Challenges of infectious pathogens in Military Operational Context

Enjeux des pathogènes infectieux dans les Contextes Opérationnels Militaires

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Abstract

Military collectivities are commonly exposed to infectious pathogens that affect their operational readiness. This review presented the most common health hazards occurring within armed forces during field operations, including FoodBorne (FB), waterborne (WB), AirBorne (AB) and VectorBorne (VB) pathogens. The main FB poisoning pathogens recorded are toxinogenic bacteria and viruses with acute gastrointestinal illnesses. Rickettsiae of the Typhus or the Spotted Fever Group, Bartonella, are the major VB diseases affecting armies along history. Many other environmental pathogens are responsible for huge medical and economic impacts on troops including Coronavirus, Chlamydia and Legionella. These pathogens lead to serious hospitalizations and deaths compared to traditional weapons. They infected not only troops, civilian populations, and peacekeepers, but also the local fauna found within the battlefield regrouping water, soil, and arthropod vectors.

Experienced outbreaks during contemporary military operations, peacekeeping and stabilization missions, and field exercises allowed a lot of lessons learned that must be highly considered for implementing future control strategies. This may be useful to guarantee the operational readiness of troops within military units and tactical deployment.

Keywords: Infections; Food; water; vector; pathogens; military operations.

Résumé

Les collectivités militaires sont exposées à plusieurs agents pathogènes qui entravent leurs capacités opérationnelles. Cette revue présente les risques sanitaires impactant les troupes lors des operations, notamment ceux d'origine alimentaire, hydrique, aérienne, et vectorielle. Les principaux agents sont les bactéries toxinogènes et les virus responsables de infections gastro-intestinales aiguës. Les maladies vectorielles comme les rickettsioses du groupe typhique ou des fièvres boutonneuses, les bartonelloses, et les arboviroses sont parmi les infections les plus graves touchant les troupes. Les pathogènes à transmission aérienne comme le coronavirus, les chlamydies et les legionelles sont responsables des pertes économiques et médicales considérables. Comparés aux armes traditionnelles, ces agents entraînent de plus en plus d'hospitalisations et de décès parce qu'elles affectent non seulement les troupes et les populations civiles, mais aussi la faune locale, l'eau, le sol et les arthropodes vecteurs.

Les expériences vécues par les armées lors des opérations militaires contemporaines, des missions de maintien de la paix et des exercices de terrain ont permis de planifier des stratégies de lutte et de prévention permettant au commandement de garder les capacités opérationnelles des troupes dans les unités militaires et lors des opérations extérieurs.

Mots clés : Infections, Aliments, Eaux, Vecteur, Pathogènes, Opérations militaires.

Introduction

During history, warfare was closely related to the emergence of devastating diseases that have often decimated military forces and civilian populations alike. Over the centuries, precarious battlefield conditions, poor hygiene and the continuous mobility of troops camping allowed the spread of these diseases (1). Armies were confronted to various epidemics of zoonotic diseases such as the plague of Athens during the Peloponnesian War, the smallpox and typhoid fever, which weakened the Roman legions during their military campaigns (2). During medieval wars, the bubonic plague (Black Death) was rapidly disseminated among soldiers, wreaking havoc on troops and civilians (3).

With the great explorations and colonial expansion, new diseases emerged. Sailors on ships of the time suffered from diseases such as scurvy, typhus and infections linked to precarious living conditions at sea (4). Deployed army and native populations in colonized regions were often decimated by diseases to which they had no immunity, such as various influenzavirus and coronavirus serotypes (5).

During the First and the Second World Wars, overcrowded trenches, poor hygiene conditions in military camps initiate the emergence and rapid spread of the trench fever caused by Bartonella quintana, which claimed millions of victims (6). Soldiers engaged in tropical theaters of war were confronted to serious infectious diseases such as malaria, dengue fever, yellow fever, that are prevalent vector borne diseases in these regions (7).

As a matter of fact, modern conflicts have been marked by the continuous outbreak of old pathogens and the emergence of other biothreats including new viral serotypes, multidrug resistant bacteria, Fungi, and toxins (8, 9). Throughout history, wars and infectious diseases have been uneasy bedfellows and these pathogens have not only determined the outcome of conflicts but have actually been developed with novel technologies, industrialized and used as intentional biological weapons of wars. The first records of such actions dating back as far as 1500 BC when victims of plague were driven into enemy lines (10). Numerous well-documented records indicated the huge medical impact of diseases in wars. Indeed, during the

Peninsular Wars, Southern Europe (1808-1815), deaths associated to diseases were estimated to 70% compared to only 30% of death caused by battle injuries (11).

The present review presents the main infections-types recognized according to One Health concept in relation with troops activities; the Food/water-Borne, Air-Borne and Vector-Borne diseases. Lessons learned throughout history have led to improvements in sanitary measures, vaccination and infection control programs to ensure better preparedness of armies.

Food–borne pathogens in military context

Foodborne microbial pathogens are increasingly responsible for serious illnesses, known also as 'collective food poisoning' or FoodBorne Illnesses (FBI). Pathogenic microorganisms in foods, can lead to more severe course of the disease, hospitalization and even death among sensible populations (12). Today, more than 200 diseases-causing agents are transmitted to humans through animal-based foods, water, and/or raw vegetables (9). Various bacterial strains are incriminated in FBI and constitute the main cause of its emergence. Hidden virus and parasites in food products constitute, alike, a new serious challenge for microbiological food analysis (12).

In military units, personnel are highly exposed to food poisoning risk, which is one of the most occupational incidents related to microbiological food quality that determines the operational readiness of armies (13). Even in developed countries, troops constitute a susceptible collectivity due to the long-term deployment, mobility, exertion, stress of operations, shortage of water, lack of good sanitation, and lack of food quality control, which confer the specificity of military contexts (13). Military combatants are, accidently or intentionally, exposed not only to the pathogenic bacterial strains hidden in foods or water but mainly to the produced toxins and enzymes which are determining for the observed issues and the clinical evolution of infections (9). In this review, only microbiological agents affecting military units are investigated. the aggregated data summarized in table 1 constitutes a review of the literature on cases of FBI reported in military establishments worldwide. it is in fact important to point out that it is not exhaustive because many cases were either not diagnosed or unreported, particularly in developing countries. for this reason, the issue of FBI still underestimated (14).

As far as dangerous, FBI are caused by a broad spectrum of viruses, bacteria, and parasites with different levels of pathogenicity. Different clinical signs may be observed according to pathogenic mechanism of causing pathogens (Table 1). Norovirus, non-typhoidal Salmonella, toxinogenic strains of Escherichia coli, Bacillus cereus, positive-coagulase Staphylococcus, and Campylobacter spp. caused the highest number of hospitalizations and deaths among American military units (15). However, many other virus and bacteria are recognized as relatively occasional but serious foodborne pathogens as Shigella spp., Yersinia spp., Enterococcus spp., and Astrovirus. Botulinum toxin, staphylococcal enterotoxins, Clostridium perfringens toxins are listed as the main bacterial toxins that may not only triggers FBI but also be, potentially used as bioweapons (16). Despite the shortage of data worldwide, diarrheal diseases related to contaminated food kills yearly 1.9 million people due to acute poisoning or long-term diseases (17). After combining the estimates for the major known pathogens and the unspecified agents, the overall annual estimate of the FBI total burden in the United States is 47.8 million illnesses, 127,839 hospitalizations, and 3,037 deaths (13). This affects troops readiness and, therefore, they will not support hard and long-term missions. Food Borne Infections are initiated and triggered by several risk factors that

facilitate the contamination of primary materials and ensure not only the multiplication of pathogens but also induce toxinogenesis and release toxins. These factors are represented by the initial microbiological charge in food, non-compliance with hygienic standards in preparing, transport and distribution of meals and water managements (18).

Water–borne pathogens in operational contexts

Water-borne pathogens represent a critical challenge in military setting, with implications that span health, and operational readiness of armed forces. Historically, contaminated water sources were a major vector for diseases, posing significant threats to troops deployed in various environments. The global nature of military deployments means that forces often operate in regions with varying water quality standards, increasing their vulnerability to water-borne infections such as cholera, typhoid fever, and dysentery. These diseases, caused by bacteria, viruses, or parasites, can incapacitate large numbers of personnel, thereby compromising the operational effectiveness of troops.

The impact of water-borne pathogens is well-documented in history. For example, during the Battle of Valmy in September 1792, the Austro-Prussian troops suffered from a severe epidemic of dysentery, which significantly impacted their effectiveness. This outbreak's debilitating effects leading to an unexpected victory for the French army and signaling a turning point in the revolutionary wars. This incident underscores how diseases can be a decisive factor in warfare (14).

In addition, during the Crimean War, poor sanitation and inadequate water treatment led to the outbreaks of water-related illnesses, significantly affecting troop morale and combat capability. In World War II, American and allied forces stationed in the Pacific theater faced severe challenges due to water-borne diseases like leptospirosis and amoebiasis, which spread through untreated water and compromised supplies.

The most frequently identified causative agents of gastrointestinal infections include enterotoxigenic Escherichia coli (ETEC), typhoid fever, Shigella species, hepatitis A virus, Caliciviridae (Norwalk virus), Entamoeba histolytica, and Giardia intestinalis. Acute gastroenteritis, commonly referred to as "traveller's diarrhoea," is a significant health concern for individuals traveling abroad, affecting up to 60% of all travelers (19).

Military personnel deployed to combat zones are highly susceptible to gastroenteritis that is particularly prevalent in this group. Studies have shown that despite the implementation of strict sanitary protocols and continuous oversight by military health services during operations in Iraq and Afghanistan, the majority of soldiers deployed to these regions experience episodes of diarrhoea. Furthermore, in over 50% of affected individuals, symptoms recur multiple times during their deployment (19).

In modern military contexts, the importance of addressing water-borne pathogens remains paramount. Troops are often deployed in austere environments where access to safe drinking water is limited. Advanced water purification systems and stringent hygiene protocols are critical for preventing outbreaks. However, despite technological advancements, the risk persists, particularly in regions affected by natural disasters or conflict where water infrastructure is compromised.

Lessons from history underscore the necessity of vigilance and preparedness. By understanding the global prevalence of water-borne diseases and their potential impact, military planners can develop strategies to mitigate risks, ensuring that troops remain healthy and operationally effective. Addressing this issue is not only a matter of protecting individual soldiers but also a fundamental aspect of sustaining military capabilities in challenging environments.

Vector–borne pathogens in military settings

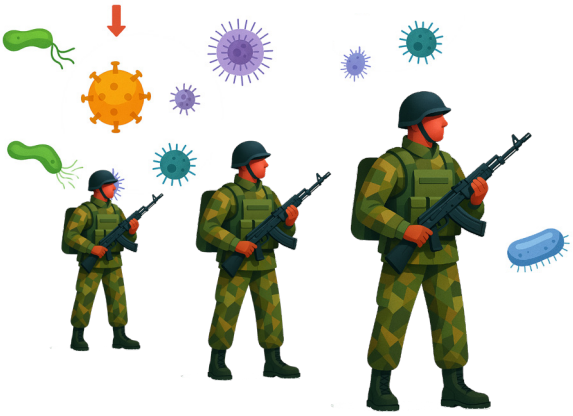
Vector-borne diseases have severely reduced the operational capacity of armies and caused suspension or cancellation of several military operations. Since World War I, VBD have no longer been the major causes of morbidity and mortality among soldiers (20). However, most recent conflicts involving

TABLE 1. The main food borne illness outbreaks recorded among military units worldwide.

Country	Deployment Army	Pathogens identified	Observed clinical signs	Estimated number of FBI	Food/water source	Ref.
USA	Military base	*Campylobacter jejuni*	Acute Gastrointestinal illness :	3650	NI	13
USA	Recruit barracks Reserve Officer Training Corps Cadet barracks	*Campylobacter jejuni* serotype 5	Loose stool, abdominal pain, diarrhoea	249	Water	63
USA	Military base	*Shigella* spp	Diarrhoea,	350	NI	13
USA	Military base	STEC non-O157	Diarrhoea	150	NI	13
San Diego -California	Marine corps	STEC	Headache, fever, diarrhea, vomiting	244	Bœuf meat	64
Saudi Arabia	US Air Force	*Escherichia coli*	Diarrhea	648	Catered meal	65
Greece	Air Force base	Staphylococcus aureus	- Abdominal pain - Nausea, vomiting	600	Raw beef Grated cheese	66
India	Military base	CP Staphylococci	Abdominal pain - Nausea, vomiting, fever	94	Raita	67
China	Military hospital	*Staphylococcus aureus*	- Nausea, vomiting	185	Bread, Oat milk	68
USA	Military unit	Staphylococcal enterotoxin A	Nausea, vomiting, diarrhea	13	chicken, sausage, rice dish	69
Norway	Military base	*Yersinia enterocolitica* (YE) O9	Diarrhea, headache, dehydratation	133	Mixed salad	70
Singapore	Military camp	Non-typhoidal Salmonella grp E	Diarrhea, headache, dehydratation	94	Mashed potato	71
USA	Military base	Non-typhoidal Salmonella enterica	Diarrhea, headache, dehydratation	2500	NI	13
Himalaya	Deployed unit	*Salmonella enterica*	Diarrhea, headache, deshydratation	78	Frozen fowl	72
Philippines	Clark Air base	Not determined	Diarrhea, dehydratation	5.000	Water	73
Inde	Military mess	Not determined	Diarrhea, dehydratation	391	Chicken	74
French	Military recruit	*Astrovirus* serotype 3	Abdominal pain, diarrhea	16	NI	75
USA	Non deployed	*Norovirus*	Abdominal pain, Nausea diarrhea, Vomiting	159	Fresh salade	76
French	Parachuting unit	*Norovirus* (genotype I)	Abdominal pain, Nausea diarrhea, Vomiting	147	Pasta, Raw vegetables	77
Central African Republic	French armed forces	*Norovirus* (genotype II)	Abdominal pain, diarrhea Nausea, vomiting	83	Pasta, Raw vegetables	78
USA	Military base	*Norovirus*	Abdominal pain, diarrhea Nausea, vomiting	38600	NI	13
Germany	Military base	*Norovirus* subtype II.4 2006b	Abdominal pain, diarrhea Nausea, vomiting	101	salad	79
Portugal	Army base	*Norovirus* GI.9	Abdominal pain, diarrhea Nausea, vomiting	46	Water, salad	80
Singapore	Military camp	*Norovirus*	Abdominal pain, diarrhea Nausea, vomiting	24	Food handlers	81
French	Military unit	Histamin	Allergic reactions : Rash, headache, nausea, Vomting, diarrhoea, Hypotension, flushing	40	Cooked yellow fin tuna fillet	82
Senegal	French Armed Forces	Histamin		78	Yellow fin tuna	83
Vietnam	US military unit	Histamin		51	Yellow fin tuna	84
Lisbon	Army base	*Norovirus* GII.P16-GII.4 Sydney	Abdominal pain, diarrhea Nausea, vomiting	31	Water, salad	85

Abbreviations: FBI : Food-Born Illness ; NI : Non Indicated ; STEC :Shigatoxinogen Escherichia coli ; CP : Coagulase positive.

Arthropod borne Diseases



Air borne Diseases

Food borne infections

Western armies have occurred overseas, exposing soldiers and the displaced populations to a serious risk of arthropod-borne diseases. Arthropod vectors and associated diseases have expanded geographically during the last century and the situation has changed within military units according to climate conditions and efficient disease control procedures (21). Researchers suggested that some diseases, such as the plague, yellow fever, and epidemic typhus, no longer hold military significance, while new other potential threats have appeared with the reemergence of associated specific vector, including West Nile encephalitis and chikungunya fever (22). For this reason, vector control and personal protection measures are the major requirements in ensuring the operational readiness of troops (19). Scientific progress has allowed a reduction in the impact of arthropod-borne diseases on military forces, but the threat is already present, and a failure in the context of vector control or in the application of personal protection measures could allow these diseases to have the same devastating impact on human health and military readiness as they did in the past (20). Almost of these pathogens are originated from animals, and showed a very high important pathogenicity within humans (23). In endemic regions, deployed armies are severely exposed to arthropod vectors particularly ticks, mosquitoes, fleas and lices that could transmit various pathogens (21).

Several viruses as Nairovirus, Phlebovirus, and other Flavivirus (West Nile disease) garded their potential pathogenicity for long years. Regarding bacteria, Rickettsia and Bartonella showed the highest genetic diversity during history associated to severe clinical infections within military units. These infectious diseases pose a particular challenges for medical officers. Rickettsial Mediterranean Spotted Fever (R. conorii and related species), epidemic thyphus (Rickettsia prowazekii) and other VB infections are commonly associated to bad sanitary conditions, arthropod activity and are already misdiagnosed. Various arthropod vectors are implicated in the transmission of Rickettisae as ticks, human body louse (Pediculus humanus corporis), fleas and bed bugs (Cimex lectularius) that may infest military logistic settings. This could explain the increase of the incidence of Rickettsia infections in relation with field operations and constitute, therefore, a serious threat for soldiers training in endemic zones (Table 2) (24).

Next to virus and bacteria, serious outbreaks caused by parasites, like Leischmania, were experienced within armed forces worldwide (25). Internal parasitic infections as echinococcosis, cycticercosis, schistosomiasis, amebiasis and strongyloidiasis may evolve among troops with too high incidence rates that could impact their operational readiness (26) (Table 2).

Environmental pathogens in military contexts

Airborne diseases are caused by pathogenic microorganisms that can be discharged and transmitted from an infected person via coughing, sneezing, laughing and close personal contact or aerosolization of the pathogen. These tiny particles can linger in the atmosphere and lead collectively, to serious respiratory diseases which may significantly impact troops wellbeing and operational readiness increased medical burden, and strained logistic resources (27). This is the case of crowded and confined military environments, such as barracks, trenches, training facilities, and deployed camping areas (28). Mitigating these risks through proper hygiene practices, well-designed ventilation systems, and vaccination is crucial to maintaining the overall health and operational capabilities of military forces (29).

Certainly, there have been instances of airborne pathogens affecting military troops throughout history; the outbreak of the H1N1 influenza virus, also known as the "Spanish flu," during World War I which is highly contagious and able to spread rapidly among crowded military camps and trenches (30,31). Additionally, the severe acute respiratory syndrome (SARS)

TABLE 2. The main Vector-Borne and Air-Borne diseases outbreaks recorded among military units worldwide.

Country	Deployed Army	Period	Pathogens incriminated	Diagnosed diseases	Estimated number of VBI cases	Potential Vectors	Ref.
French Guiana	Military unit training in the rainforest	2020	Leishmania guyanensis	Cutaneous leishmaniasis	30	Phlebotomus spp.	25
Iraq, Iran	USA forces	1943-1944	Leishmania infuntum	Cutaneous ulcere	1000	Phlebotomus spp.	86 87
Saudi Arabia	Desert Storm operation, USA	1990-1991	Leishmania major	Cutaneous leishmaniasis	20	Phlebotomus spp.	86 87
Kuwait	Desert Storm operation, USA	1990-1991	Leishmania tropica	Viscerotropic form	12	Phlebotomus spp.	86 87
Kuwait, Iraq, Afganistan	USA forces	2002-2003	Leishmania major	Cutaneous leishmaniasis	827	Phlebotomus spp.	7, 88, 89
Kuwait, Iraq, Afgainstan	USA forces	2002-2003	Leishmania tropica Leishmania donovani	Viscerotropic form	5	Phlebotomus spp..	7, 88, 89
Iraq	USA forces	2004	Leishmania sp.	Cutaneous leishmaniasis	2	Phlebotomus spp.	90
Amazon Basin	Peruvian Army	2010	Leishmania braziliensis Leishmania guyanensis	Cutaneous leishmaniasis	76	Phlebotomus spp.	91
Belize	Dutch Armed Forces	1998	Leishmania braziliensis Leishmania mexicana	Cutaneous leishmaniasis	25	Phlebotomus spp.	92
Belize	Dutch Armed Forces	2004	Leishmania braziliensis Leishmania mexicana	Cutaneous leishmaniasis	14	Phlebotomus spp.	92
Walcheren Expedition	British troop	1809	Plasmodium falciparum	Malaria	10000	Infected mosquito	20, 93
WWI	Alied and axis military forces	1914	Plasmodium falciparum	Malaria	1.5 million	Infected mosquito	94
Contingency operations	US forces	2021	Plasmodium falciparum	Malaria	21	Infected mosquito	95
Contingency operations	US forces	2021	Plasmodium vivax	Malaria	5	Infected mosquito	95
Afghanistan	US Army troops	2011	Rhabdovirus	Rabies	1	Dog bite	96
WWII	US Army	1945	Flavivirus	Dengue fever	90000	Infected mosquito	97
Reunion Island	French Army	2005-2006	Alphavirus	Chikungunya fever	269 000	Infected mosquito	98
Chad	French troops	2001	Phlebovirus	Rift Valley Fever	50	Infected mosquito	99
Afghanistan	Civilian poepole	2008	Nairovirus	CCHF	23	Infected ticks	100
Afghanistan	US soldier	2008	Nairovirus	CCHF	1	Infected ticks	101
Kosovo	NATO troops	1996-2000	Nairovirus	CCHF	162	Infected ticks	102, 103
Vilnius, Lithuania	Napoleon's Grand Army	1813	Bartonella quintana	Trench fever	7	Infected lice	104
WWI	British troops	1915	Bartonella quintana	Trench fever	>1million	Infected lice	6
Germany	British Forces	2002-2003	*Borrelia* spp.	Lyme disease	4	Infected ticks	105
Northern Sri Lanka	Military force	2011	*Rickettsia* spp.	MSFR	33	NI	106
WWII	US military unit	1945	Rickettsia typhi	Endemic typhus	786	Infected ticks	107
Saigon arsena	French Army	1945	Rickettsia typhi	Murine typhus	9	Infected fleas	108

Country	Deployed Army	Period	Pathogens incriminated	Diagnosed diseases	Estimated number of VBI cases	Potential Vectors	Ref.
Arkansas	US military unit	1989	Rickettsia rickettsii	RMSF ; MSFR	15	Infecetd ticks	109
Vilnius, Lithuania	Napoleon's Grand Army	1813	Rickettsia prowazekii	Epidemic typhus	3	Infected lice	104
Botswana	US military unit	1989	Rickettsia africae	African tick bite fever	51	Infected ticks	110
Botswana	USA forces	1992	Rickettsia africae Rickettsia conorii	MSFR	38	Infected ticks	111
Northern Sri Lanka	Local military force	2011	Orientia tsutsugamushi	Scrub typhus	1	NI	106
WWII	Allied forces Japanese forces	1945	Orientia tsutsugamushi	Scrub typhus	18000-20000	Infected mites	107
Indochina war	French Army	1977	Orientia tsutsugamushi	Scrub typhus	6536	Infected mites	112
Battalion aid station	US Marines	1981-1983	Orientia tsutsugamushi	Scrub typhus	65	Infected mites	113
Camp Fuji	US Marines training	2001	Orientia tsutsugamushi	Scrub typhus	8	Infected mites	114
New Jersey	Army reserve unit	1989	Ehrlichia canis	Ehrlichiosis	9	Infected ticks	93
Virginia	US military unit	1989	Ehrlichia canis	Ehrlichiosis	2	Infected ticks	109
Dakar	Local population	1945	Yersinia pestis	Plague	1005	Infected fleas	115
Vietnam	US troops	2004	Yersinia pestis	Plague	5	Infected fleas	116
USA	Military base	2010	Legionella pneumophila	Legionnaires' disease.	29	Contaminated air	35
USA	Military base	2010	Legionella pneumophila	Pontiac fever	38	cooling tower	35
San Diego	Marine Corps Recruit Depot	2004	Legionella p neumophila	Pneumonia	5	Contaminated air (cooling air)	117
Iran	Tehran	2010	Legionella pneumophila	Pneumonia	56	Air conditioning system	118
Finland	Military trainees	1987	Chlamydia pneumoniae	Acute Pneumonia	43	Contaminated air	119
Iraq	US troops	2003	Coxiella burnetii	Q fever, Pneumoniae	19	Contaminated air	120
Iraq	US troops	2003	Coxiella burnetii	Q fever, Pneumoniae	2	Contaminated air	121
Brazil	Military Firefighters Academy	2016	Coxiella burnetii	Q fever, Pneumoniae	5	Contaminated air	122
Bosnia	UN Stabilization Force	1997	Coxiella burnetii	Q fever, Pneumoniae	26	Contaminated air	123
WWI	US soldiers	1918	Influenzavirus	Pandemic influenza	32.000	Contaminated air	30
WWI	French soldiers	1918	Influenzavirus	Pandemic influenza	28.000	Contaminated air	30
USA	US Army	2019-2022	Coronavirus	COVID-19	453.456	Contaminated air	124
Burundi	N'Gozi prison	1993	Rickettsia prowazekii	Epidemic typhus	76	Infected louse	125

Abbreviations: CCHF: Crimean-Congo Hemorrhagic Fever; MSFR: Mediterranean Spotted Fever Rickettsiosis; RMSF: Rocky Mountain Spotted Fever; NI: Not Indicated, USA: United States of America; WWI: World War I; WWII: World War II.

Coronavirus and the Covid-19 pandemic has emerged within military personnel stationed in war areas (32, 33). In recent times, military forces worldwide had implemented strict measures to prevent the spread of these pathogens among their ranks, including quarantine procedures, testing protocols, and adjustments to training and deployment activities (34).

Furthermore, Legionella is one of the most dangerous airborne bacteria that affect collectivities including military personnel. It is responsible for a severe respiratory illness known as Legionnaires disease or Pontiac fever. Serious outbreak of legionella infection had occurred in the United States at the U.S. Army's Fort Bragg in 2018 with serious clinical cases requiring hospitalizations (35). Studies investigating epidemiological risk factors revealed that infection was related to the water distribution systems and to the air conditioner tower (35,36) (Table 2). The incident highlighted the need for thorough monitoring and maintenance of water systems in military installations to prevent the growth and spread of Legionella bacteria and to ensure the troops wellbeing.

These outbreaks underscore the importance of maintaining proper hygiene and safety measures in military facilities to prevent the spread of airborne pathogens. Proper maintenance of water systems, regular testing, and swift responses to potential outbreaks are essential to protect the health of military personnel.

Pathogens used as biological weapons

During history, pathogens showed serious deadly potential for development and application in wars due to their virulence, human and/or animal specific tropism, and the wide spread among susceptible populations. Efficient biological weapons might be an existing infectious agent or new strain of an existing pathogen leading to an unexpected large outbreak (37). For example, the extremely virulent Ebola virus caused up to 90% of death if left untreated (38).

Weaponized pathogens could be used as devastating agents for biological warfare as done by the German and Russian armies during the first world war (39). Experienced conflicts between 1904 and 1921, proved that these new arms contributed to more deaths in Russian military forces than did traditional weapons. In this context, the Geneva Protocol was established in 1925 and aimed at prohibiting the use of all commonly known biological weapons during conflicts (40, 41).

Original operations were adopted using both anthrax and glanders agents to infect livestock through contaminating animal feed of their enemy countries (42). After the war, with no lasting peace established, various European countries tried to develop their own biological warfare programs by laboratories and open-air testing sites, long before the onset of the Second World War (10, 43, 44).

Pathogens considered for weaponization are numerous and include bacteria such as Bacillus anthracis, Brucella spp., Burkholderia mallei, Burkholderia pseudomallei, Chlamydia psittaci, Coxiella burnetii, Francisella tularensis, Rickettsia of the Typhus or the Spotted Fever Rickettsiae Group, and Yersinia pestis (45, 46). Besides, many viral agents have been investigated and/or weaponized, including the Bunyaviridae family (as the Rift Valley fever phlebovirus), Flaviviridae, Ebolavirus, Coronavirus, Marburg virus, and Variola virus. In addition, fungal agents have been also studied, including amoebas and mycotoxins (8, 46, 47).

In the realm of Soviet warfare, the program achieved notable successes. Notably, it engineered bacteria strains resistant to various antibiotics and modified Bacillus anthracis to nullify existing vaccines (8). Particularly concerning was its alteration of Legionella pneumophila, to incite an immune response against myelin, the primary insulation in the human nervous system. This induced a rapid-onset disease akin to multiple sclerosis, posing significant health threats among soldiers (48).

The delivery mechanism of these diseases-causing bioweapons can take different forms like missiles, bombs, hand grenades and rockets. A lot of delivery devices were designed to be fitted to aircraft, cars, trucks and boats (like spray-tanks) and to be used in assassinations or sabotage operations, including a variety of sprays, brushes and injection systems as well as means for contaminating food, water and clothing (49).

Lessons learned and recommendations

The history of warfare provides valuable lessons related to the importance of infectious pathogens impacting the readiness of military forces. Different strategies of prevention and control of epidemic outbreaks within military units during historic wars and conflicts were adopted. The Lessons Learned process was assumed by the NATO members as a key to fostering a culture and operational doctrine that prioritize continuous improvement and development. The NATO's Lessons Learned Policy improve security, bolster education, training, exercise, evaluation, and experimentation between allies and partners (50). In order to support these operational and strategic level processes, a deep analysis called the "Joint Analysis and Lessons Learned Centre (JALLC)" was underwent to provide guidance on how to conduct logistic and tactical solutions to encountered issues (51).

Even in ancient times, military leaders recognized the importance of hygiene in preventing the spread of disease among troops. For example, during the Roman Empire, soldiers were required to maintain personal hygiene by washing their hands and bodies regularly to reduce the risk of foodborne and waterborne illnesses (52). During the Middle Ages, armies faced outbreaks of infectious diseases such as bubonic plague and typhus, by implementing quarantine measures to isolate infected individuals and prevent the spread of disease within military encampments (53). Additionally, efforts were made to improve sanitation in camps and minimize exposure to contaminated water sources.

The Napoleonic Wars witnessed advancements in military medicine, including the establishment of field hospitals and the implementation of rudimentary vaccination programs against diseases like smallpox, influenza, and Malaria. Military surgeons also developed techniques for wound management and infection control to reduce morbidity and mortality among wounded soldiers (54).

The American Civil War highlighted the importance of disease prevention and sanitation in military camps. Both Union and Confederate armies suffered from significant losses due to infectious diseases such as dysentery, typhoid fever, and malaria (52). Military leaders took steps to improve camp hygiene, provide clean water supplies, and implement proper waste disposal methods to reduce the incidence of environmental diseases (52). This has been highly developed and taken into consideration in today's armies, with hygiene norms, camping standards, sanitary facilities, vector control, water management, food safety monitoring systems and mobile units that produce and treat water, such as the reverse osmosis water purification units (55).

Additionally, the conditions of trench warfare during World War I posed significant challenges for disease control. Soldiers faced increased risk of infections such as trench foot, typhus, and respiratory illnesses due to overcrowded and unsanitary living conditions. Military medical personnel implemented measures to improve sanitation in the trenches, distribute clean clothing and footwear, and provide medical care for wounded and sick soldiers (56).

The World War II brought about new challenges in disease prevention and control, including the emergence of antimicrobial-resistant bacteria and the threat of biological warfare. Military medical research focused on developing vaccines, antibiotics, and improved hygiene practices to protect troops from infectious diseases. This has begun with the discovery of penicillin during World War II which revolutionized the treatment of bacterial infections among military personnel (57).

In contemporary warfare, military forces continue to face infectious disease threats, including emerging pathogens and antimicrobial resistant bacteria. Prevention and control strategies incorporate elements such as vaccination programs, surveillance systems, rapid diagnostic testing, and adherence to strict hygiene protocols. Military forces also collaborate with civilian public health agencies and international organizations to address global health challenges and mitigate the impact of infectious diseases on military operations.

Food defense process and control strategies

The food defense process in military operations involves safeguarding food supplies from deliberate contamination or tampering to ensure the health and safety of military personnel. This process includes strict food handling protocols, regular inspections, surveillance systems, and training programs to identify and mitigate potential threats (58). Additionally, it may involve implementing security measures along the supply chain, from procurement to distribution, to prevent unauthorized access to food stores (58).

The main principles of food defense involve strategies and protocols to protect food supplies from intentional contamination or sabotage. These principles are crucial in ensuring the safety and well-being of military personnel. The key principles include firstly, the threat assessment represented by conducting comprehensive assessments to identify potential threats to food supplies, as deliberate contamination, adulteration, or tampering. Secondly, the vulnerability assessment which consist on evaluating vulnerabilities in the food supply chain (VACCP), from procurement to distribution, to identify weak points that could be exploited by malicious actors. Finally, the risk management resumed in

implementing risk analysis strategies to mitigate identified threats and vulnerabilities, including developing protocols for food handling, storage, transportation, and disposal (58). The tactical tool for food defense strategy is the CARVER-Shock which is adopted from military applications to assess and prioritize vulnerabilities in food systems in particular in operational deployments (59). It deals with the importance of a target within the system (Criticality), how easily an attacker can access the target (Accessibility), the ability to recover if the target is compromised (Recuperability), the likelihood of successful tampering or attack (Vulnerability), the impact of an incident on public health, the economy, and operations (Effect), how easily the target is identified by a potential adversary (Recognizability), and the broader psychological and societal impacts of an attack (Shock). By scoring each criterion, we can pinpoint the most at-risk components of their supply chain and prioritize protective measures accordingly (59).

Many other measures should be considered during military operations, regarding enhancing physical security measures to prevent unauthorized access to food and/or water resources storage facilities, including restricted access, surveillance systems, and perimeter security. Providing training, simulation exercises and awareness programs to military personnel involved in food handling and distribution to recognize and respond effectively to potential threats. By the same way, developing surveillance, monitoring systems, and comprehensive emergency response plans to address potential incidents of food contamination or sabotage, including protocols for rapid response, containment, and recovery (60). By adhering to these principles and implementing robust food defense measures, military troops can safeguard their food supplies and ensure the health and readiness of their personnel in the face of potential threats. Nowadays, one of the selected solutions adopted by different armies, is the design and conception of the individual combat rations (61). Canned food is a ready-to-eat compound meals adapted to individual combatant, light, energetic, diversified, safe, and steady in ambient temperature (60). These preparations have undergone a very high heat treatment associated to acidic pH solution. This hampers all bacterial activity in both vegetative or spore-forming forms and guarantee the stability of these dishes. Armies competes todays to develop their facilities to rapidly detect, identify, and neutralize all types of bio-weapons that may be disseminated through food or water. Innovating vaccines, antitoxins, and antidotes against wide range of toxic substances were the subject of highly funded researches all over the world (62).

Conclusion

In conclusion, pathogens circulating within military units, poses serious challenges in relation with the operational readiness of armed forces. Implementing effective control strategies is paramount to mitigate the risks associated with foodborne, waterborne, and vectorborne infections. Regrettably, these pathogens continue to be used as biological weapons despite regulations banning their industrialization. Comprehensive learned lessons and exchanges of experiences are helpful to set up systems for securing potential contamination routes and ensure the readiness of troops in diverse operational environments.

Competing interests

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