (upper ΔR values) and expiratory resistance (lower ΔR values). The bar on the left represents the "no mask" condition. Note that wearing the CB mask with no measureable airflow resistance (second bar from left) decreased exercise endurance. Data source: Stemler FW, Craig FN. Effects of respiratory equipment on endurance in hard work. *J Appl Physiol.* 1977;42(1):28–32.

gen consumption were associated with short respiratory muscle endurance times. Thus, maximal exercise V̇E may be limited by (1) the development of respiratory muscle fatigue and (2) a protective mechanism within the respiratory controller that limits ventilation to retard development of respiratory muscle fatigue.[58,110,111] Consequently, any garments or equipment that decreases the maximal breathing capacity increases the risk of a ventilatory limitation to physical work.

There are no published measures of the effect of the CB mask on MSVC but, given the decreased MVV (see Table 36-5), it is reasonable to estimate that CB masks bring about a similar decrement in MSVC. Demedts and Anthonisen[99] observed that at each level of added resistance, maximum exercise V̇E was approximately 70% of the MVV measured with that resistance. This suggests that the reduced maximal ventilatory capacity contributes to the decreased maximal exercise performance with CB mask use by lowering the threshold for development of respiratory muscle fatigue. Furthermore, just as the threshold ventilation for development of respiratory muscle fatigue is lowered, the added airflow resistance is *increasing* the respiratory muscles' work and oxygen cost per unit of ventilation.[64,66,67] Thus, by simultaneously imposing both a constraint and a load on the respiratory muscles, the CB mask reduces respiratory muscle endurance and, subsequently, physical work capacity. Alternatively, in the absence of respiratory muscle fatigue, the greater oxygen cost of breathing through a CB mask may limit physical work by diverting a larger proportion of the cardiac output to the respiratory muscles,[67] thus limiting oxygen availability to the skeletal muscles that are performing the physical work.[58,111]

The CB mask also impairs ventilation through constraints imposed on the pattern of breathing. Usually, increases in respiratory frequency result from shortening of both the TI and the TE, although the latter is shortened proportionately more.[90] Given the CB mask's increased inspiratory flow resistance, studies[62,105,112] have shown that the limitation of ventilation during exercise results from attempts to minimize the total work of breathing by reducing the TE in order to prolong the TI of each breath. Because CB masks produce their greatest resistance to breathing during inspiration, this strategy reduces inspiratory work while letting expiratory work increase slightly. Johnson and Berlin[112] demonstrated in 10 subjects that a minimum TE of 0.66 seconds corresponded to the voluntary termination of exercise. However, Stemler and Craig[85] observed a variable TE at the termination of exercise. They suggested that the minimal TE attained is more a function of expiratory resistance than a general limitation on expiratory performance. Recognizing that the degree of constraint on TI and TE is proportional to the added airflow resistance to each phase, these data suggest that the CB mask restricts the range of pattern of breathing adjustments necessary for optimizing respiratory muscle efficiency.

Another, but not an exclusionary, hypothesis states that attempts to prolong TI decrease the respiratory sensations associated with the development of the inspiratory muscle force.[113] Conscious humans demonstrate a wide range of psychophysical respiratory load sensitivity (ie, a given resistive load to breathing may be perceived to be of greater or lesser magnitude among individuals).[69] Harber and colleagues[114] found that healthy adults with high psychophysical respiratory load sensitivity did not tolerate physical work while breathing through a CB-masklike resistance as well as the subjects with low psychophysical load sensitivity. Likewise, in a study of healthy young soldiers, Muza, Levine, and Latzka[115] found a positive correlation between high perceptual sensitivity to added resistive loads and the score for the symptom “hard to breathe” during exercise while wearing a CB-style mask. Because the peak inspiratory pressure generated against the added inspiratory resistive load is the primary stimulus of the sensation of dyspnea[97,100,116] (shortness of breath), these studies suggest that subjects may alter their pattern of breathing to minimize adverse respiratory sensation associated with breathing against the added resistance of a CB mask. Cerretelli, Rajinder, and Farhi[100] suggested that when breathing against added resistance, exercise ventilation may consciously be restrained to confine the inspiratory and expiratory pressure swings to some internal limit. Thus, exercise ventilation through a CB mask may be limited by perceptual sensitivity to respiratory loads with consequent reduction in physical work capacity.

There is a wide range of psychophysical respiratory load sensitivity in the normal adult population. This mechanism may account for the large between-individual variability in soldiers of similar age and physical capability in the degree of their discomfort and tolerance to exercise attributed to use of the CB mask.[114,115] Another source of variability among normal healthy individuals is the wide range of ventilatory chemosensitivity.[117] Generally, the magnitude of an individual’s ventilation per liter of carbon dioxide produced is directly related to his or her hypercapnic ventilatory responsiveness (HCVR).[98,118–120] The HCVR is a measure of the gain of an individual’s respiratory control system to an increase in Pa_{CO_2}. Two studies[98,99] found that during exercise, when breathing was opposed by added resistance, subjects with low HCVR minimized their ventilatory effort and let their alveolar carbon dioxide rise; in contrast, those subjects who were most sensitive to carbon dioxide increased their respiratory work and maintained alveolar carbon dioxide near normal. Consequently, the latter subjects—by sustaining their $\dot{V}_E$ at levels appropriate to the metabolic demand of the exercise—demonstrated lower exercise endurance and tolerance to the added resistance. More recently, Muza and colleagues[95] reported that V_I/T_I was positively correlated to HCVR during moderate- to high-intensity exercise while breathing against added inspiratory resistance. These data suggest that individuals with high HCVR perform greater inspiratory muscle work compared with individuals with low HCVR. Thus, the exercise limitation imposed by added resistance to breathing depends both on the ventilatory limitations produced by the resistance per se and on the ventilatory chemosensitivity of the individual, which influences the level of respiratory muscle work performed to support the physical work task.[99]

Adaptation to Wearing the CB Mask

Because the respiratory muscles are skeletal muscles, they should respond like other skeletal muscles to appropriate strength- and endurance-training programs. Several studies[107,121–124] have evaluated respiratory muscle training protocols for their effectiveness in increasing ventilatory capacities and respiratory muscle endurance in healthy adults. A few[107,121,122] used sustained, normocarbic hyperpnea as the training stimulus because it most closely mimics the action of the respiratory muscles during exercise. One ventilatory muscle training program consisted of 30- to 45-minute training sessions conducted 5 days per week for 5 weeks. During each training session, subjects voluntarily ventilated to exhaustion at more than 81% of their pretraining MVV. Researchers found that this ventilatory muscle training program increased MVV and MSVC by approximately 14% (the 30-min training sessions) and approximately 18% (the 40-min sessions).[107] A similar training program, with the addition of added inspiratory resistance, resulted in greater increases in respiratory muscle endurance.[125]

Although respiratory muscle training can improve ventilatory capacities and endurance, this type of training requires monitoring and controlling alveolar ventilation and gases to maintain normocarbic conditions, and the appropriate ventilatory target. To achieve similar levels of ventilation during aerobic exercise would require sustaining near maximal aerobic exercise intensities for periods of time that exceed the endurance times for such exercise. One study[126] attempted to see if a program of daily, short (< 5 min), intense (80% $\dot{V}O_2$max) exercise wearing a CB mask improved exercise tolerance in the mask. Although the findings demonstrated a slight improvement in exercise endurance, it was not statistically significant. The authors[126] reported that the pattern of breathing changed, resulting in reduced work of breathing. However, because the study lacked a control group, these results must be confirmed.

Two studies of the value of respiratory muscle training on aerobic exercise performance used a program of specific respiratory muscle training similar to that described above.[11] In a study[121] of sedentary adults, submaximal (~ 64 % $\dot{V}O_2$max) cycle exercise endurance to exhaustion increased by approximately 50% following respiratory muscle training. However, another study[124] of moderately trained cyclists did not find an improvement in high-intensity cycle exercise performance following respiratory muscle training. Thus, from a physiological perspective, properly conducted respiratory muscle training will slightly increase ventilatory capacities and endurance, but a practical method of implementing this training is lacking. Moreover, whether respiratory muscle training will improve aerobic exercise performance in physically fit individuals during CB mask wear is inconclusive.

Additional Dead Space From the CB Mask

Each breath of air is composed of an anatomical dead space volume (non–gas-exchanging) and alveolar volume (gas-exchanging). A CB mask adds an external dead space to the wearers' anatomical dead space. At the end of an exhalation, the VDS contains oxygen-depleted and carbon dioxide–enriched expired air. Consequently, this hypoxic, hypercapnic gas will be inhaled during the next inspiration before any fresh, filtered air can enter. Thus, added VDS decreases the partial pressure of alveolar oxygen (PAO_2) and increases the partial pressure of alveolar carbon dioxide ($PACO_2$), with corresponding changes in the arterial blood. Arterial hypercapnia is a potent ventilatory stimulus. Several studies measured the effect of added VDS on ventilation during rest and exercise.[127–130] Bartlett, Hodgson, and Kollias[127] studied a range of VDS (36–300 mL), encompassing the VDS typical of many CB masks. They concluded that an added VDS larger than 50 mL will increase $\dot{V}E$, although they did not test a VDS between 48 and 215 mL. Results of their study are illustrated in Figure 36-11. Added VDS (215 or 300 mL) significantly increased $\dot{V}E$ during rest and exercise. The added VDS appeared to increase $\dot{V}E$ more at rest than during exercise.

This latter observation may be of significance when personnel attempt to sleep while wearing a CB mask. During sleep, $\dot{V}E$ decreases and $PACO_2$ rises.[131] However, arousal from sleep may occur if $PACO_2$ increases too much.[132] The VDS of modern CB masks is generally between 150 and 300 mL.[94] Moreover, a poor seal of the mask's nose cup or internal partitions with the wearer's face can result in internal mask leaks, which may greatly increase the volume of the mask's VDS. One study[133] observed that removing the nose cup of a CB-style mask increased $\dot{V}E$ approximately 5% during mild exercise. Consequently, every CB mask imposes a VDS load on respiration, to which the wearer must compensate by increasing ventilation.

Although by itself VDS causes a compensatory increase in $\dot{V}E$, how VDS interacts with the flow-resistive loads imposed by CB masks is less well known. Craig, Blevins, and Cummings[105] showed that an increase in inhaled carbon dioxide (mimicking added VDS) was not well tolerated when combined with increased resistance. Harber and colleagues[130] reported the exercise ventilatory responses to imposition of VDS and inspiratory and expiratory flow resistive loads, individually and in combination. During steady state exercise ($\dot{V}O_2$ ~ 1.2 L/min), an added VDS of 300 mL without added airflow resistance increased ventilation approximately 13%. However, added inspiratory flow resistance [5 cm $H_2O/(L/s)$] without added VDS decreased exercise $\dot{V}E$ approximately 20%. In combination with increased resistance, the added VDS increased ventilatory effort and work of breathing, although $\dot{V}E$ was not significantly different from the unloaded condition. Finally, the effects of VDS on $\dot{V}E$ tended to decrease as exercise intensity and $\dot{V}E$ increased. This decreased effect of VDS on exercise $\dot{V}E$ is probably due to both a decreased VDS/VT ratio and the increased magnitude of the added flow-resistive load, which will rise proportionally with ventilation as exercise intensity increases. In summary, the results reported by Harber and colleagues[130] suggest that while added inspiratory flow resistance affects $\dot{V}E$ more than added VDS, the aversive effects of the added resistive load are accentuated by the added VDS.

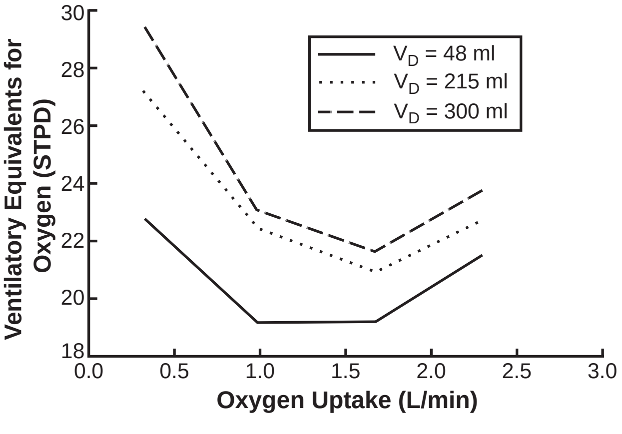

Fig. 36-11. The effect of adding volumes of external dead space (VDS) on ventilation at metabolic rates ranging from rest to moderate-intensity exercise. As VDS increases, ventilation increases to maintain appropriate level of alveolar ventilation. Note that the effect of added VDS on ventilation is greatest at rest. Data source: Bartlett HL, Hodgson JL, Kollias J. Effect of respiratory valve dead space on pulmonary ventilation at rest and during exercise. *Med Sci Sports Exerc.* 1972;4:132–137.

The VDS may be responsible for some of the between-individual variability observed during CB mask use. Because the ventilatory sensitivity to carbon dioxide varies greatly among individuals, a given volume of external dead space can produce a wide range of ventilatory responses.

Effects of the NBC Uniform and Individual Equipment on Breathing

CB masks have usually been the focus of research relative to respiratory impairment associated with NBC ensemble to the exclusion of other components of the protective garment, load-carriage equipment systems, or both, that may interact and synergize impairment of respiratory function. Several studies[134–136] have demonstrated that load-carriage equipment systems worn over utility uniforms reduce MVV by approximately 10%. In a study[137] in which male soldiers walked on a treadmill at 35% to 65% peak oxygen uptake, the wearing of load-carriage equipment over the utility uniform caused increased sensations of breathlessness that accompanied a reduction in the inspired volume of each breath. However, $\dot{V}_E$ was maintained by increasing the rate of breathing. This pattern of breathing is a typical compensatory response to an elastic load.[138] In addition to changing the pattern of breathing, restricting the chest wall displacement requires increased respiratory muscle activity. Green, Mead, and Sears[139] reported that restricting rib cage expansion alone increased diaphragm electromyographic activity by nearly 50% at rest. Moreover, each additional layer of clothing worn increases the metabolic cost for walking,[13] further increasing ventilation and respiratory muscle activity.

In 1996, Muza, Banderet, and Forte[51] proposed that a portion of the ventilatory impairment when wearing NBC uniforms is the result of restricted motion of the chest wall (ie, increased elastance) caused by both the overlying protective clothing and load-carriage equipment. This combination would form an elastic load on the chest wall, which is usually compensated for by reducing the inspired volume of each breath and increasing the rate of breathing to maintain the desired minute ventilation.[87,138] However, as described above, the CB mask imposes a resistive load to breathing, which typically elicits (1) an increase of inspired volume and inspiratory duration and (2) decreased respiratory frequency[87] to reduce flow-resistive work. The CB mask also increases upper-airway dead space, which is typically compensated for by increasing inspired volume.[127,130] Thus, the ventilatory compensations for increased dead space and inspiratory resistance are the opposite of those used when ventilation is opposed by a pure elastic load.

Muza, Banderet, and Forte[51] measured ventilatory performance in a variety of standard US Army uniforms, including the standard ground troop NBC uniform (US Army MOPP 4 with M40 CB mask and standard C2 filter canister). Over the NBC garment, the volunteers wore body armor (ground troop fragmentation protective vest) and load-bearing equipment (pistol belt with shoulder suspenders) that was configured with two full canteens and two ammunition carriers loaded with the equivalent of four 5.56-mm 30-round magazines. Compared with the loose-fitting physical training uniform, the NBC uniform configuration decreased MVV by approximately 25%, with nearly one fifth of this reduction attributed to the external load on the chest wall (Figure 36-12). As expected, the CB mask significantly decreased respiratory flows and had little impact on lung volumes (see Table 36-5). On the other hand, the overgarments and personal equipment significantly decreased maximal lung volumes by approximately 5% to 10% and potentiated the decrement in airflow.[51] Muza and colleagues speculated that the decreased lung volumes were caused by the "corsetlike" action of the combination of overgarments and personal equipment on the chest wall. Accordingly, they found that total respiratory system elastance was increased by approximately 16% in the NBC uniform–CB mask combination, compared with the standard US Army BDU. By comparison, assuming a normal adult value of 4 cm $H_2O/(L/s)$ for total respiratory resistance,[42] the M40 CB mask increases resistive opposition to breathing by approximately 85%. Nevertheless, wearing the NBC uniform overgarments and personal equipment increases the "stiffness" of the soldier's respiratory system, contributing to the decrease of MVV and most likely increasing the work of breathing.

Muza, Banderet, and Forte's study[51] also found that during submaximal treadmill exercise (~ 600 W), the exercise pattern of breathing was more influenced by the elastic forces opposing breathing than by the resistive forces. An approximately 8% smaller VT during exercise while wearing the NBC overgarments and personal equipment was probably a compensation for the increased total respiratory system elastance. With a smaller VT, $\dot{V}_E$ was maintained by a small increase in breathing rate. Although the NBC overgarments and personal equipment presented a smaller mechanical impairment on the respiratory system than the CB mask,

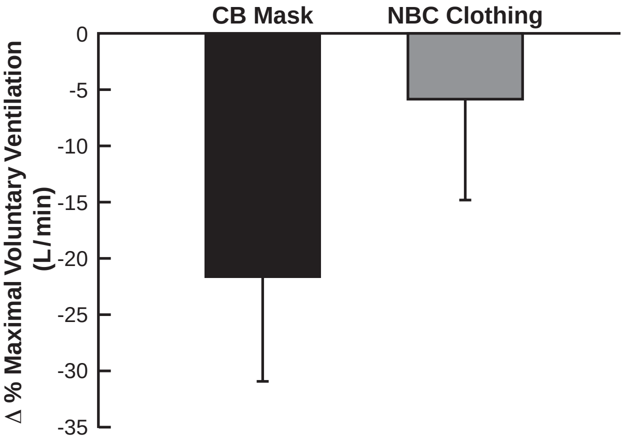

Fig. 36-12. The relative contributions of (left) the US Army M40 Chemical–Biological (CB) protective mask, presenting a flow-resistive load to breathing, and (right) nuclear–biological–chemical (NBC) overgarments with load-bearing equipment and body armor, presenting an elastic load to breathing, on decrement in maximal voluntary ventilation. Data source: Muza SR, Banderet LE, Forte VA. Effects of chemical defense clothing and individual equipment on ventilatory function and subjective reactions. *Aviat Space Environ Med.* 1996;67:1190–1197.

the subjects chose to adjust their pattern of breathing to compensate for this small elastic load rather than the larger resistive load opposing breathing. This suggests that elastic loads to breathing may not be subjectively tolerated as well as resistive loads (ie, the CB mask) and may be related to the fact that the psychological function for magnitude scaling of elastic loads is greater than for resistive loads.[140] Thus, although small, the constraint on the respiratory system imposed by external loading of the chest wall (NBC overgarments, body armor, load-carriage equipment) may, by its effect on the perception of respiratory sensations, present a significant mechanism for impairing exercise breathing and physical work performance.

CB Mask Effects on the Head and Face

The CB mask is likely to feel awkward and uncomfortable when it is put on for the first time or has been worn for only a few hours (cumulatively).[141–144] The initial reaction of many soldiers is that the mask, which weighs 1.0 to 1.5 kg, is heavy; when secured on the face and head, the weight of the mask is very noticeable. The mask and its interfacing surfaces and attaching straps also exert pressure on many areas of the head that are normally uncovered. If the straps are pulled too tight, soldiers may report that the straps seem to be cutting into their scalps. In field studies with troops, about 10% to 25% of soldiers reported headaches after wearing the mask a few hours.[141] This was especially true for younger soldiers who had little prior training or experience with NBC protective uniforms and equipment. They secured the straps on the mask too tightly in their attempt to create a good seal on the mask to protect themselves from simulated chemical agents. Fortunately, with practice and greater experience with the mask, such excessive tightening of the straps and many objectionable features of the mask can be minimized.[141,145]

Impaired Communications

Wearing the CB mask and hood hinders face-to-face transmission and reception of speech and radio and telephone communications. The CB mask and hood adversely affect speech intelligibility and amplitude.[19,146,147] Bensel, Teixeira, and Kaplan[19] demonstrated that listeners, unencumbered by CB mask or hood, only achieved a mean score of 65% on the Modified Rhyme Test when the person to whom they were listening wore either an M17 or an M40 CB mask. This score was less than the 75% level of acceptability for voice communications.[18] This finding is of concern because the newer M40 CB mask has two voice resonators (vs one in the M17) but still does not produce speech of adequate quality.

Thus, CB masks attenuate and distort speech; these degradations eliminate many of the tonal qualities of speech that indicate humor, joking, sarcasm, camaraderie, or a questioning attitude. Without relevant acoustical data in speech, less information and cues for behavior are available during informal or social communication. Likewise, the opportunity for misunderstanding mission communications or not hearing them is increased because of the sound-attenuating properties of the mask and hood.

Reduced Sensory Capabilities

CB masks often restrict visibility by blocking part of the visual field.[19,146,148,149] The newer M40 CB mask offers some advantages over the standard M17, but both respirators restrict vision significantly in the temporal and supernasal regions of the visual field, compared with viewing with no mask.[18] Especially at night, more head-turning movements are needed to see objects and receive information in the peripheral visual field.[20] Protective eye lens viewing ports affixed to the CB mask are usually made of flat, sturdy plastic, which contributes to visual parallax and distortion of important images during target detection and identification. Also, some regions in the pilot's visual field are obscured by the mask, a degradation of vision that can be critical during flight for helicopter pilots reading instrument panel indicators or looking for low-level flight hazards such as utility wires.[20]

There is also a practical problem of seeing through the CB mask when the lenses fog over, owing to exhaled moisture or an accumulation of perspiration inside the mask, creating a severe problem for a service member who must maintain good visual contact.[20] The moisture is not easily alleviated without breaking the mask-to-face seal to let the accumulation drain out the bottom of the mask. However, in certain crew-served weapon systems and aircraft, conditioned air can be circulated through the CB mask to minimize this problem.

The CB mask and filter system alters or eliminates olfactory cues, the "smells of the battlefield."[20(p267)] Personnel rely on detection of odors to indicate the status of diesel or electric motors and other equipment, to identify battlefield smokes and obscurants, and to detect the aroma of field food.

Degraded Optics From Prescription Insert Lenses

Soldiers who typically wear prescription eye wear (spectacles) should wear prescription insert lenses inside the CB mask. Getting corrective lens inserts for a CB mask has been a significant logistical problem, and even during field studies that involved the wearing of NBC protective uniforms, wearers of eyeglasses frequently do not have insert lenses for their CB masks.[141,143] Using a CB mask with insert lenses can be problematic, as the lenses are usually secured in a metal frame affixed on the lens well of the mask, and it is difficult to maintain the alignment of the lenses for comfortable visual acuity,[149] especially during visually demanding tasks such as rifle firing.[150] Furthermore, with prescription lens inserts in place, the lenses are more prone to fogging.

Various military occupational specialties (eg, aviation) involve tasks requiring exceptional visual functioning, even if it is achieved via use of prescriptive correction.[20] Because 20% to 30% of US Army aviators require optical correction,[151] the Army equipped its attack helicopter crews with extended-wear contact lenses so these pilots could have corrective lenses compatible with the aviator's CB mask and helmet-mounted display sighting systems. Unfortunately, some soldiers could not be fitted adequately with contact lenses because of presbyopia or astigmatism.[152]

Eating and Drinking

Although exploratory research has developed a means to supply soft food via tube feeding through the CB mask, a more popular alternative for personnel is to wait for the battle action to slow, doff the mask in a safe place, and eat solid food.[20] Few tube-feeding systems have been fielded. Drinking fluids, however, is critical to maintaining hydration during extended wearing of the NBC protective uniforms. Avoiding contaminants while drinking through the mask is difficult at best, but a new drinking-tube arrangement with snap-over connectors to affix to 2-qt water canteens protects both the mask and the water supply from contamination.[153]

Body Waste Management

The processes of urinating and defecating while wearing an NBC protective uniform are rarely written about.[20] It is difficult to eat and drink while wearing the CB mask; however, a regularized drinking regimen to protect against heat stress still requires periodic urination. NBC protective clothing, containing zippers and rear flaps, is poorly designed for waste elimination without the risk of compromising the protective capabilities of the uniform.[154] Most soldiers, when faced with the need to urinate or defecate during a training exercise in the presence of a simulated threat, simply unzip and void without fear of consequences. However, combatants exposed to an imminent chemical threat are likely to seek collective shelter (inside a vehicle or building) and only there doff portions of the clothing to meet this need.[20] Adequate provisions for special male and female hygiene are not accounted for in the present design of NBC protective clothing.

Sleep

It is difficult to sleep comfortably while wearing a CB mask.[20] Sleeping posture has to be carefully selected. When sleeping on one's side, for example, the somewhat rigid structure of the hard rubber mask may be displaced from its tight fit on the wearer's face. If the seal of the mask is compromised, the protective value of wearing the mask is sacrificed.

Although Lieberman and colleagues[155] noted that soldiers who slept in M40 masks tolerated them for most of the night, measurements with wrist-activity monitors indicated that soldiers required more time and found it more difficult to fall asleep when wearing the mask. Their sleep was significantly disturbed; length of time awake increased from 25 to 86 minutes per night, and the number of arousals increased from 8 to 20.

Depending on the integrity of the mask–face seal, protection provided by the mask against potential chemical agents varied among participants; some soldiers were protected throughout the night, others only intermittently.[155] On the other hand, when soldiers sleep on the ground or in armored vehicles, they frequently mention that the NBC protective uniform provides a certain amount of cushioning and warmth in cold weather.[20]

PSYCHOLOGICAL REACTIONS TO NBC PROTECTIVE UNIFORMS

Impact on the Young, Inexperienced Soldier

Younger (and therefore less experienced) soldiers are more impaired by NBC protective uniforms than are older soldiers.[141,143,144,156] Older, more experienced military personnel exhibit fewer symptoms and appear less anxious about training in NBC protective uniforms. It is thought that older service members have learned how to cope with many of the troublesome aspects of wearing NBC protective uniforms. The mask, hood, and other items of NBC protective uniforms present many aspects that are stressful; adaptation to and gradual experience with them is usually helpful.

Because many soldiers lack detailed familiarity with chemical and biological weapons, it is essential that they understand that the NBC protective uniforms issued to them *will* protect against chemicals on the battlefield.[145] This knowledge and understanding will do much to reduce fear, anxiety, and adverse reactions to the NBC protective uniform. Although familiarization training while wearing NBC protective uniforms varies widely in military units of all countries, most military forces effectively accomplish sufficient orientation through classroom didactic training, which usually includes photos of gruesome chemical wounds from past wars or industrial chemical accidents.[145] Students are assured that NBC protective uniforms, if used correctly, will protect them. Practical exercises usually include donning a CB mask and visiting a small enclosure filled with tear gas vapors. This demonstration helps recruits gain familiarity and confidence that the mask will protect them from airborne agents. Since the early 1980s, the US Army has conducted live nerve agent decontamination training for small numbers of chemical specialists in a controlled setting.[157]

Breathing and Its Psychological Effects

In response to the added breathing resistance imposed by CB masks (discussed above in the Effects of Resistive Loads subsections), altering physiological responses by conscious modification of the breathing pattern—such as attempting to breathe too little or too much—can lead to breathing distress, hyperventilation, shortness of breath, tremors, and claustrophobic reactions.[51,146] Many CB warfare agents provoke intense psychological concerns because they contaminate the air that we breathe to stay alive. Thus, NBC agents are linked to the most basic and urgent of all biological drives—the urge to breathe.[145] When troops who do not have NBC protective uniforms think about NBC agents, they may feel impotent and that nothing is within their control. Likewise, lack of confidence in their NBC protective clothing and equipment or their ability to use it may also evoke a profound sense of helplessness or hopelessness.[145]

Problems with breathing through a mask are also familiar to those in the civilian workforce (eg, firefighters) who wear respiratory protective devices.[158] Psychological anxiety encountered with such breathing resistance can be decreased through familiarity training with the CB mask. Troops should also practice sleeping in the mask after receiving advice on ways to avoid compromising the CB mask's protective seal and preventing respiratory distress or intermittent obstruction of breathing (sleep apnea) from occurring.[145] Performance of tasks requiring high aerobic power (eg, handling of ammunition) is hindered greatly by breathing resistance, as breathing is greater under high workload conditions.[112,159] Thus, more time is usually required to perform certain tasks when the CB mask is worn.

Maladaptive Psychological Reactions

Combat with CB weapons is likely to produce many more casualties with psychological stress than with actual CB injuries. That prediction reflects the adverse impact of fears and anxieties that troops experience in dealing with the threat of a CB-contaminated battlefield. In part, such anxieties are attributable to the insidious, ambiguous nature of many CB agents, which prompt fears of dying a hideous death on the battlefield. Maladaptive responses of soldiers to the battlefield include the psychological overreactions of hyperventilation, claustrophobia, gas-mask phobia, compulsive practices or obsessive concern with decontamination, congregating in safe or collective protection areas, finding excuses to never come out or let others into a safe space, and hoarding or stealing protective items. Underreactions to the chemical threat, such as psychological denial, fatalism, rationalization, or intellectualization, may also occur.[145] All of these prevent troops from taking adaptive actions or enacting useful countermeasures.

Muza, Banderet, and Forte[51] demonstrated that an NBC protective uniform evokes predictable psychological reactions such as anxiety, feelings of not getting enough air, and perceptions of abnormal breathing and of stress. For combatants, such concerns can be fueled by their lack of confidence in NBC protective uniforms and their inability to use them properly for protection.[141,143] Taylor[160] emphasized the benefits of coping strategies, relaxation techniques, good leadership, and training to decrease or prevent extreme fear and many adverse reactions. Education, training, and experience with NBC protective uniform can go a long way toward reducing these fears.[145,157,160]

Soldiers who spend lengthy training sessions garbed in NBC protective uniforms occasionally report loneliness, a distorted sense of time passage, and alterations in distance estimates.[20] For example, armor crews in MOPP 4, when approaching prominent terrain that narrows, "bunch up their vehicles" so they are five or six vehicles abreast waiting their turn to go through narrow terrain gaps.[20] This makes them an opportunistic high-value target, so that their risk of enemy attack from the air or from his artillery is greatly increased. At Fort Irwin, California, a National Training Center cadre sergeant stated:

> every group coming here for training does the same thing in MOPP IV, they bunch up their vehicles; … it seems that they just want to feel closer together despite the obvious risks.[20(p274)]

Military history provides other illustrative examples and lessons regarding adverse psychological reactions. During World War I, when rumors suggested that new chemical agents could penetrate the gas masks, whole units fled after smelling an unfamiliar odor.[145] Units who were exhausted or demoralized were especially susceptible to panic. However, among the lessons from World War I was the suggestion that combat experience with the chemical threat often led to positive psychological adaptation.[145] Training was developed to build confidence in the CB mask and motivate troops to use it. Gas-chamber training (using tear gas) during World War I had troops wearing their gas masks for more than 1 hour in the chamber before they took them off to experience the effects of a simulated chemical agent.[161] Newly assigned troops sometimes died in gas attacks if they lacked both adequate training and mentors, just as they were more likely to be victims of conventional weapons.[145] The survivors of chemical attacks were troops who had mastered the drill and tactics of chemical defense.

Accounts of maladaptive reactions during the 1990/91 Persian Gulf War include the following examples[145,162]:

- many soldiers who took no precautions with the CB mask and NBC protective uniforms when air (missile) alerts were sounded because prior alerts in the theater had been uneventful;
- a sergeant with gas-mask phobia who was evacuated to the United States;
- at least one case of inappropriate and premature atropine self-injection; and
- a physician who was barred from entering a collective protective shelter after an alert because fellow soldiers feared he would contaminate the shelter.

Another manifestation of maladaptive reactions is that troops may become obsessively concerned with decontamination procedures, which they then perform compulsively.[145] This consumes precious time needed for critical tasks and wastes scarce decontamination supplies. Excessive skin cleansing with decontamination solutions can cause rashes that might then be misinterpreted as confirmation of exposure to a chemical agent.

Civilian populations confronted with terrorist actions involving chemical agents also manifested maladaptive reactions. Newspapers and television in the United States reported (incorrectly) that 12 people were killed and 5,500 were "injured" during the March 1995 sarin nerve agent attack in the Tokyo, Japan, subway.[145,163] Findings from 5,110 victims of the sarin attack evaluated at hospitals in the first 24 hours document the overreactions and excessive concern that chemical warfare agents can create.[164] Overall, 73.9% of these so-called casualties showed no effects of exposure to nerve agent. These patients were instead the "worried well."

IMPACT ON MILITARY OPERATIONS

Sources of Information and Findings

Wearing NBC protective uniforms impairs the performance of several military tasks and limits soldiers' dexterity, mobility, communications, vision, and task endurance. It is important to try to specify and predict the impact that wearing NBC protective uniforms will have on military operations. Information comes from several sources[3,4] to help anticipate the impact of NBC protective uniforms on small-unit and large-scale military operations. Since the early 1980s, a variety of systematic programs were initiated to provide such information. Headley, Hudgens, and Cunningham[165] reviewed three military research programs involving field studies of soldiers wearing NBC protective uniforms in hot environments during extended operational military work scenarios, often 24 hours or longer, therefore including night operations. These studies[3,165,166] of military teams (military program titles: DO49, P^2NBC^2 [Physiological and Psychological Effects of NBC and Extended Operations on Combat Vehicle Crew Performance], and CANE [Combined Arms in a Nuclear Environment]) were reviewed in great detail and included

- two-person teams performing cooperative tasks (eg, disassembling a tank engine for a DO49 project) while wearing an NBC protective uniform;
- about 20 different P^2NBC^2 controlled scenarios with specific, crew-operated, military systems (eg, three to four crew members in tanks, self-propelled howitzers, and armored personnel carriers);
- five large-scale CANE tests, including a study of 40-person, platoon-sized military units performing infantry operations (ie, CANE I in 1986); and
- large, free-play operations of hundreds of soldiers (ie, CANE IIB in 1989) in tests of full, battalion-sized scenarios on simulated battlefields.

These field experiments demonstrated that although most standard military tasks can be performed satisfactorily, extra time is required to perform them in NBC protective uniforms.[20,167] High ambient temperatures and high work loads are especially detrimental to endurance in NBC protective uniforms.

Many measures of combat effectiveness degrade in MOPP 4, including[3,165,166]

- difficulty in locating and reporting enemy positions;
- poorly timed battle synchronization;
- engaging enemy forces at closer ranges than desirable;
- firing fewer primary weapons;
- lengthy time intervals to alternate battle positions; and
- general degradation in command, control, and communications.

These field studies, especially those engaging sizable numbers of soldiers carrying out military task scenarios on large stretches of terrain, tended to be exploratory and descriptive in nature.[165] They involved determining operational principles of practical importance to the military community, and some were noteworthy field demonstrations, but making trustworthy scientific extrapolation of findings from some of these studies is difficult. Some studies could be classified as indelicate experiments[168] because they incorporated many tenets of rigorous experimental design, but like many large man–machine system experiments,[169] they also involved numerous uncontrolled variables inherent in military field operations.[20] Frequently, good baseline performance data were not established before testing, and in some tests the presentation of experimental conditions was not counterbalanced.[3,170]

Despite such cautions, the overriding lessons of these studies[20] are

- that the present NBC protective uniforms used by the US military must be redesigned with more attention to human engineering factors, and
- that repetitious realistic training in NBC protective uniforms is essential to sustain performance on a CB contaminated battlefield.

Lessons learned, in particular, called for more-realistic training for military leaders at all levels to enhance understanding of how the behavior of individual soldiers changes within a unit when many soldiers are wearing NBC protective uniforms.[20]

Other information, especially on large-scale operations, results from efforts with operations research models. Military planners, combat developers, and tacticians use such models to help anticipate and prepare for threats envisioned on the next battlefield.[167]

Combat models involve aspects of offensive and defensive military operations and include safety analyses and projections of requirements concerning personnel, training, human factors, and survivability. Developing predictive models of soldier behavior on a dynamic battlefield is one of operations research's biggest challenges. Ramirez[167]emphasized what a daunting task it is to predict the outcome of many time- and task-linked sequential activities on a fluid, dynamic battlefield; it is particularly difficult when the combatants wear NBC protective uniforms intermittently. Useful, valid, predictive models must rely on reliable behavioral computer-accessible databases that can be used to foresee impacts of the battle theater on soldier performance.

Ramirez[167] described US Army and Air Force efforts to develop behavioral models of soldier performance while wearing NBC protective uniforms in simulated chemical warfare environments. Models to predict the times required to accomplish various military tasks and the debilitating psychological effects of wearing NBC protective uniforms are complex undertakings that are challenging to modify or verify. Early work in modeling concerned predictions of the time to complete or perform tasks by either individuals or small military units, then was extrapolated to larger units. Air Force and Army studies with an operations research approach yielded several useful insights[167]:

- The degradation in task performance varied with crew experience; larger degradations were usually associated with crews of less task experience.
- Performance of routine military tasks required 50% to 70% more time when crew members wore MOPP 4.
- Wearing NBC protective uniforms impeded performance of tasks requiring manual dexterity because of the encumbrance of the bulky NBC protective uniform.

The models also estimated the impact of dramatic heat effects on performance. Such models predicted heat-related casualties (heat exhaustion or heatstroke) resulting from sustained operations while wearing NBC protective uniforms in hot environments with little food and water.

Obtaining suitable quantitative data on large military units is a difficult and expensive proposition. Eventually, the US military, primarily the US Army, collected such data[3,165,171] to support computerized analyses and predictive modeling of unit performance in various chemical battlefield scenarios. From these and other data, Ramirez[167]devised a task taxonomy, which suggests some military tasks that do not require increased time to perform while wearing NBC protective uniforms, and ranges to tasks that take 3-fold longer to complete while wearing NBC protective uniforms. Tasks that are affected so dramatically by NBC protective uniforms are usually modified (redesigned) by the soldier or not completed at all.[167]

Use of actual data collected from soldiers can greatly increase the usefulness, robustness, and validity of operations research models. Such models can predict individual soldier and military unit performance, offer computer tools and cost-effective methods to designers of NBC protective clothing for evaluating new designs, enable testers of equipment to better perform their evaluations, and provide battlefield planners with tactical insights for deployment of forces.[167]

Soldier Readiness and Training

In combat involving chemical warfare agents during World War I, psychological stressors caused more casualties than did chemical injuries.[172] In a remarkable instance involving 281 casualties of gas attacks who were evaluated at a field hospital, 68%[172(p65)] showed no signs of chemical injuries. In this situation, two[172(p65)] psychological (stress) casualties were noted for each actual chemical injury. Such statistics of medical casualties may even underestimate the total number of dysfunctional stress cases because they do not include troops who bolted in panic at the threat of gas attack, unless those troops were subsequently evacuated for medical care. Panic reactions were triggered by many events.[172,173] Units who were exhausted or demoralized were especially susceptible to panic. Stokes and Banderet[145] emphasized that if soldiers are not prepared for chemical warfare and experienced with the CB mask and NBC protective uniforms, the number of ineffective soldiers will be much greater. The wearing of NBC protective uniforms and the thoughts or sights of chemical warfare provoke many stressors, some largely psychological, which should be mastered through training, drill, and familiarization with NBC protective clothing and the CB mask.[145]

Military units experience a high turnover of personnel. Therefore, to ensure that they are adequately trained to use their NBC protective uniforms, troops should train frequently in their NBC protective uniforms on common military tasks and, as well, in larger-scale team scenarios in which they practice working together.[20] Because NBC protective uniforms usually encumber movement, breathing, heat exchange, and mission performance (especially during heavy physical work in high ambient temperatures), it is important that training be conducted under realistic conditions for maximal transfer of training. Lack of experience with the CB mask and NBC protective clothing are good predictors of soldiers who most likely will experience difficulties or terminate during a field training exercise. As discussed above in this chapter, soldiers with corrected vision who do not have prescription inserts for their CB masks are vulnerable when wearing NBC protective uniforms,[141,143] and therefore the logistical system should address their specific needs for individual prescription eyewear.

Intensive training to do critical tasks in NBC protective uniforms can promote confidence, reduce adverse emotions, and better prepare all forces to fight successfully on a contaminated battlefield.[20] Today's multimedia training technologies provide many low-cost, sophisticated, high-technology alternatives for training that can be used to present information and scenarios in militarily relevant ways that troops will enjoy and learn from. Many such multimedia training systems are interactive and the level of complexity can be adjusted, providing troops with training for combat situations with more alternatives and fewer static options. Training must be realistic for maximum benefits to result, and realistic training could reduce some adverse emotional effects and even help alleviate some performance impairments associated with NBC protective uniforms. Today, the tactical play of many Army field exercises (eg, National Training Center, Joint Readiness Training Center) provides much greater feedback and realism as warfighters practice skills and acquire "lessons learned"—lessons that are better gained in training than in combat.[174]

As concerns about the likelihood of terrorist actions involving chemical and biological agents in large cities persist,[175–178] the orientation and training of federal, state, and local officials and first-responders are essential so that the mass casualty effects of terrorist attacks can be managed optimally.[179] Holloway, Norwood, and Fullerton[175] emphasize the importance of realistic training for medical personnel so they can experience the numbers and types of casualties and to see how such disruption will create unprecedented demands within medical facilities. Lessons learned from simulations or realistic training in the impact of chemical and biological attacks should benefit agencies that will provide services and assistance to casualties[179]; service providers and public officials will then be better able to anticipate how terrorist attacks would perturb and disrupt public facilities, essential services, and life styles of those in the affected city.[175,179]

Difficulty Identifying Friend or Foe

A psychological complaint is that the CB mask and NBC protective uniform make everyone look identical and hide the usual cues by which we recognize team members, leaders, and followers.[145] When all combatants are garbed in MOPP 4–level NBC protective uniforms, identification is difficult largely because characteristics such as hair, skin color, stature, and body shape are disguised or not visible.[20] Furthermore, voices are distorted and their distinctive tonal qualities are masked. Many military units therefore resort to supplemental identifying markings on the ensemble and to hand signals to ensure visual feedback in intraunit communication.[145] Distinctive symbols are sometimes added to the face part of the hood to represent the team, unit, rank, and individual soldier.[180] However, symbols placed on the mask must not compromise durability, camouflage, operational security, and public sensibilities.

In warfare and in training, when the enemy is difficult to distinguish from others, fratricide and other tragic mistakes can result.[3,165,166] Such situations, like trying to recognize and identify soldiers in NBC protective uniforms, are very stressful because cues normally used to identify fellow soldiers and leaders are no longer available or reliable.

OPTIMIZING TRADE-OFFS IN FUTURE NBC PROTECTIVE UNIFORMS

In the future, warfare will be highly mobile and often fought in urban and suburban areas. Combat will be dynamic and require initiative and actions by teams or individuals to cope with fast-moving, changing situations and sites of resistance. Currently, NBC protective uniforms of the US military protect troops from many NBC threats; however, as this chapter emphasizes, NBC protective uniforms also impose performance, physical, and psychological liabilities for the combatants who wear NBC protective clothing.

Evolving doctrine, training, and advances in materiel should optimize practices associated with wearing NBC protective uniforms and find new ways to reduce the limitations of such protective clothing so that troops can function effectively on future NBC-contaminated battlefields. The current (published in 1992, revised in 1996) manual for NBC protection for the US Army and Marines[5] devotes one page to describing a mask-only posture and variations to the standard protective postures. This brief section in the manual emphasizes the need for greater flexibility in the use of protective uniforms and protective postures and that much more is required. A more-extensive effort would involve computer modeling with salient variables to investigate, such as

- the NBC weapons capabilities of different countries,
- other countries' ways of deploying NBC weapons,
- likely theaters of combat and their climates,
- types of NBC agents (respiratory vs skin-penetrating),
- protection from varied components of NBC protective uniforms, and
- expected missions.

Such iterations could synthesize expert information on risks and the likelihood of respiratory and skin-contact threats, the protection that components of NBC protective uniforms such as the CB mask or a lighter-weight overgarment would offer for special situations, and the increased comfort and performance that would be realized from the use of lightweight NBC protective clothing or CB masks with less inspiratory resistance. Such an effort could also facilitate reexamination of current procedures and assumptions of application of MOPP gear and ensure that NBC protective uniforms of the future sustain military performance and offer optimal protection against the NBC threat.

NBC Protective Uniforms of the Future

Much is known about the effects of NBC protective uniforms (eg, their effects on the soldier's respiration, thermoregulation, ambulatory mobility, manual dexterity, and sensorimotor and psychomotor performance).[20] Considerable data describe degrading effects of NBC protective uniforms on visibility, communications, and respiration. Most proposals call for significant improvements in human engineering of the encapsulated microenvironment of NBC protective uniforms. Many such enhancements will come as developments in future technologies become mature enough for implementation. Parallel efforts are also being made to minimize the effects of chemical or biological agents in other ways.[180] The Defense Advanced Research Projects Agency (DARPA), an agency that has funded defense-related engineering and novel electronics applications for over 30 years, is encouraging and funding projects that seem highly unusual, such as placing an "electronic canary" on a silicon chip to detect a wide variety of CB agents, immunizations that would offer general protection against classes of noxious CB agents rather than protection against a specific threat (eg, smallpox), and skin creams or ingested substances that would provide protection against many noxious agents. Significant advances in detection or prevention against NBC threats would reduce requirements for protective uniforms of the future.

Several biomechanical restrictions imposed by NBC protective uniforms might be lessened if protective-level design criteria could be made slightly less stringent when applied to select military scenarios (eg, quick offense vs slow defense) or to functional specialties (eg, aviators, armor crewmen, infantrymen). This might lead to adopting several alternative inventories of NBC protective uniform systems.[20] Operational doctrine, regarding the use of NBC protective uniforms at the unit level, might be improved if local commanders had more flexibility in determining what MOPP level their troops would assume during operations.[20,145] Each of these notions is described below.

Systems View: Human Engineering

It is essential that an improved NBC protective uniform be designed and evaluated as a "soldier protective system."[18,20] This approach includes accounting for the interactions of NBC protective uniforms with different environments, crucial equipment interfaces such as optical sighting systems, and critical military operational tasks. Bensel[181] provided an important perspective for systems design with her outline of the characteristics of NBC protective uniforms and associated equipment; the physiological and mechanical effects they impose; and her commentary on soldier differences and the influences of leadership, cohesion, and training. Her perspective was similar to and reinforced that proposed by Taylor.[160] Johnson and colleagues[182] offered an equipment-performance rating scheme for CB masks to permit decisions involving trade-offs, an approach that could be adapted to evaluate components of NBC protective uniforms such as gloves, boots, and overgarments. Multinational cooperative programs are now prevalent to address these important issues.

CB Mask

The CB mask is implicated as the primary NBC protective uniform item responsible for negative psychological reactions among soldiers and for much of the operational performance degradation.[18,20,145,181] Design changes should include reduced resistance to breathing, improved visibility through the mask, an easy system for use with prescription lenses, an antifogging system, enhanced speech intelligibility through innovative use of electronic technologies, a better interface of the mask with other equipment, especially optic sights, and easier access to food and drink.[20]

Protective Overgarments

Extensive redesign of NBC protective uniforms is required to improve gross body movement and fine psychomotor control while wearing the suit. Lightweight protective materials that impose less heat burden also should be integrated with personal, wearable cooling devices or a source of cool, conditioned air from a vehicle.[20] Other desiderata include thinner handwear to provide adequate tactile feel and features to permit easier donning and doffing, compatibility with sleeping, and a convenient means of voiding excess perspiration and exhaled moisture resulting during work in excessive heat.[20] Special attention will need to be given to waste elimination and personal hygiene so that soldiers can utilize these uniforms and capabilities rapidly, conveniently, and in a manner acceptable to all users.[154]

Lightweight Protective Uniforms

Developmental programs of North Atlantic Treaty Organization (NATO) forces and other western nations strive to devise suitable, lightweight NBC protective uniforms with less risk of heat stress. McLellan and colleagues[8,183] described Canadian efforts to evaluate protective clothing ensembles, designed by the Canadians and the French, that are worn directly over the skin or, at most, over underpants and shirt, eliminating the usual utility uniform worn under an NBC protective uniform. In a similar program, Levine and colleagues[7] described one of a series of tests to evaluate chemical protective undergarments designed in the United States.

Such developments undoubtedly will find their way into the design of an integrated protective ensemble, which might offer modular clothing and equipment systems for combat ground troops. Cadarette and colleagues[184] evaluated the first components of such a system and published the associated physiological data. The four branches of the US military presently collaborate on a Joint Service Lightweight Integrated Suit (JSLIST) technology program to produce lighter and less-bulky protective uniforms.[185] Using recent improvements in carbon absorber technology, the Australians claimed that their CB suit, developed to provide protection against liquid and vapor chemical agents, significantly reduced heat strain in tropical environments.[9]

Individual Cooling Systems

Military laboratories in the United States have experimented with varied personal microclimate cooling systems worn under the NBC protective uniform.[186] Banta and Braun[187] used ice vests in high-heat environments to reduce heat strain of helicopter pilots based on US Navy carriers. Ice cooling is generally less effective than air or liquid cooling. Although the wearer can move about without being tethered, ice cooling necessitates repeated access to ice, so it may be suitable only for short-term work.[188]

More frequently, liquid-cooled or air-cooled vests are worn under NBC protective uniforms.[186,189–193] Both systems have benefits and limitations. Air cooling can increase tolerance time 4-fold, whereas circulation of hot ambient air provides little cooling and may be dangerous. Air cooling is less efficient, however, than liquid cooling, because the specific heat of air is lower. Liquid cooling is more effective in reducing heat strain at light-to-moderate work loads when applied on large body surfaces (eg, on the thighs during lower-body exercise). However, if overcooling results, discomfort may occur due to cutaneous vasoconstriction. Also, liquid-cooled systems are heavy and require excessive maintenance, and the flow of coolant can be interrupted if the tubes are pinched or bent.

Temperature-conditioning technologies that use liquid- or air-cooled systems are especially promising for use by crews in armored vehicles, helicopters, or airplanes with access to suitable power sources. Cadarette and colleagues[194] demonstrated the utility of air-cooled microclimate vests and ventilated facepieces for armor personnel in desert and tropic environments; Thornton and colleagues[195,196] explored the use of liquid- and air-cooled microclimate cooling systems for helicopter pilots; and, for the ground soldier, Masadi, Kinney, and Blackwell[191] evaluated liquid-cooled vests in which the coolant was chilled by ice packs carried on the back. These investigators found that batteries for electric-powered, portable air-conditioning systems added too much weight to an infantryman's backpack. Also, although such self-contained systems provide substantial body cooling, the reduction in heat is not adequate under highly stressful conditions.[184,197]

It may be necessary to select the best cooling system for crew-served vehicles and other situations on a case-by-case basis. For ground-based and other personnel who do not have access to a power source, much more design work needs to be done on portable cooling systems, including lightweight batteries or alternate sources of power for microclimate cooling systems that are carried by the soldier on his back.[20] Improving cooling systems will increase comfort, allowing soldiers to perform more efficiently for longer durations in toxic chemical environments.

Adopting More Than One Type of NBC Protective Uniform

US military forces and others train for deployment to combat theaters anywhere in the world. These theaters vary dramatically in terms of their climatic conditions, the enemy to be engaged, the type of military operation, and the tasks performed by the soldier. Reardon and colleagues[198,199] evaluated 14 US Army aviators in a UH-60 simulator and compared their flight performances, physiological parameters, and moods, for two different flight uniforms (standard aviator uniform or NBC protective uniform, MOPP 4, with aviation life-support equipment vest and the laminated ballistic plate) and two environmental conditions (21°C, 50% relative humidity [rh]; or 38°C, 50% rh). Personnel who wore NBC protective clothing and associated flight equipment in a hot cockpit showed decreased flight performance, increased physiological parameters (heart rate, core body temperature, and dehydration), and heightened symptoms of heat stress (nausea, dizziness, headache, and thirst). These two studies suggest that helicopter pilots do not tolerate high ambient temperatures in the cockpit well when they must also wear NBC protective uniforms during flight.

Caldwell[200] surveyed 148 Army personnel after the Desert Storm phase of the Persian Gulf War (1991) to describe wear compatibility and logistical problems associated with NBC protective uniforms during desert combat. Helicopter pilots frequently commented that NBC protective uniforms were incompatible with night-vision goggles or with head-up displays (8%), were bulky or heavy (6%), were unavailable in the quantities required or that the expected usefulness was exceeded (5%), presented mask-related problems (4%); and that the NBC protective overboots were incompatible with flying (4%). From this survey, it is evident that NBC protective uniforms were somewhat incompatible with both the mission and the special equipment associated with flying a helicopter. No doubt similar stories could be told by armor, mechanized infantry forces, and others.

The many constraints that NBC protective uniforms impose seem in part attributable to a logistical scheme of providing a single, standardized design: NBC protective uniforms with thick layers of protective materials.[20,145] This strategy provides maximum personal protection to all combatants. US military field tests of NBC protective uniforms (eg, P^2NBC^2 in the mid to late 1980s) often set goals for participants to wear NBC protective uniforms for 3 days or more at the MOPP 4 level.[20,165] Such testing told much about what soldiers can and cannot do in studies of endurance. In future conflicts, it is unlikely that our forces will be wearing the maximal protection NBC protective uniform (MOPP 4) for several days at a time. Given the enormous distances covered in an open desert by today's fast-moving armor and air forces (eg, the 100-hour war of Desert Storm), it is also unlikely that any military force could keep an open battlefield continuously bathed in CB agents long enough to prohibit vehicle-mounted forces from navigating their way out of danger.[20]

Perhaps, therefore, the military supply system should provide multiple NBC protective uniforms, including lighter-weight clothing, which might provide less absolute protection but allow greater personal mobility for fast movement on a fluid battlefield. If multiple NBC protective uniforms were adopted, that decision might permit better optimization of the characteristics of an NBC protective uniform to the military mission (environment and threat), and better matching of NBC protective uniforms with the soldier and the tasks that he or she performs (eg, US Army Rangers or Light Infantry on a ground reconnaissance mission vs a driver in a vehicle or a pilot in a high-performance aircraft). Although the strategy of having several sets of NBC protective uniforms will increase developmental costs, inventory requirements, and distribution efforts for the military, the US military already issues numerous other uniforms and clothing systems and issues several different versions of the CB mask for infantry, aviators, and tankers.[20,145] It seems to make sense in the case of NBC protective uniforms as well.

Adaptive Doctrine for Lowest Feasible Protective Posture

Military doctrine should support training and fighting whenever possible at the lowest safe MOPP level so that adverse effects of NBC protective uniforms can be minimized. Because not all enemies have the same chemical capabilities, tactical situations determine the likelihood that specific chemicals will be used; environmental conditions influence chemical agent effectiveness; and differing mission requirements dictate how much NBC protective uniforms will compromise soldier performance.[20,145] In any event, the employment of NBC protective uniforms in combat is a calculated risk, matching the level of personal protection from NBC warfare agents against adverse effects of the uniform on soldier health, performance, and psychological well-being.

The greatest performance-limiting factor of NBC protective uniforms is excessive buildup of metabolic heat during work in hot environments. If more training with lower protective postures (eg, MOPP 1, 2, and 3) is to occur, military doctrine must guide and specify conditions under which training is appropriate. It should also establish how decisions are to be made with regard to changes toward more- or less-restrictive protective postures in training and in combat. The decision logic must be communicated so forces involved understand the ground rules at both the centralized command level and the unit level, where local protective conditions might differ from those of other units. These concepts should be practiced so troops learn to operate confidently and comfortably in training, and in combat situations, at lower levels of protective posture.[20,145]

SUMMARY

NBC warfare protective uniforms encapsulate the wearer, producing a barrier to the ambient environment and simultaneously creating a microenvironment within the uniform. Protective uniforms may impair essential human functions. The energy cost of performing tasks, particularly tasks requiring mobility, is increased when wearing an NBC protective uniform. The higher metabolic rate is associated with both the added weight of the protective uniform and the friction produced by the multiple layers of garments. Furthermore, the bulky NBC protective uniform limits the range of motion around body joints and reduces manual dexterity, thus increasing the difficulty and accuracy of relatively simple tasks. These impediments can be reduced by wearing the fewest layers of clothing possible and fitting service members with properly sized NBC overgarments, boots, and gloves.

Heat stress is a major limitation to work performance and tolerance in NBC uniforms. NBC protective uniforms have high insulating and low moisture-permeability properties. Heat stress, and subsequently heat illness, in NBC protective uniforms can be decreased by (1) reducing the barrier by wearing the lowest MOPP level appropriate to the NBC threat, (2) decreasing metabolic heat production, or (3) cooling the service member by mechanical means. Because metabolic heat production is the main source of thermal stress in NBC uniforms, reducing it is the most effective way to reduce heat illness in protective uniforms. The use of work/rest cycles will increase tolerance times and decrease heat casualties but will also increase the time required to perform tasks.

Protective uniforms impede breathing by adding three external loads to the respiratory system: (1) flow-dependent resistive loads, (2) dead space, and (3) volume-dependent elastic loads. The CB mask opposes breathing by applying a nonlinear, phasic, flow-resistive load, which decreases maximal breathing capacity while simultaneously increasing the work of breathing. The increased intrathoracic forces generated to breathe against the CB mask heighten the perception of adverse respiratory sensations (eg, breathlessness). The added external dead space of the CB mask increases ventilatory effort and the work of breathing. The NBC uniform overgarments, load-carriage equipment, and body armor produce an external constraint on the chest wall separate from that imposed by the CB mask. These factors interact to impair breathing and consequently the performance of military operations. Respiratory problems can be managed by using moderate work rates and by frequent training in the CB mask to become familiar with the respiratory sensations associated with it.

The NBC protective uniform also reduces sensory capabilities and impairs bodily functions. Gloves impair tactile sensations. The CB mask and hood restrict the visual field, impair hearing, distort speech, and eliminate olfactory clues. NBC protective uniforms make eating, drinking, eliminating body wastes, and sleeping difficult. Through-the-mask tube drinking systems are commonplace but time-consuming to use, and the possible risk of contamination may deter service members from drinking as frequently as they should. Elimination of body wastes while wearing the NBC protective uniform is cumbersome at best. These functions are easier if performed in in a collective shelter. It is difficult to sleep comfortably while wearing a CB mask; in protective clothing, personnel require more time to fall asleep and once asleep are more likely to awaken spontaneously.

In combat with CB weapons, many more casualties with psychological stress than actual CB injuries are likely. This prediction reflects the adverse impact of fears and anxieties that troops experience in dealing with the threat of a CB contaminated battlefield. Maladaptive responses include hyperventilation, claustrophobia, gas-mask phobia, and compulsive practices or obsessive concern with decontamination, congregating in safe or collective protection areas, finding excuses to never come out or let others into a safe space, and hoarding or stealing protective items. Psychological denial, fatalism, rationalization, and intellectualization may also occur; all prevent troops from taking adaptive actions or enacting useful countermeasures. These responses are more common in younger and less-experienced soldiers than in older ones. Because many soldiers lack detailed familiarity with CB weapons, it is essential that they understand that the NBC protective uniforms issued to them will protect against chemicals on the battlefield. This will do much to reduce fear, anxiety, and adverse reactions to NBC protective uniform. Many field experiments have demonstrated that most standard military tasks can be performed satisfactorily in NBC protective uniforms, but extra time is required to perform them. Adaptation and gradual experience with NBC protective uniforms and equipment is usually helpful. Younger, less-experienced soldiers are more impaired by NBC protective uniforms than are older soldiers. Older military personnel exhibit fewer symptoms and appear less anxious about training in NBC protective uniforms.

Because personnel in military units turn over frequently, all troops should train frequently in their NBC protective uniforms on common military tasks and, as well, in larger-scale team scenarios in which they practice working together. Intensive training to do critical tasks in NBC protective uniforms can promote confidence, reduce adverse emotions, and better prepare all forces to fight successfully on a contaminated battlefield.

Future doctrine, advances in protective uniforms, and training should strive to develop new ways to reduce the limitations of NBC protective uniforms so that troops can function effectively on future NBC-contaminated battlefields.

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