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Review: The risk of contracting anthrax from spore-contaminated soil – A military medical perspective

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ABSTRACT

Anthrax is an infectious disease of relevance for military forces. Although spores of *Bacillus anthracis* obiquitously occur in soil, reports on soil-borne transmission to humans are scarce. In this narrative review, the potential of soil-borne transmission of anthrax to humans is discussed based on pathogen-specific characteristics and reports on anthrax in the course of several centuries of warfare. In theory, anthrax foci can pose a potential risk of infection to animals and humans if sufficient amounts of virulent spores are present in the soil even after an extended period of time. In praxis, however, transmissions are usually due to contacts with animal products and reported events of soil-based transmissions are scarce. In the history of warfare, even in the trenches of World War I, reported anthrax cases due to soil-contaminated wounds are virtually absent. Both the perspectives and the experience of the Western hemisphere and of former Soviet Republics are presented. Based on the accessible data as provided in the review, the transmission risk of anthrax by infections of wounds due to spore-contaminated soil is considered as very low under the most circumstance. Active historic anthrax foci may, however, still pose a risk to the health of deployed soldiers.

KEYWORDS

bacillus anthracis, anthrax, soil, transmission, soldier, risk assessment, spore

INTRODUCTION

Epidemiology in a nutshell

Anthrax is an acute bacterial zoonosis of mainly wild and domestic herbivores (e.g. cattle, sheep, goats, donkeys, horses, reindeer, antelopes and camels) although any warm blooded animal might circumstantially get infected. It is caused by *Bacillus (B.) anthracis* and is occasionally transmitted to humans [1–2]. Humans might get affected by activities such as hunting, breeding and occupational or nutritional exposure to contaminated animal products (Fig. 1). Ecological, social, cultural, political and economic factors continue to influence this process, generating and shaping nosoareals of anthrax worldwide [3–5]. Anthrax is endemic in some countries in Asia, Africa, the Americas, and southern Europe. World Health Organization (WHO) [6] estimates that the worldwide annual occurrence of anthrax is less than 100,000 cases. There are, however, likely a large number of additional cases due to unreported outbreaks.

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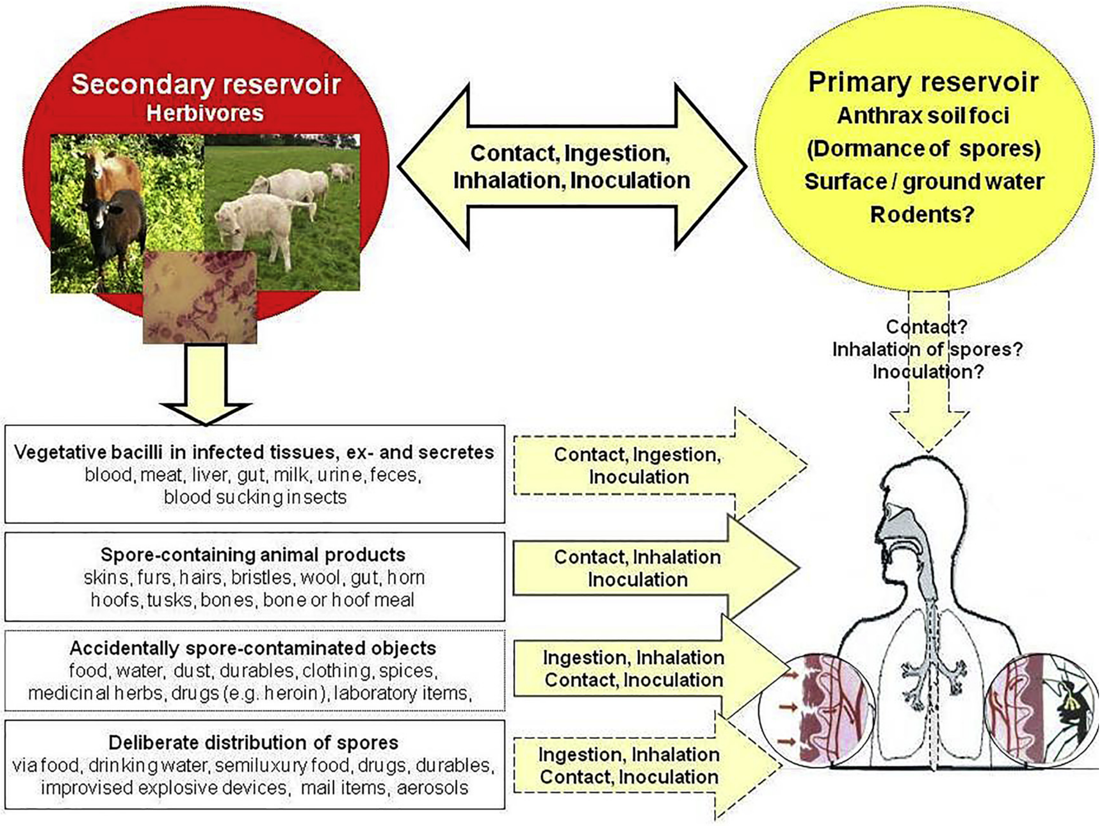

Fig. 1. Key features of the epidemic process of anthrax and possible routes of transmission on military personnel in endemic areas [6, 7, 27, 28, 31, 36, 38, 41, 43, 56, 57, 59–61, 87, 88, 173, 209, 275]

The pathogen and molecular mechanisms of pathogenicity

The causative agent is a Gram-positive, non-motile, encapsulated, facultatively anaerobic, endospore forming bacterium, which is approximately 0.8–1.2 μm by 3–5 (10) μm in size [7]. Like all *Bacillus* species, *B. anthracis* forms spores that are commonly found in the soil. Unlike other species in this genus, it is the only obligate pathogenic *Bacillus* of mammals [8]. Phylogenetically, there are three main lineages (A, B, and C clades) of *B. anthracis* [9]. The A clade is the most important, globally dispersed causative form of anthrax (>90% of all cases) [9]. Modern whole genome sequence single nucleotide polymorphism- (SNP-)analyses and the definition of derived canonical SNPs (canSNPs) are used to further subdivide these main clades into phylogeographical sub-branches [10–14].

The virulence of *B. anthracis* is based on an anti-phagocytic poly-gamma-D-glutamic acid capsule, an exotoxin complex (lethal toxin and oedema toxin), and exoproteases that can lyse macrophages and release interleukin-1 (IL-1) and tumour necrosis factor (TNF) [15].

The anthrax toxin complex consists of three components, i.e. protective antigen (PA), lethal factor (LF), which is a zinc protease [16–18], and oedema factor (EF), which is an adenylate cyclase [19, 20]. PA is a pore-forming protein that complexes with LF or EF. After binding to cellular receptors, PA mediates the entry of LF or EF into mammalian cells [15]. The anthrax toxins exhibit immunosuppressive and cytotoxic properties that enable the micro-organism to grow and spread unimpeded in a host [21, 22]. The so-called pXO2 plasmid contains the genes that encode for the capsule, which confers resistance to phagocytosis, and the pXO1 plasmid carries the genes for anthrax toxins [6, 20, 23, 24]. The loss of one or both plasmids leads to a decrease in virulence [4, 25–27]. This occurs in a small part of bacteria in released blood prior or during the sporulation.

Sporulation as a survival strategy

Vegetative *B. anthracis* in unopened carcasses are destroyed by putrefactive bacteria. After release to the environment they may become rapidly destroyed by exposure to ultraviolet light, low humidity, high temperature and by competing soil and water micro-organisms [6, 28, 29]. They are, however, able to replicate for some time in soil where blood has spilt [6]. Once released and under appropriate conditions [30], *B. anthracis* forms endospores (sporulation) in response to various stress factors such as the absence of adequate nutrients. These endospores are infectious, dormant and highly tenacious forms of the bacterium [31, 32]. Spores are 1 μm by 3 μm in size and consist of a core, which contains the DNA, and three concentric layers (cortex, coat and exosporium) [32] which protect them from environmental effects. Following infection of a susceptible host, the spores germinate in the presence of cellular germinants (e.g. amino acids, ribonucleotides) and develop into new vegetative bacterial cells [32]. These cells initially grow and multiply at the point of entry or in lymphatic tissues. Then they spread throughout the body via the lympho-haematogenous route and cause haemorrhagic necrotic lesions, toxaemia and septicaemia [33, 34].

Mode of infection in animals

Domestic animals (Fig. 1) usually become infected through the ingestion of anthrax spores (grass, soil or water) while grazing or browsing [7, 28, 31]. Horseflies (and other tabanids) and mosquitoes, too, can transfer *B. anthracis* of infected animals in their final stage of the disease or through spore-contaminated water [7, 27, 35, 36, 37].

Sheep and pigs might have been infected via inhalation of spore-containing dust [28, 31, 38–40].

In highly susceptible animals (e.g. sheep and goats), anthrax progresses as a peracute haemorrhagic infection leading to death. In the final stage of the disease, large amounts of anthrax bacilli are released in bloody exudates from all body orifices [7, 25, 28, 41, 42]. In these cases and when animal carcasses decompose or are opened by scavengers, anthrax bacilli are exposed to the outside environment (pastures, water) and sporulation commences again [7, 25, 28, 43–45].

Persistence of anthrax spores in the environment

Anthrax spores are relatively resistant to heat, desiccation and certain disinfectants. Depending on the type and nature of contaminated material and the biotic and abiotic characteristics of the outside environment, they can thus survive for decades not only in soil, surface waters and mud but also in or on skins, hides, fur, wool, hair, bristles, hooves, horns or bones from diseased animals, in wastewater and sludge from tanneries, or on surfaces such as wood and metal [7, 21, 27, 28, 41, 43, 46–52].

Viable spores were present in 200-year-old bones that were retrieved during archaeological excavations at a site in the Kruger National Park [53]. *B. anthracis* was isolated from dried soil that had been stored for sixty years [54].

Infective spores that lie dormant in environmental habitats ensure the survival of *B. anthracis* in nature in anthrax soil foci or nosoareas where animals can become infected while grazing [3, 5, 55–57]. Since the soil is the most important reservoir of *B. anthracis*, anthrax was previously referred to as a soil-borne infection [58]. The transmission of organisms from and to different living and non-living reservoirs, e.g. soil, herbivores and (possibly) rodents [59], maintains the epizootic cycle of anthrax even after an extended latency period (Fig. 1).

Transmission to humans

Epidemiologically, anthrax in humans can result from occupational (agricultural or industrial) exposure and non-occupational (accidental or everyday) exposure (Table 1) [38, 60–62]. Animal graves and burial sites, biothermal pits and other places for the disposal of animals that died of anthrax are referred to as anthrax (soil) foci, anthrax districts or permanent anthrax foci [28, 61, 63, 64]. In Russia and some former Soviet republics, inhabited areas, including livestock farms, pastures or natural areas, where an epizootic anthrax focus was found (regardless of the time of occurrence) are termed “stationary unfavourable by anthrax sites” (SUS) or “stationary anthrax-affected areas” (SAA) [64, 65].

The vegetative forms of *B. anthracis* can be transmitted by *direct* contact with bloody discharges or with the body and organs of animals that died of anthrax [4, 6, 7, 28]. *Indirect* transmission of the spore form of *B. anthracis*, however, plays a far more important role. Humans become infected during occupational or private activities involving contact with infected carcasses as well as raw, semi-finished and finished products and through exposure to spore-contaminated objects (Table 1).

In Germany between 1910 and 1957, human anthrax occurred during forced slaughter in 30–50% of cases by contact with furs, hides and skins in 12–31%, with animal hairs and brushes in 8–24%, with carcasses of sick animals in 4–14%, and with sick animals in less than 5% of cases [60]. Other professional exposure caused infection in 2–8% of patients and 4–29% of them had no professional history or it could not be clarified.

Anthrax outbreaks can also be caused by laboratory accidents or as a result of the accidental release of anthrax spores from laboratories and production facilities (e.g. the Sverdlovsk incident in 1979) or as a result of the deliberate spread of an anthrax aerosol that can penetrate deeply into the lungs (e.g. the letter attacks in the United States in 2001) [28, 64, 66–68].

Non-occupational exposures to *B. anthracis*, e.g. to spore-containing drugs or articles of daily use that are made of raw animal materials from endemic countries (goat skin, horse hair, bristles or tusk) such as leather goods and toys, bongo drums, rugs, toy animals, or shaving brushes (Table 1), are relatively rare [28, 69–73].

Clinical manifestations

Clinical manifestations of anthrax depend on the portal of entry to the body (skin, respiratory tract or gastrointestinal system). The illness then takes either the cutaneous, inhalational or intestinal form [6, 44, 61 74, 75].

Cutaneous anthrax. Cutaneous anthrax accounts for approximately 90–95% of all cases. Infection usually occurs through small lesions (abrasions, cuts, fissures) on exposed skin surfaces [6, 28, 38, 44, 61, 76].

The organisms are transmitted either directly by contact (killing, slaughtering) with diseased or dead animals, their discharges, blood, meat, milk or internal organs or indirectly through processing, storing or transporting infected animal products and objects contaminated with spores [6, 28, 64]. Infections can also occur as a result of bites of blood-feeding insects [35, 36, 64]. Biting flies can cause 1–12% of infections during epizootic periods [38, 77]. In former times, anthrax

Table 1. Overview on possible sources of human anthrax [6, 7, 28, 38, 41, 44, 60, 61, 62, 66, 72, 87, 88, 94, 95, 97, 107, 111, 184, 223, 224, 234, 236, 275, 277, 353–355]

Industry/critical items		Agriculture and horticulture		other	
Tannery	raw leather, waste water	Milk and meat stockbreeder cattle dealer shepherd farmer	Sick or death animals contaminated animal food, grass, water sources (e.g. dwells)	Waste water treatment	Waste water sludge
Leather manufacture	Leather goods				
Brush factory	Brushes, shaving brushes			Carriers	Bags containers
Wool combing factory	Wool, wool yarn (Garn)				
Woolen blanket factory	Woolen blanket	Market garden Gardener	Contaminated fertilizers: animal bone meal hoof meal	Building trade roadworks, civil engineering channel workers	Soil surface and ground water in arthrax districts
Hair yarnspin factory	Animal air yarn (garn)				
Glue and soap boiling	Glues, soups				
Fertilizer & horn factory	Bone-roof meal, horn goods	Veterinary surgeon keeper in Zooparks	Sick or death animals infectious tissues, secreates,excetes, contaminated items and environmental objects		
Hide and fur trade	Hides and fur			Diagnostic & Research Laboratories (medical, veterinarian pharmaceutical) Bioweapon's facilities	Diagnostic specimens animals laboratory equipment Aerosols Contaminated items (e.g. food, drugs, water)
Carpet & fur manufactory	FUR good, carpet (Wool)				
Catgut manufactory	Catgut (animal gut!)	Abbatoirs	Death animals infectious tissues, secreates,excetes, contaminated items and environmental (soil, water)		
Instrument manufactory	Piano (ivory), bongo drums				
Meat instrument	Meat, meat product				
Slaughter house	Meat, innards, bones, horn, hoof	Butchers	Infectious meat, innards, bones	Postfacilities	Mail transportbag
Animal food factory	Meat and bone meal			Soldiers travellers	Shaving brushes fur goods, soap, drums

Fig. 2. A soldier presenting with cutaneous anthrax. Source: Photograph (repro): Military Pathology Collection of the Military Medical Academy, Berlin *(Kriegspathologische Sammlung der Militärärztlichen Akademie Berlin)*, 1945, missing. German Armed Forces Medical Academy, Military History Collection *(Sanitätsakademie der Bundeswehr, Militärgeschichtliche Lehrsammlung)*, no signature

infections of the face and neck often occurred in wool mill workers who had processed infected animal wool and touched their face or neck with contaminated fingers [37, 38] reported that in case of a bite 10 spores constitute the subcutaneous dose of infection.

The rare possibility of an infection through contact with spore-containing soil is discussed later.

Clinically, cutaneous anthrax (Fig. 2) can present as carbuncular (anthrax carbuncles), oedematous (malignant oedema), or bullous or erysipeloid lesions [44, 76, 78]. If treatment is started early, prognosis is good in uncomplicated cases. The differential diagnosis of cutaneous anthrax includes a wide range of infectious, parasitic and non-infectious conditions (Table 2).

Oropharyngeal and gastrointestinal anthrax. Oropharyngeal anthrax (anthrax angina) and gastrointestinal anthrax most often result from the ingestion of infected slaughterhouse products (meat, dry meat, offal, minced pork, sausages) and milk that had been insufficiently cooked or heated [6, 27, 28, 38, 79, 80]. Dobreizer [28] observed outbreaks of intestinal anthrax caused by contaminated drinking water. Oropharyngeal anthrax can result also from the inhalation of spore-containing dust that enters the oral cavity through the nose and trachea and is swallowed [38, 73, 81]. This form of manifestation can be associated with massive neck oedema and may therefore be initially mistaken for diphtheria [82]. Other conditions to be considered in the differential diagnosis are listed in Table 2.

Inhalation anthrax. Spore-containing aerosols or dusts (with a particle size <5 μm) that reach the deep airways can cause inhalation anthrax, which is also known as pulmonary anthrax, ragpickers' disease or woolsorters' disease [83–88]. This form of anthrax often begins with non-specific influenza-like prodromal symptoms and a brief period of seeming recovery. In many cases, infection leads to life-threatening respiratory distress syndrome as a result of severe haemorrhagic necrotic inflammation of the mediastinum, hilar lymph nodes and pleura [6, 28, 61, 67, 89, 90]. Differential diagnosis includes a wide range of bacterial infections (Table 2).

Inhalation anthrax is a typical occupational disease. Until the 1950s, cases of inhalation anthrax occurred in workers who processed infected skins, hides, rags, wool, or animal hair from anthrax endemic regions [28, 38, 41, 91–95]. With the exception of a single case in 1976, no more such cases of anthrax have been reported in the USA since the 1960s [96] as a result of the introduction of the anthrax vaccination [96] licensed in 1970 (https://www.avma.org/KB/Resources/LiteratureReviews/Pages/Anthraxfacts; last assessed 19 March 2020). Occasionally, inhalation anthrax was caused by imported spore-containing bone meal fertilisers and African goat skins used for producing bongo drums [28, 68, 72, 97, 98]. If left untreated or if treated too late, all forms of manifestation can lead to sepsis syndrome and haemorrhagic meningitis, followed by death [44, 61, 75, 76, 99–101].

Injection anthrax. Another manifestation of anthrax was reported for the first time in 2000 in an injecting heroin addict in Norway and later in other European countries [102, 103]. These cases presented with severe inflammation of subcutaneous and muscle tissue (necrotising fasciitis, compartment syndrome) with a relatively high mortality rate [103–107]. Since this uncommon form of anthrax was seen after para-venous injection of heroin probably contaminated with spores, it was termed "injection anthrax" [101, 105, 108, 109]. Between 2000 and 2013 alone, a total of 230 suspected cases of injection anthrax were reported in Britain, Norway, Denmark, France, and Germany [109]. It is assumed that the heroin had been contaminated with spores (soil, infectious animal blood, infectious animal skins, etc.) in the country of origin or in transit [107, 110]. In 1903, Risel [28] reported a similar case of anthrax caused by drugs that had been wrapped in raw animal skins.

At present, it is not easy for clinicians to detect anthrax at an early stage. Even typical forms of anthrax are associated with problems in differential diagnosis. In an anthrax outbreak in a Swiss textile factory, for example, most cases were diagnosed only retrospectively [111]. Following the postal anthrax attacks in the United States in 2001, the index patient presented to half a dozen physicians and visited two emergency rooms before receiving the diagnosis of cutaneous anthrax [112].

Table 2. Possible clinical presentations of anthrax [6, 27, 28, 44, 61, 68, 72, 74, 75, 87, 88, 91, 95, 101, 105, 107, 110, 111, 113, 192, 196, 313, 356–370]

Cutaneous anthrax	Inhalational anthrax	Oropharyngeal/ Intestinal anthrax	Injection (subcutaneous) anthrax
Non-specific skin infection (paronychia)	Severe acute respiratory disease	Diphtheria	Streptococcal cellulitis
Staphylococcal furuncle, carbuncle or cellulitis	Influenza-like illness	Tonsillitis	Necrotising fasciitis
Streptococcal cellulitis, necrosis, fasciitis or phlegmons	Type A influenza	Streptococcal pharyngitis	Non-specific inflammation
Haemorrhagic necrotic erysipelas	Atypical community-acquired pneumonia (*L. pneumophila, M. pneumoniae)*	Plaut-Vincent angina	Abscess of skin and soft tissue
Furuncle-like swelling	Bilateral haemorrhagic pleurisy	Parapharyngeal abscess	Deep thrombosis of leg veins
Necrotic carbuncle (*B. pumilus*)	Pulmonary tularaemia	Oropharyngeal tularaemia	Compartment syndrome
Gas gangrene	Diphtheria	Peptic ulcer	Sepsis
Traumatic infection	Tonsillitis	Appendicitis	Phlegmons
Pyogenic granuloma	Cervical lymphadenitis	Bacterial peritonitis	Malignant oedema
Infected atheroma	Haemorrhagic gastroenteritis	Acute abdomen	Severe soft-tissue infection (SSTI)
Orbital cellulitis	Pasteurellosis	Typhoid	*C. novyi* type A infection
Dactrocystitis	Pneumonic plague	Food poisoning	
Infected necrotic abrasion	Acute bronchitis	Acute gastroenteritis	
Oedematic swelling	Mediastinitis	Ileus	
Infected insect bite	Fever of unknown origin	Cholera-like disease	
Ulcero-glandular tularaemia		Food poisoning	
Ulcero-cutaneous tularaemia		Necrotising enteritis caused by *C. perfringens*	
Gas gangrene		Bacterial or amoebic dysentery	
Pasteurellosis		Mesenteric ischaemia	
Orf			
Cowpox			
Vaccinia			
Plague (flea bites)			
Glanders			
Erysipelas (*V. vulnificus)*			
Tropical ulcer			
Syphilitic chancre			
Cutaneous leishmaniasis			
Foot-and-mouth disease			
Nodular dermatitis			
Ecthyma contagiosum			
Necrotising herpes, herpes zoster (Diabetic) Mucormycosis			
Bursitis			
Emboli, thrombosis, vasculitis			
Bites (viper, spider, bat, insects)			
Rat-bite fever			
Rickettsiosis			
Artefacts			
Ferret bites			
Werlhof's disease			

Since anthrax is a rare disease, medical and veterinary practitioners are seldom confronted with it during their training and professional life resulting in a low awareness [101, 113–115].

For this reason and because of the non-specific initial symptoms of anthrax, there is a relatively large spectrum of initial diagnoses (Table 2) and it is often too late when anthrax is considered in the differential diagnosis [33, 72, 107, 112, 116]. Moreover, clinically inapparent or subclinical infections with *B. anthracis* which heal without specific treatment and thus remain undetected are not uncommon [117–119].

Injection anthrax is particularly difficult to diagnose since it shows pathognomonic signs and symptoms that are different from those of classical forms of anthrax. In some cases, these unfamiliar characteristics led to delays of 3–12 days from hospital admission to diagnosis [107]. Similar types of soft-tissue inflammation can also be seen after wound infections caused, for example, by *Staphylococcus, Streptococcus, Vibrio* or *Clostridium* species (Table 2).

Biosafety issues

The World Organisation for Animal Health (*Office Internationale des Epizooties* – OIE) lists anthrax as a List B notifiable disease. *B. anthracis* is a risk group 3 biological agent that was classified as a Category A bioterrorism pathogen by the Centers for Disease Control and Prevention (CDC) because it has high bioterrorism potential (www.bt.cdc.gov/agentlist_category.asp, last accessed 19 March 2020).

In Germany, the Biological Agents Ordinance (*Biostoffverordnung*) provides that *B. anthracis* may be handled only in Biosafety Level 3 laboratories. In accordance with Sections 6, 8 and 9 of the German Act on Prevention and Control of Infectious Diseases in Man (*Infektionsschutzgesetz*), suspect cases and clinical cases of anthrax and deaths from anthrax must be reported. Table 1 shows that persons at particular risk of exposure and infection are workers in animal husbandry settings as well as workers who slaughter animals, or process, pack, store, transport or use raw animal hides and skins, bristles, hair, wool, intestines, bones, horns or products made from them, which are imported from endemic areas in subtropical and tropical countries [6, 28, 38, 49, 60, 78].

Preventive approaches and their obstacles

Most industrial countries were able to control animal anthrax through effective measures for preventing epizootic diseases, e.g. police orders and livestock vaccination, and to largely eliminate autochthonous foci of anthrax [6]. As an occupational disease, industrial anthrax has been rare in Germany since the 1990s owing to strict regulations and controls on the importation of raw animal products from endemic areas. The last case was reported in 1994 [49, 105].

By contrast, anthrax is still highly endemic in parts of the Middle East, Asia, Africa and South America because of a lack of measures to control epizootic diseases or because the availability of veterinary and public health services is limited as a result of economic crises or political or military conflicts [6, 27, 120]. For cultural reasons or out of necessity, meat, hair and skins of diseased or dead animals are often still used in these regions and anthrax carcasses are not burned but buried without compliance with veterinary hygiene standards. Such sites, which are not always designated as animal burial sites, can be the source of anthrax outbreaks in livestock and the local population even after decades [6, 31, 64].

For this reason, potential exposure to anthrax spores and a risk of infection still cannot be excluded for construction, waste disposal, and wastewater treatment workers, especially at former industrial sites such as tanneries, leather factories, rendering facilities and knackeries [49, 64, 78, 121]. As a result, activities involving the movement of soil (e.g. construction of buildings, roads or canals) in stationary anthrax-affected areas (SAA) are subject to special biosafety regulations in Russia and some other former Soviet republics [59, 64, 122].

In the European Union, too, a directive requires that workers in potentially contaminated areas (e.g. former tanning facilities) be protected from micro-organisms classified as biological agents that may be a hazard to human health [123, 124]. In Germany, the Civil Engineering Professional Association passed safety regulations in 1990 for the civilian sector in order to protect workers from infection with Group 2 soil-borne pathogens during activities involving soil disturbance [124]. These regulations also apply to spores from *Clostridium* species (e.g. the causative agents of tetanus and gas gangrene) and *B. anthracis*.

Preventive challenges from a military medical point of view. No data are available on potential health hazards and any required protective measures associated with military exercises or combat operations in endemic regions. This is of military medical relevance since such activities involve the movement of large amounts of soil, too, which may lead to the release of anthrax spores.

During World War II, an area of 3.3 million km^2 was affected by combat activities in Europe [125]. Grenade and bomb attacks as well as military vehicle movements caused considerable damage to the earth's surface and structure. Several billions cubic metres of earth were moved for the building of field fortifications (e.g. trenches, bunkers, shelters, roads, and wells) and soil-microflora was brought from deeper layers to the surface of the earth [125]. In World War I, years of trench warfare likely resulted in similar soil damage.

During both wars, natural anthrax foci and potentially contaminated industrial sites in occupied areas were probably affected by military activities. Time and again, members of the land forces of the countries involved in the wars (and in particular infantry, armoured and engineer units) had close contact with soil and were exposed to dust. When soldiers were wounded, spore-containing soil could enter wounds together with projectiles, fragments or other objects and could cause infection (cutaneous or injection anthrax) similar to the development of gas gangrene or tetanus.

It is unknown, however, whether sufficient amounts of virulent spores of *B. anthracis* from soil foci were released into the environment and presented a risk of infection for military personnel and military animals (e.g. riding animals or draught animals) and for the local population and their animals.

Furthermore, anthrax is of relevance in terms of the biological medical defence of armed forces. *B. anthracis* spores can be used as biological warfare agents and have been tested, produced and weaponised by several countries on the basis of biological weapons programmes and have been used for terrorist and other criminal purposes [126–134]. Soil, vegetation, roads and buildings were contaminated by spores from highly virulent laboratory strains as a result of British tests with anthrax spores on Gruinard Island in 1942 and 1943, the laboratory accident in Sverdlovsk in 1979, and the postal anthrax attacks in the United States in 2001 [9, 68, 135]. Only after several large-scale decontamination operations was it possible to use the contaminated areas again, for example Gruinard Island in the late 1980s [48, 136].

The need for large-scale decontamination was based on the assumption that humans can contract inhalation or cutaneous anthrax when they breathe in spore-containing soil particles floating in the air or when they come into contact with contaminated surfaces.

Aim of the review

Against this background, the present review investigates whether direct contact with anthrax spores or exposure to airborne anthrax spores from spore-contaminated soils or surfaces can lead to anthrax infections in military personnel. Where appropriate, recommendations for protecting military personnel during deployments in endemic areas are suggested. In addition to the presented speficially military medical experience, a more general summary of reports on soil-borne and air-borne anthrax transmission is shown in the Supplementary material 1 [137–172], [173–194], [195–240].

ANTHRAX IN WAR

Anthrax before the era of microbiology

From ancient times until the 19th century, anthrax was always present in wartime. In August 1,623 during the Thirty Years' War, for example, Wallenstein lost approximately 15,000 of 20,000 men, his cavalry and almost all of his draught animals when his forces moved across pastures in Silesia and Hungary. These pastures were obviously contaminated with anthrax spores and led to devastating outbreaks of cutaneous anthrax (carbuncles) and intestinal anthrax (bloody diarrhoea) [241]. In times of war and need, soldiers often wore untanned fur and skins from diseased or dead animals underneath their armour in order to provide padding, to protect their skin or to protect themselves from the cold and they ate infected meat [241]. When Finland was occupied by Russia in 1719, anthrax spread from horses, cattle, sheep and pigs to soldiers and the civilian population [241].

In the spring of 1745, during the Silesian Wars, Prussian grenadiers suffered from "bubonic plague" or more likely from anthrax carbuncles [241].

At that time, many people died after contact with apparently contaminated wool in weavers' villages in Silesia. Their signs and symptoms included large malignant buboes, bloody cough and fever (presumably inhalation anthrax in our opinion) [241].

The persistent recurrence of epizootics among horned animals or sheep persuaded Empress Maria Theresa in 1753 to pass the first Regulations on Livestock Diseases (*Vieh-Seuch-Ordnung*) for the territory under her rule. They stipulated that everything that had come into contact with the animal had to be destroyed, all livestock that had been killed because it had been affected by the epizootic had to be buried in the ground to a depth of five to six feet, and the pits had to be covered with lime and then with earth [241].

During Napoleon's siege of Glatz in the anthrax year of 1807, epizootics were observed in horses and then outbreaks of cutaneous carbuncles and bloody diarrhoea occurred among Bavarian and Wurttembergian soldiers [241]. Dominique Jean Larrey, who was Napoleon's personal physician and surgeon-in-chief, observed repeated outbreaks of "charbon" (the French word for anthrax) especially during the French invasion of Russia [241]. Supply problems and hunger apparently forced the French soldiers to slaughter animals that suffered from anthrax and to eat the meat and use the skins of these animals.

The last major outbreaks of anthrax (syn.: "Siberian plague" or "Siberian ulcer", "*sibirskaya yazva*") occurred on the European part of Russia between 1864 and 1870. At that time, several thousand deaths were reported throughout Russia, and 65,000 horses, cows and sheep as well as 528 humans died in Novgorod Governorate, only [28, 91, 241].

During the American Civil War, diarrheal diseases, malaria, typhus fever (typhoid fever, typhus), pneumonitis and pleuritis, sexually transmitted infections, other "miasmatic diseases", and diphtheria were the diseases that most commonly affected the northern soldiers from 1 May 1861 to 30 June 1966. Anthrax was not included in statistical data [242].

In Germany, 5,228 of 25,000 horses of the VII and VIII Army Corps underwent treatment in a veterinary facility in 1866; anthrax, however, was not identified as a cause of disease [243].

On 18 May 1867, the Kingdom of Bavaria passed the Law on Contagious Animal Diseases Act (*Gesetz über ansteckende Viehkrankheiten*) in order to provide protection against epizootics; this law was also adopted by the Military Veterinary Service of the Bavarian Army [244]. The law prohibited the use of carcasses of animals known or suspected to be infected with anthrax [244].

No anthrax cases in animals or soldiers of the Royal Bavarian, Wurttembergian and Prussian Armies were reported between 1867 and 1873 (with the exception of the war from 1870 to 1871) [245–248]. At that time, the main focus of military medical care was on typhoid fever, erysipelas, intermittent fever (malaria), dysentery, cholera, acute respiratory diseases, inflammation of the tonsils and lungs, tuberculosis, scarlet fever, measles, venereal diseases and skin conditions such as footsores and saddle sores, skin ulcers and abscesses, as well as inflammatory conditions, furuncles, and exanthems [248].

Available data do not allow conclusions to be drawn on whether or not anthrax occurred during the Franco-German War from 1870 to 1871. It should be noted that this zoonotic disease was not yet notifiable upon suspicion or diagnosis in the German armies at that time [244]. For this reason, there was no information on anthrax in reports on Bavarian hospital trains [249] and the 4th Royal Bavarian Division [245, 250], in an analysis on losses caused by weapons and diseases during war [250], in the several volumes of the Medical Report on the German Armies in the Franco-

German War of 1870 and 1871 [247, 250, 251, 252], or in *Die Kriegschirurgen und Feldärzte Preussens und anderer deutscher Staaten in Zeit- und Lebensbildern* [253], which presents military surgeons of the Prussian army and other German states in several volumes. The same applies to the Statistical Medical Report of the Royal Prussian Army and the XIII (Royal Wurttembergian) Army Corps between 1870 and 1873 (first quarter), with the exception of the war from 1870 to 1871 [246].

This relatively short military campaign involved typical diseases such as cholera, typhus, relapsing fever, typhoid conditions, smallpox, dysentery and malaria which cost the lives of 14,904 soldiers [248, 250].

A total number of 116,821 German soldiers were wounded in this war [247]. Of the 9,737 patients who were treated in field hospitals, 2007 died of (wound) erysipelas, hospital gangrene, wound diphtheria, pyaemia, septicaemia, acute purulent oedema, tetanus, and osteomyelitis [251]. There are no data specifying whether the patients had primary or secondary wound infections. Whether the above-listed medical conditions also included anthrax remains unclear since microbiological diagnostic procedures were not yet available at that time.

Surgical management consisted of early wound drainage, debridément and the application of antiseptics such as potassium permanganate, aluminium acetate, chlorine water, zinc chloride, and carbolic acid, which were used to prevent the occurrence of the much-feared hospital gangrene [251].

During the war, the Veterinary Service treated approximately 21,000 injured and diseased horses, 1859 of which died [243]. At that time, anthrax, which was known to veterinarians as an epizootic, was never reported as a cause of disease or death.

During the war, Robert Koch came into contact with the disease when he was employed as a military physician in the Auvergne region in France in 1871. Sheep from local farmers died of anthrax when they grazed on “the green hills of death” [241]. “Damned pastures,” “cursed hills” and “anthrax farms” or “dangerous mountains” were also found in Burgundy, Champagne, Dauphiné, Auvergne, Beauce, Sologne, Eure-de-Loire and Nivernais, where sheep became infected every year until the end of the 20th century [91, 241]. Similar foci existed in the German Reich in the Bavarian Alps, the Lower Rhine region, the District of Potsdam, and in the Provinces of Saxony (Mansfeld area), Silesia and Posen [91].

Anthrax in the military and the civilian population before World War I

When the Franco-German War was over, Koch worked as a district physician in Wollstein in the Province of Posen and investigated the anthrax outbreaks that occurred every year in animals, animal keepers, slaughterers, and veterinarians. In 1876, Koch was the first to isolate and describe *B. anthracis* as the causative agent of anthrax and to demonstrate the role of anthrax spores in infection [254]. Koch was thus a founder of bacteriology as a science and a pioneer of laboratory diagnostics and the control of this epizootic both in the civilian and military sectors of the 19th century.

In the 1870s, Louis Pasteur, Roux and Chamberland discovered the causes of the recurrence of epizootic diseases in anthrax regions and demonstrated the presence of infective anthrax spores in superficially buried animal carcasses after as many as seventeen years [241]. Infection recurred in animals that grazed on these sites or were fed dry feed or grass harvested from these sites. Since hides and skins from diseased animals were infective for several months or even years, tanners and brushmakers contracted the disease. Waters and adjacent pastures located below tanning facilities were contaminated with spores and provided infected material to existing or new anthrax foci [241]. Neither Koch nor Pasteur, however, described cases of human anthrax caused by contact with spore-containing grass or soil at contaminated sites.

Louis Pasteur, who developed the first anthrax vaccine and successfully tested it on sheep in 1881 and 1892, created the basis for preventive immunisation and anthrax control in animal populations, which are still effective today [241].

From 1873 to 1877, a total of 13,698 service horses received treatment in the Kingdom of Saxony. Of these, 12 died of “anthrax-like diseases” (including anthrax and shingles of the head) [243]. Disease names were inaccurate at that time because it was not always possible to identify the causative agent.

On 18 May 1877, the Regulations Regarding the Reporting on Service Horses for Horse Veterinarians (*Bestimmungen betreffend die Rapportführung und Berichterstattung über die Dienstpferde für Roßärzte*) were passed in the German Reich for the Army Veterinary Service [244].

The Reich Law on the Prevention and Control of Livestock Epizootics (*Reichsgesetz betreffend die Abwehr und Unterdrückung von Viehseuchen*) of 23 June 1880 then required that anthrax cases be registered as well [244].

On 1 April 1881, the Implementing Law on Livestock Epizootics (*Viehseuchen-Ausführungsgesetz*) and the Instruction Regarding the Prevention and Control of Epizootics Among Horses of the Armed Forces (Epizootics Instruction) (*Instruktion betreffend die A. und Unterdrückung von Seuchen unter Pferden der Truppen –Seucheninstruktion)* were passed [244]. Large parts of these regulations were adopted by the Kingdom of Bavaria as well [244]. The Epizootics Instruction provided that horses be inspected, epizootics or suspected epizootics be identified, and an Epizootics Commission be sent to the unit affected by the epizootic. Animals suspected of having anthrax and all associated items of equipment had to be immediately isolated, the site where the animals were kept had to be cordoned off and investigated by the Epizootics Commission. Tar or petroleum had to be poured over dead animals before the carcasses were buried at a place designated by a police authority [244].

An Epizootics Reporting Service had to inform the responsible authorities of suspected or confirmed anthrax outbreaks, the course and the successful control of an outbreak. Moreover, personnel had to be educated about the signs and symptoms as well as the course and causes of anthrax. For the first time, the diagnosis of anthrax required microscopic identification and animal testing [244].

In 1886, a Military Veterinary Ordinance (*Militär-Veterinärverordnung*) was passed which contained all relevant regulations including an Epizootics Instruction in its Annex. In 1897, it was replaced by a new Military Veterinary Ordinance. This ordinance made anthrax in horses a disease that was notifiable upon suspicion [244].

The Military Veterinary Ordinance of 1906 provided that autopsies of horses that were killed or died in the setting of anthrax required the presence of a senior Veterinary Corps officer (*Korpsstabsveterinär*) and that autopsy reports be submitted to the General Command through official channels. In 1913, this provision was changed and autopsy reports had to be submitted directly to the General Command (*Generalkommando*) [244].

In 1909, the Reich Law on Livestock (*Reichs-Viehgesetzes*) [244] and new Epizootics Regulations (Annex II of the Military Veterinary Ordinance) were passed and made anthrax a disease that was notifiable upon diagnosis [244].

Anthrax provisions remained unchanged in the Epizootics Regulations of 1913, which was based on the Reich Law on Livestock of 1 May 1912. These provisions also regulated slaughter and meat inspections and the prohibition of slaughtering animals suspected of having anthrax in order to prevent human infections through the consumption of meat from anthrax-infected animals [91]. Effective vaccinations were available and effectively prevented the spread of the disease [91].

Epizootic control measures continuously improved so that only isolated cases of anthrax occurred in the animal population of German Army contingents in the pre-war period [255]. The Prussian Army, for example, reported only 66 sporadic cases from 1886 to 1914, most of which occurred during military exercises [255]. Most of these cases were caused by infected animal feed, stable bedding, or water (e.g. from collector wells). The Bavarian Army reported only a single case during this period. Rigorous epizootic control measures invariably prevented anthrax from spreading among animal populations [255].

In the German military, anthrax cases were rare and the incidence of this infectious disease continued to decrease from 32 cases in 1899/1900 to one case in 1908/1909 among members of the German armed forces [91] (Table 3).

In the colonies of the German Reich, increased numbers of anthrax cases [256] were observed in German South West Africa during the rainy season in 1905/1906 and occurred among draught animals (oxen) and local personnel accompanying military transport elements and among personnel of transport elements. Occasional cases were also reported in equids and the local population in German East Africa [257]. Cutaneous anthrax was the most common form of the disease since dried skins of cattle that had died of anthrax were used as bed coverings. By contrast, there is no evidence of the occurrence of anthrax in Cameroon, China or Turkey [257] although the disease was endemic in China and Turkey.

Table 3. Anthrax cases in the Prussian, Saxon and Wurttembergian Army Corps [91]

Year	Cases	Year	Cases
1899/1900	32	1904/1905	7
1900/1901	24	1905/1906	9
1901/1902	21	1906/1907	6
1902/1903	6	1907/1908	1
1903/1904	14	1908/1909	1

Table 4. Officially reported human anthrax cases in Germany [91]

Year	Number of cases	Case-fatality rate[b] %
1904	123 (10)[a]	8.1
1905	114 (16)	14.0
1906	133 (18)	13.5
1907	156 (21)	13.5
1908	120 (19)	15.8

[a]In parantheses: number of deaths
[b]Case-fatality rates were added.

In the German Reich, the control of anthrax in humans was regulated in the Law on Epidemics of 28 August 1905 and its implementing regulations [91]. This law required the reporting of all cases of disease, deaths and suspected cases and defined the necessary isolation and disinfection procedures. In Germany, special trade and industrial regulations applied to the production, handling, storage and distribution of objects capable of spreading anthrax [91].

In the civilian sector, the authorities that enforced trade and industrial regulations increased their efforts to control anthrax in livestock settings and thus continuously reduced the risk of infection for humans. At the same time, the risk increased for those whose work involved processing infectious spore-containing animal products (e.g. meat, bones, hides, skins, hair, or bristles), most of which had been imported from endemic areas [28].

From 1889 to 1899, a total of 290 anthrax cases were reported and consisted of 180 butchers, 48 shepherds, 31 wool sorters, 24 knackers/renderers, and 7 veterinarians [38].

From 1899 to 1908, a total of 646 anthrax cases (Table 4) were officially registered in the German Reich and included 203 butchers, 8 veterinarians, 28 knackers/renderers, 19 shepherds, 8 tanners, 2 brushmakers, 5 meat inspectors, and one livestock trader [28, 91].

During the period 1910–1929, anthrax cases occurred as a result of emergency slaughtering (39%), the handling of living (1%) and dead animals (9%), the handling of hides and skins (31%) and animal hair and bristles (8%), or other occupational activities (2%). In 10% of the non-occupational anthrax cases, the source of infection remained unknown [60]. In no case was contact with spore-containing soil reported as the cause of anthrax in humans.

The reduction in the number of anthrax cases in the German Reich was probably one of the reasons why anthrax was the subject of only three of 510 articles that appeared from 1903 to 1914 in the *Centralblatt für Bakteriologie, Parasitenkunde und Infektionskrankheiten*, the German central journal of bacteriology, parasitology and infectious diseases [258]. In these articles, two patients with cutaneous anthrax had become infected by contact with spore-containing animal products.

Likewise, the *Deutsche Militärärztliche Zeitschrift*, which was the professional journal of the German Army Medical Service, did not report any cases of anthrax during the period 1871–1914. The focus of attention was on typhoid fever, tuberculosis, cholera, tetanus, scabies, plague, smallpox, pneumonia, colds, influenza, dysentery, diphtheria, and venereal diseases [259]. These were also the most common infectious diseases in the peacetime Prussian Army between 1867 and 1872 [248].

A total of 261 anthrax cases were reported in England between 1889 and 1904. Of these, 88 patients had processed wool, 86 patients had handled animal skins, 76 patients had been occupationally exposed to bristles and brushes, and 17 patients had become infected in other industrial situations [38].

In Russia, 268,000 cases of anthrax and a mortality rate of 25% were reported during the period 1896–1913 [260]. The number of cases of animal anthrax was 50 times higher than the number of human anthrax cases. The majority of human anthrax cases resulted from handling skins and hides in industrial settings but also from exposures at home.

From 2,634 occupational anthrax cases reported between 1884 and 1916, 1,466 were farmers or owners of livestock, 37 shepherds, coachmen or blacksmiths, 824 workers processing wool and sheepskin, 257 tanners, and 36 persons processing animal hair, bristles and horns, and one veterinarian [260].

No German, English or Russian statistical data on occupationally related infections suggested that anthrax cases were caused by direct contact with spore-contaminated soil.

Anthrax during World War I (1914–1918)

Anthrax in animal populations. In World War I (1914–1918), the German Field Army (*Feldheer*) had an average of 1,236,000 horses [261]. A total of 1,372,000 animals were treated in horse hospitals; there are, however, no data on the number of anthrax cases among these animals [261].

Medical reports for horses required that unit, depot, and hospital veterinarians registered and reported cases of anthrax, glanders and tetanus [262]. The German Army Veterinary War Report of 1914–1918 (*Kriegsveterinärbericht des deutschen Heeres 1914–1918*) [262] noted that there were sporadic anthrax cases in horses in all theatres of war. Moreover, outbreaks occurred between January 1916 to August 1918 in 39 formations on the Western Front and in 48 formations on the Eastern Front.

Statistics on the number of military horses that were infected with or died of anthrax are unavailable. Likewise, the report did not provide information on whether wartime veterinary research facilities of the Western Army used methods for diagnosing anthrax. The following is known about the anthrax situation on the fronts.

At the Eastern front thirty cases of anthrax among horses were registered in Lithuania, the Bialystok-Grodno district and Courland. Further cases occurred on two farms during the period 1916–1918.

At the Southern front (Romania, the Danube Front), larger numbers of anthrax cases in horses were reported.

Major outbreaks occurred in cattle at livestock depots or during transport in the General Government of Warsaw, at Modlin Headquarters, in Brest-Litovsk (Bug area), in cattle and sheep on the Danube Front, and in pigs on the Western Front in Roulers in 1915.

On 5 December 1916, the chief veterinarian in the East prohibited the dissection of animals infected with anthrax because of the risk of infection during animal autopsies: *"During the dissection of a cow that had died of anthrax and in which the presence of B. anthracis had earlier been bacteriologically confirmed, two persons, including the veterinarian who performed the autopsy, contracted an anthrax infection. Because of the risk of disease transmission during the dissection of animals with diseases that are transmissible to humans, the Supreme Commander of All German Forces in the East (Oberbefehlshaber Ost) prohibits the dissection of animals if the animal that died or was killed has a bacteriologically confirmed diagnosis of anthrax."*

In addition, he issued the following regulations for his area of responsibility: *"Animals known or suspected to have anthrax and all associated items of equipment must be immediately isolated. All other horses of the affected formation can be used for military duties without limitations both inside and outside the premises.*

The stalls where horses known or suspected to have anthrax are kept must be disinfected and cordoned off after the removal of litter. Carcasses, as well as discharges, feed, and the litter at the site where diseased horses were kept, must be destroyed in a safe manner at remote locations in accordance with the Epizootics Regulations. Skinning is forbidden.

Regardless of immediate action taken, the diagnosis of anthrax must be confirmed by microscopy. Blood and splenic pulp specimens (Annex 2 of the Epizootics Regulations) must be sent to a blood analysis facility.

Sites where anthrax carcasses were buried must be enclosed by a fence and "Anthrax!" signs must be visibly posted; grass, hay, etc. from such sites can cause anthrax. The causative agents of anthrax are extremely resistant and difficult to destroy. For this reason, carcasses, discharges etc. must be destroyed thoroughly." [262].

In September 1917, the Eastern Administration reported that anthrax as an infectious disease was "*seuchenpolizeilich*" not relevant [262].

In 1917 and 1918, carcass disposal facilities were established in the east, in the west and in the Balkans [262]. At these sites, too, the skinning of animals known or suspected to have anthrax was forbidden with a view to preventing the spread of epizootics or their transmission to humans.

In the period 1916–1918, German agents were suspected of covert attempts to infect horses, mules, cattle and reindeer that were bound for the armies of the Entente Powers with anthrax spores and glanders in Romania, France, Argentina, Finland, Spain, and the United States [129]. There is no clear evidence, however, whether, and to what extent, these efforts were successful [129].

Anthrax in the armies of World War I. In World War I, 17,837,860 soldiers served in the German Field Army (*Feldheer*) and 8,780,728 soldiers in the Replacement Army (*Ersatzheer*) [263]. During the four war years, 4,819,557 soldiers (5,587,244 soldiers according to [264]) were wounded and 14,657,324 soldiers were affected by diseases [265].

The number of soldiers who acquired infectious diseases in the field was 1,426,091 [263]. Of these, 449,702 received treatment in field hospitals primarily for influenza (11.2%), inflammation of the tonsils (6.5%), dysentery (5.3%), typhoid fever (4.0%), malaria (4.0%), other infectious diseases (4.0%), diphtheria (0.77%), typhus (0.28%), and tuberculosis (0.28%) [265].

According to Report No. 18 of the German Medical War Report 1914/1918 [265], there is evidence of only a single case of anthrax in the German Field Army and Replacement Army. The patient was *"an assistant pointsman with a history of five days of stomach pain who was dying when he arrived at the field hospital in Warsaw."* Anthrax lesions involving the right tonsil, the stomach and the intestine were detected during the post-mortem examination.

Soldiers of the Field and Replacement Armies most commonly suffered from diseases of the skin, appendages and subcutis (e.g. boils, inflammation of cellular tissue and sweat glands, abscess formation, or similar conditions) (1,049,947 diseased soldiers). In addition, 3,600 wounded soldiers had tetanus [263, 265].

Most injuries were caused by all types of fragments of munition (58.7%) and infantry projectiles (35.7%) [263].

Initial surgical wound care was provided at main dressing stations and front-line field hospitals and consisted of the application of iodine to the wound area, the removal of foreign particles from open wounds, bleeding control, and immobilisation [266].

According to Läwen et al. [266], *"most projectiles that were removed from human bodies contained (skin-borne and soil-borne) micro-organisms from particles of soil, clothing or skin that were dragged into the wounds; moreover, there were fragments and secondary projectiles, stones, pieces of wood, coins, metal particles, etc."* and *"clothing must be considered as a means of transmitting soil-borne bacteria into wounds"*. This observation was confirmed elsewhere [267, 268].

A poster from the Military Academy of Berlin which dates back to that time shows examples of foreign bodies embedded in wounds (Fig. 3).

A wide variety of micro-organisms were detected in fresh war wounds and on projectiles after only one or two hours [266]. Among them were staphylococci, streptococci, *Micrococcus tetragenus (Gaffkya tetragena)*, Gram-negative diplococci, diphtheria-like bacilli, *Proteus*-like bacteria, *Bacterium (Escherichia) coli*, and bacilli that are commonly found in the upper soil layers.

Klose [269] investigated 111 cultures from combat areas in the vicinity of Verdun, Flanders, Brest-Litovsk and the Vosges and performed serological tests on 130 strains from wound and autopsy specimens. He detected Welch-Fraenkel gas gangrene bacilli in 34%, blackleg bacilli in 32%, and *Bacillus putrificus* Bienstock, the causative agent of malignant oedema, in 24% of the specimens.

Fig. 3. Foreign bodies in war wounds. Photograph (repro): Military Pathology Collection of the Military Medical Academy, Berlin, 1945, missing. German Armed Forces Medical Academy, Military History Collection, no signature

Klose [268] further analysed 12 soil samples that he collected in different sections of the Western and Eastern Fronts during the war and detected all three types of the causative agents of gas oedema in seven samples and two types of the causative agents in five samples. These agents were often found in mixed infections when contaminated soil entered the wound together with fragments and pieces of clothing. For this reason, the samples had to be incubated under strictly anaerobic conditions for several weeks and animal tests were required. It was, however, not always possible to meet these requirements [268]. Apparently, anthrax spores were not detected.

Läwen et al. [266] detected bacteria in fresh war wounds and on projectiles after only one or two hours. Among these

Table 5. Items that caused primary wound infections during World Wars I and II, the Korean War and the Vietnam War and composition of the primary wound micro-flora [263, 266–272, 290, 295, 302, 311, 312, 315–319, 328, 350]

Primary wound infection by contaminated items	Composition of primary wound micro-flora[a]	
	Soil micro-flora	Body micro-flora
Handgun or machine gun projectiles	Gas gangrene and gas oedema complex:	*Staphylococcus* spp.
Grenade fragments	*Cl. perfringens*, *Cl. novyi*, *Cl.*	*Streptococcus* spp.
High-velocity missiles	*histolyticum*	*Micrococcus tetragenus*
Pieces of clothing	Blackleg bacilli	Gram-negative diplococci
Pieces of wood	*Clostridium tetani*	*E. coli* and coliform bacteria
Metal particles	Fusiform bacteria	*Proteus*-like bacteria
Stones	*Bacillus* spp. (e.g. hay bacilli)	*Corynebacterium* spp.
Soil particles	Anthrax-like bacilli	*Pseudomonas* spp.
Coins		*Klebsiella* spp.
Parts of buildings		*Hafnia* spp.
Foreign corpses		*Citrobacter* spp.
Human and animal faeces		*Providencia* spp.
		Aerobacter spp.
		Enterobacter spp.

[a]Most of the bacterial species included in this table were also isolated from soil and water samples.

were staphylococci, streptococci, diplococci, *M. tetragenus*, *Bacterium coli*, *Proteus*-like bacteria, and micro-organisms that are found in the upper soil layers such as Fraenkel's gas bacillus, bacilli that cause malignant oedema, tetanus bacilli, other gas-forming anaerobic organisms, diphtheria-like bacilli, anthrax-like bacilli with or without spores, and hay bacilli.

It is interesting to note that French researchers identified a similar spectrum of pathogens in war wounds [266].

Klose [267] reported that most wound infections were caused by anaerobic bacteria in wartime and by aerobic bacteria in peacetime. From the very first years of the war, gas oedema, gangrene, phlegmons and malignant oedema were common in trench soldiers and appeared in almost epidemic numbers [267, 269]. Trench warfare was primarily associated with wounds from indirect projectiles and primary wound infections that were mainly caused by anaerobic bacteria that are ubiquitous in the soil [270].

Not all organisms that entered wounds, however, had pathogenic effects [270, 271].

Neither Klose nor later authors who studied the wound infections of World Wars I and II mentioned *B. anthracis* as a pathogen or reported the occurrence of a type of wound anthrax [271, 272] (Table 5).

In the multi-volume *Handbuch der Ärztlichen Erfahrungen im Weltkriege 1914/1918* (Handbook of Medical Experiences During the World War of 1914–1918) [273], Matthes reported five patients with intestinal anthrax who showed acute cholera-like signs and symptoms and then died. Apart from these five cases, two cases were mentioned in the German Army Veterinary War Report [262] and one case in the German Medical War Report 1914/1918 [265] so that there were altogether eight anthrax cases during the entire war.

Anthrax, however, was not mentioned as an infectious disease or as a cause of wound infections in statistics on communicable diseases.

Diseases of epidemiologic relevance were typhoid fever, paratyphoid fever, shigellosis, Asian cholera, Weil's disease, typhus, smallpox, malaria, meningococcal meningitis, diphtheria, influenza, and Russian trichinosis [265, 273]. A similar spectrum of infectious diseases was found in prisoner-of-war camps [266]. The German Congress on Internal Medicine that took place in Warsaw in 1916 also addressed the aforementioned wartime epidemics but did not discuss anthrax [260].

Anthrax thus was not of relevance to the German Army Medical Service in the various theatres of war, which included highly endemic regions such as the Balkans, Eastern Europe and the Middle East. For this reason, Hoffmann [273] concluded in retrospect that *"Army epidemics like those from the past no longer exist. Robert Koch, the great genius, has broken their power by his aetiological research."*

Problems were mainly associated with hygiene practices at battle positions, trenches and shelters when measures were taken to drain off water and dry out the ground or when latrines were established or disinfected [273]. The potential risk of exposure to, for example, anthrax spores in the soil or water was, however, not addressed.

During World War I, the number of wounded soldiers who received medical treatment was 367,500 in the French Army, 2,576,058 in the British Forces, and 260,783 in the American Expeditionary Forces [264]. There are no data on anthrax infections of wounds.

Morillon (personal communication) reported that there were only 15 anthrax infections in French Army soldiers serving on the front. These infections were single cases of typical cutaneous anthrax presenting as malignant pustules or malignant anthrax oedema. The initial lesions were located on the neck and chest in the majority of cases and on the face (frontal and temporal regions) in three cases. Dopter [274], a French microbiologist during World War I, described seven patients with cutaneous anthrax in the region of the neck and chest. They became infected as a result of wearing sheepskin jackets under their uniform during the cold season (Fig. 4). Contact with acute or previous animal cases of anthrax was excluded on the basis of investigations into the aetiology of the infections. There was no acute epizootic among livestock and the front lines did not run through endemic anthrax areas. Moreover, there was no evidence supporting the hypothesis that contamination was caused by anthrax carcasses that had been excavated when trenches were built.

Roger [274] assumed that the soldiers became infected most likely by spore-contaminated sheepskin hats that provided protection against the cold in winter. This assumption is supported by the fact that cutaneous anthrax occurred on the temples in those patients who wore hats with sheepskin ear flaps. Roger also reported that soldiers in the Russian army contracted anthrax because they wore uniforms with sheepskin applications [274].

Ireland [275] and Siler [276] observed that the U.S. Army reported a total of 149 primary admissions for anthrax (2 officers, 146 enlisted men, 1 case among native troops, 22 deaths) from 1 April 1917 to 31 December 1919. Of these, 100 cases were seen in the territory of the United States and 43 cases in the U.S. Army American Expeditionary Forces in Europe (excluding Russia). The majority of cases occurred sporadically in 22 camps across the entire United States, during transport, or upon arrival in France and England. It had already been known before the beginning of the war that anthrax infections were most likely caused by contaminated animal products such as skins, hair, bristles (shaving brushes), and wool.

Fig. 4. Greeting card of World War I. Members of the French Medical service wearing sheepskin for protection in cold environments. Right: Medical officer (second lieutenant). Photography: Courtesy of Professor Marc Morillon, 2014

The majority of U.S. soldiers developed cutaneous anthrax, which presented as malignant pustules and was most commonly located on the shaving areas of the face and neck. Ireland [275] and Siler [276] reported no cases of inhalation anthrax, several cases of intestinal anthrax and anthrax meningitis as well as anthrax septicaemia in the majority of cases.

The United States Public Health Service found that soldiers used shaving brushes made of spore-contaminated horse hair that had been imported to the United States from China and Siberia and had been processed without having been cleaned and disinfected as required. Bacteriologists in the United States, England and France were able to detect agents in batches of these shaving brushes [275].

During the war, shaving brushes accounted for the majority of anthrax cases in the army, but leather chin straps and toilet soap were also found to be vehicles of transmission in some soldiers.

Ireland [275] did not report any anthrax cases that resulted from contact with soil possibly contaminated with spores (e.g. in trenches or shell craters) or that occurred after injury.

In Europe too, anthrax infections caused by spore-containing shaving brushes were a general problem during World War I since animal hair and bristles were often imported illegally because of the Blockade of Germany established by the Entente Powers [28]. This was also alleged to be the cause of anthrax cases that occurred in England (including 50 British soldiers) as well as in Denmark, the Netherlands and Italy [28, 38].

Already during the Russo-Japanese War (1904–1905) too, spore-containing sheepskin hats and jackets caused several hundreds of anthrax cases among Russian soldiers [38]. Shljachov [277] reported that 6.5% of all anthrax cases were caused by clothing made of the furs or hides of infected animals, too. These cases, however, were not included in the statistics of the armies of Tsarist Russia armies on infectious diseases during this war. According to these statistics, there were 90,902 patients with influenza, typhoid fever, malaria, dysentery, typhus, relapsing fever, and smallpox smallpox [278].

Before the Revolution, there were at least 15,000 cases of human anthrax in Russia each year [279].

During World War I from 1915 to 1917, the Russian armies reported a total of 5,069,920 wounded and 3,748,669 sick soldiers including 291,926 (6.5%) patients with infectious diseases. Data on anthrax cases were not given. From February 1915 to January 1917, hospitals in Moscow Governorate provided treatment to 1,092 patients with infectious diseases [280]. Data on anthrax cases on the fronts or in hospitals are not available although there was likely no improvement in the epidemic situation of this zoonotic disease in the Eastern theatre of war when compared to the years preceding the war. Therefore, it is unknown whether the large Russian cavalry units were unaffected by anthrax.

Even before combat commenced in the theatre of war in Southwestern Asia and before the Ottoman Medical Service

Table 6. Human and animal anthrax cases in Germany from 1913 to 1924 [28, 60]

Year	Humans	Animals	Including	
			Horses	Cattle
1913	224	6,816	97	4,498
1914	203	7,181	57	4,218
1915	67	2,398	13	2077
1916	37	2,320	16	1,093
1917	34	1,370	13	1,064
1918	29 (18)	1,002	22	826
1919	18	743	15	600
1920	35	875	23	699
1921	80	1,315	19	943
1922	118	1,506	38	1,136
1923	106	1,569	59	1,196
1924	49	1,512	175	1,209

was reorganised at the end of 1913, anthrax as well as typhus, cholera, relapsing fever, typhoid fever, glanders and influenza had a devastating impact on the armed forces and the population [281].

Epidemic and epizootic control measures were insufficient and affected by religious rules of Islam. In addition, there was a lack of qualified veterinarians, medications and vaccines [281, 282]. For example, the killing and burial of injured or sick animals was not permitted. These animals were left to vultures. As a result, outbreaks of epizootic diseases, especially glanders, mange and cattle plague, occurred [282]. Surprisingly, there was no evidence of anthrax in the population, among domestic and military animals (horses, oxen, camels) or in the Turkish and German-Austrian troops during the war, at least not in available reports of German hygiene experts and physicians or in patient lists from hospitals on the Sinai and Palestine Front [283].

Table 7. Number of anthrax cases in selected countries during the period 1923–1925 [28, 60]

Country	Cases	Country	Cases
Bulgaria	10	Poland	202
Free City of Danzig	1	Russia (Soviet republics)	31,668 (1924–1925)
Denmark	12	Switzerland	8
Germany	406	Serbia, Croatia, Slovenia	501 (1925)
Estonia	8	Czechoslovakia	168
Finland	4	Hungary	8
Italy	6,536	United States of America	277 (1924–1925)
Latvia	6	Uruguay	235 (1924–1925)
Lithuania	21		
Austria	28		

Anthrax in the civilian sector. During the period 1911–1919, a total of 1,175 industrial cases of anthrax occurred in Germany. For the period 1910–1920, 405 industrial cases were reported in France and 714 in England [28].

The number of anthrax cases among humans and domestic animals dropped considerably in the German Reich during World War I (Table 6) as a result of the blockade established by the Entente Powers [284]. Between 1914 and 1919, it decreased from 203 to 18 human cases and from 7,181 to 743 animal cases [285].

Among tanners, the number of cases fluctuated between 92, 77, 78, 65 and 56 during the period from 1910 to 1914 but only between 15, 7, 3, 12 and 6 during the period from 1915 to 1919 [60]. When the importation of animal products such as skins, hair and bone meal from endemic anthrax areas (India, China, The Balkans, African colonies) resumed in 1920, the number of anthrax cases increased again (Table 6).

Stricter veterinary police measures and import controls led to a decrease in the incidence of anthrax in the German civilian population from 252 cases in 1927 to 68 in 1934 and 49 in 1940 [60]. Where available, Tables 7 and 8 provide the

Table 8. Number of human anthrax cases in selected countries during the period 1923–1947 ([28, 60])[a]

Country	1923–1925[b]	1924–1926	1927–1929	1930–1932	1933–1935	1936–1938	1939–1941	1942–1944	1945–1947
USSR (Union of Soviet Socialist Republics)	31,668[b]	15,435	15,950	4,542	2,569	–	–	–	–
Bulgaria	10	–	465	856	1,026	914	624	709	1,525
Italy	6536[b]	2,288	2053	1,653	1,278	1,128	787	826	1710
Romania	–	–	–	–	1,293	2,228	1,089	674	880

[a]Annual means.
[b]Number of cases from 1924 to 1925 [28].

Table 9. Anthrax cases in different occupations (as percentages of all occupational diseases) [38]

Occupations	Germany (1910–1923) %	England (1910–1922) %	France (1910–1920) %
Farmers	4.9	7.9	–
Slaughterers	34.4	5.8	–
Knackers/renderers/skinners	12.0	1.6	–
Tanners	36.9	21.3	64.7
Wool workers	–	47.5	26.7
Bristle workers/brushmakers	8.1	6.2	6.6
Other occupations	3.7	8.1	2.0

numbers of anthrax cases for several countries that did not take part in World War II from the beginning.

In Russia according to Burgasov [279], there were at least 15,000 cases of human anthrax every year until 1917. In Tsarist Russia and later in the Soviet Union, more than 70,000 anthrax cases were reported for the period 1900–2003 [78]. An annual mean number of 31,668 human anthrax cases occurred in the population during the period 1924–1925 alone (Table 7) [28].

Similar to World War I, the blockade of imports of raw animal products from endemic areas, which was established by the Entente Powers, led to a decrease in the incidence of anthrax from 0.11 to 0.010, 0.016, 0.014, 0.008 and 0.004 cases per 10,000 population from 1939 to 1944 [28]. A similar decline in the incidence of anthrax was also reported for some of Germany's allies (Table 8). Where available, Table 8 provides the number of anthrax cases for several countries that did not take part in World War II from the beginning.

It is interesting to note that, before and after World War II, civil engineering activities involving soil disturbance such as the construction of roads and canals were not included in Western European statistics as causes of occupationally related cases of anthrax (Table 9).

Anthrax in the troups during World War II (1939–1945)

Data on infectious diseases and wound infections from medical reports that are available from countries that participated in World War II, i.e. Germany, Britain, the United States and the Soviet Union, do not provide evidence of anthrax cases. Apparently, this zoonotic disease did not present a problem to the *Wehrmacht* (German armed forces) either before or during World War II. Accordingly, there are no articles on anthrax or references to 'anthrax,' '*B. anthracis*' or 'anthrax bacilli' in *Der Deutsche Militärarzt*, which was the official journal of the German Medical Service from 1936 (Volume 1) to 1944 (Volume 9), or in the five volumes of *Der Deutsche Sanitätsdienst 1921–1945* by Fischer.

Anthrax in animal populations during World War II (1939–1945). From 1939 to 1945, the German military used an estimated number of 2.75 million equids (especially horses and mules). Three quarters of the horses were employed on the Eastern Front alone [261]. Exact figures are unavailable since relevant statistical data were destroyed during the last months of the war [261].

From a veterinary perspective, anthrax obviously played no role during World War II and did not affect the animals that were used by the *Wehrmacht*.

This is noteworthy since combat activities took place in highly endemic countries with many anthrax foci (the Balkans, Italy, European parts of the USSR) (Tables 6 and 7).

The surveillance, prevention and control of epizootic diseases in the *Wehrmacht* was addressed in Army Veterinary Regulations 56 of 6 April 1932 (*Heeresveterinärvorschrift* – H. Dv. 56) including Epizootics Regulations (*Seuchenvorschrift*) in Annex 2, Wartime Veterinary Regulations 56/3 (*Kriegsveterinärvorschrift* – H. Dv. 56/3), and Wartime Veterinary Regulations 90 (*Kriegsveterinärvorschrift* – H. Dv. 90), which entered into force in 1940 [261].

Number 51 of the Wartime Veterinary Regulations provided, for example, that unit medical officers be notified in the event of anthrax cases. Enlisted personnel had then to be informed about routes of anthrax transmission. Animals known or suspected to be infected with anthrax and associated pieces of equipment, including drinking buckets, had to be isolated, the cleaning of affected animals was prohibited, and the stalls where the animals were kept as well as both adjacent stalls had to be disinfected and cordoned off [285]. The use of anthrax-infected carcasses was prohibited. These carcasses as well as discharges from the affected animals and contaminated objects (e.g. feed, fertiliser) had to be disposed of in a safe manner. In addition, the use of contaminated areas for grazing animals and hay production was prohibited [285].

The *Wehrmacht* Veterinary Service had 26 veterinary laboratory units (*Veterinäruntersuchungsstellen*) that were able to conduct laboratory tests for the diagnosis of animal diseases and the control of food of animal origin [261].

The Army Veterinary Laboratory Unit (*Heeresveterinäruntersuchungsamt*) alone analysed food of animal origin and performed serological and bacteriological tests of approximately 1,750,000 samples in order to detect glanders, dourine and other (epizootic) diseases. There is, however, no evidence of samples that were positive for anthrax [261].

It should be noted that there was an order requesting Mobile Veterinary Laboratory Unit 509 to report in writing all positive test results indicative of anthrax, malleus (glanders) and piroplasmosis [261]. Bacteriological food inspections, however, were deficient because veterinary laboratory units were often locally unavailable.

Food safety was controlled in accordance with Army Veterinary Regulations 43a and applicable laws and regulations on meat inspections and food. The focus of food safety control measures was on the illegal slaughtering of animals since an increasing number of outbreaks of trichinosis and tapeworm infections were noted especially in Poland, the Soviet Union, and the Balkans [261]. Although many anthrax foci existed in these countries, anthrax apparently did not present a problem. In addition, carcass disposal facilities, rendering facilities and knackeries, which were legally required in Germany, were often absent in the occupied areas. As a result, animal carcasses were buried after usable animal materials, e.g. skins, animal meal, bone oil, horse skins, hides and hair, had been obtained in mobile rendering installations of veterinary companies [261].

Although these activities were associated with potential risks of exposure, no anthrax cases among military personnel were reported. This suggests that the processed animals had been free of anthrax.

Whether acts of sabotage led to relevant outbreaks of anthrax in occupied Poland is doubtful. For example, Rowecki, a Polish general, reported on 27 April 1941 that cattle had been infected with anthrax in four counties and in three towns [286].

In 1943, however, the Chief of Staff of the *Wehrmacht* Medical Service provided a list of actions that had been carried out in the General Government and included the following [287]:

> "(1941–42): . . . in Poznań . . . anthrax bacteria were successfully used in horses in two stud farms."

> "(August 1942): Forty-five boxes were seized at Lublin station; among other things, the boxes contained . . . bottles, each of which filled with 200 ccm of . . . glanders bacteria or anthrax suspension."

It should be noted that there was a Department for Bacteriological-Toxicological Warfare in Poland before the German invasion [286]. This department had access to eight bacteriological laboratories and thus to anthrax strains that were suitable for use in acts of sabotage.

In spite of tens of thousands of individual cases of disease, there were no major outbreaks of feared epizootic diseases such as glanders, equine contagious pneumonia, equine viral arteritis, equine infectious anaemia, and mange in military horses because of extensive veterinary preventive and police measures including vaccinations and epidemiological investigations in theatres of war on the basis of data from the International Veterinary Office in Paris [261]. Military animals were mainly affected by strangles and contagious catarrh of the airways, pneumonia, fatigue as a result of overexertion and malnutrition, frostbite, and direct weapon effects [261].

No outbreaks of anthrax are mentioned in a monograph entitled *Das deutsche Heeresveterinärwesen im Zweiten Weltkrieg* (The German Army Veterinary Service in World War II). This is confirmed by Betzler [261], who reported that *"all other epizootics such as equine infectious anaemia, equine viral arteritis, rabies, . . . anthrax etc. have not occurred."*

It is highly probable that the strict implementation of the aforementioned regulations and directives relating to the extensive prohibition of transporting meat and other animal products and the import of live animals from occupied areas contributed to preventing the introduction of epizootic diseases, including anthrax, into Germany during the war [261].

Many clinical and epizootological documents and situation reports, however, were lost during the retreat from the fronts [261].

According to a draft version of *Geschichte des Kriegsveterinärwesens 1939–1945* (History of the War Veterinary Service 1939–1945, Military History Research Office, p. 328), 1,580,000 animals were lost from 1 September 1939 to 31 August 1944. Exact numbers of cases and statistics on losses for specific (epizootic) diseases are not available. This applies also to epizootic diseases from September 1943 to April 1945 [261]. For this reason, there is no definitive information on the occurrence of anthrax in military animals of the *Wehrmacht*.

If Britain had dropped linseed cattle cakes in retaliation to an anticipated biological attack from Germany, a drastic deterioration in the epizootic situation would likely have occurred [136]. By 22 April 1943, five million cattle cakes, each filled with a lethal dose of (500 million) anthrax spores were ready for aerial drops over German farmland where cattle or sheep would eat them (Operation Aladdin). The use of this highly infective dry feed would have caused extensive livestock losses in Germany and – similar to the situation on Gruinard Island – may have contaminated agricultural land for many decades [136]. Appropriate protective measures prevented anthrax infections during the preparation of suspensions with high concentrations of spores and the packing of cattle cakes [129, 136].

Anthrax in military personnel. About 18.2 million members of the *Wehrmacht* and *Waffen-SS* took part in World War II. Of these, approximately 5.3 million died [288]. There is, however, no Medical Report for all years of the war so that definitive data on the total number of sick and wounded and the incidence of infectious diseases are unavailable.

Information can thus be obtained only from the unit medical records of the German Medical Service, according to which a total of 13,475,764 Field Army (*Feldheer*) and 9,135,722 Replacement Army (*Ersatzheer*) soldiers received medical care during the first four years of the war. According to a German Army Medical Report [289], there were 3,015,589 wounded and 16,517,879 sick soldiers from 1 September 1939 to 31 August 1943.

The Field Army accounted for 2,100,511 sick soldiers and the Replacement Army for 1,292,754 sick soldiers during this period [290]. The main causes of disease were inflammation of the tonsils, colds, dysentery, malaria, scarlet fever, and diphtheria. According to Müller [263, 291], there were 175,570 members of the Field Army and 7,852 members of the Replacement Army who had "other communicable diseases" between 1939 and 1943. These diseases included rare zoonotic diseases, i.e. trench fever (five-day fever), Pappataci fever, mud fever, tularaemia, trichinosis, dengue fever, and relapsing fever. The author concluded that the number of reported cases of anthrax was too low to be included in the statistics.

According to Zimmer [292], medical treatment was most commonly provided for dysentery, cholera, typhus, typhoid fever, paratyphoid fever, trench fever, malaria, tuberculosis, diphtheria, scarlet fever, tularaemia, Pappataci fever, amoebic dysentery, Malta fever, and trichinosis. These findings were confirmed in a study on the role of consulting physicians of the German Army Medical Service from 1939 to 1945 [292]. There are no data on anthrax.

The 744,807 reported cases of diseases of the skin, appendages and subcutis included boils, inflammation of cellular tissue and sweat glands, abscess formation, and similar conditions, but not anthrax [263]. This zoonosis obviously played such a minor role in the Medical Service of the *Wehrmacht* that no special vaccinations were required [293].

In the reports that were submitted by consulting surgeons and physicians during World War II, there was no mention of anthrax for the period 1939–1944 [290, 292, 294]. The main causes of wound infections were gas oedema and gangrene caused by anaerobic spore-forming organisms as well as phlegmons and pus formation caused by staphylococci and streptococci, and wound diphtheria [290, 295]. Knofloch [295] distinguished four groups of bacteria that caused wound infections:

Pyogenic bacteria, including different forms of *Streptococcus* spp. and *Staphylococcus aureus*
Haemolytic bacteria, *Micrococcus tetragenus* in rare cases
Anaerobic bacteria, gas-forming infections caused by Welch-Fraenkel bacilli, *Bacillus novyi, Bacillus histolyticum*, blackleg bacilli, tetanus bacilli, fusiform bacteria
Putrid infections caused by putrefactive bacteria
Mixed infections with *B. coli, B. pyocyaneus*, hay bacilli, and others.

Single cases of tetanus, tularaemia and suspected glanders were reported [290].

It should be noted that the idea of using anthrax spores for military purposes dates back to as early as the 1920s. According to British intelligence in 1939, Germany was allegedly working on attempts to "infect" grenades with anthrax cultures. If anthrax organisms had entered wounds, the mortality rate would have been 95%. This information, however, was found to be incorrect since Hitler always ruled out the use of biological weapons and the responsible German agencies refused to perform such work [129, 287].

Documents relating to the French biological weapons programme, which fell into the hands of the German occupiers in 1940, revealed that there had been theoretical considerations *"to infect projectiles with bacteria . . . in order to make the effects of projectiles more malicious"*. The plan was to place glass ampoules filled with anthrax and other organisms in bombs and rifle grenades in order to make these devices "infectious". In field trials that were conducted in 1939, for example, spore-contaminated fragments were produced through the explosion of grenades that had been filled with *B. pseudoanthracis* spores. Previous experiments on guinea pigs had shown that such projectiles could cause lethal infections [129, 287].

From a military medical perspective, zoonotic communicable diseases were of no relevance [296]. No mention of anthrax was made in a manual on internal medicine [297], in a manual on the special prognosis of internal diseases [298] or in a book on the occurrence and control of wartime epidemics [299]. Schloßberger [299] regarded especially plague, cholera, typhoid fever, dysentery, typhus, and epidemic hepatitis as infectious diseases that were typically encountered in times of war.

In a manual entitled *Wehrhygiene* (Military Hygiene), anthrax was briefly described as a *"rare disease"* and *"soil-borne epidemic"*, which, however, was *"of almost no relevance"* to the *Wehrmacht* [300, 301].

This was probably the reason why there were no special rules for the construction of field fortifications involving the movement of soil in front sectors known to be anthrax foci [302, 303]. Potential risks of infection for engineers were associated only with gas oedema (mine injuries contaminated with soil) and tetanus (wood splinters) [302].

From 1 July 1941 to 18 February 1943, a total of 102,843 autopsies were carried out and demonstrated 19,291 aerobic wound infections (including wound diphtheria) and 6,053 anaerobic wound infections [290]. The most common causes of death were typhoid fever, parathyphoid fever, dysentery, cholera, influenza, typhus, and Weil's disease. A total of 9,664 deaths were attributable to "other" causes of infection [290]. It is no longer possible to determine whether this figure includes anthrax infections.

According to unit medical records, 175,000 cases of "other communicable diseases" (fourteen infectious diseases other than typhoid fever, paratyphoid fever, dysentery, cholera, smallpox, and typhus) were reported for the Field Army and 7,852 cases for the Replacement Army.

Owing to a lack of concrete data, a statistical evaluation of approximately 12,000 further patients in this category was not possible. Among them were a few patients with Bang's disease, yellow fever and anthrax [291].

The preventive health care that the *Wehrmacht* provided in the occupied areas consisted of preventing and limiting typical wartime epidemics in the civilian population [304]. Anthrax played no major role. This applied to war missions of the Wehrmacht in subtropic and tropic areas, too [305].

For this reason, it is not surprising that anthrax was not addressed in articles on infections in the *Wehrmacht*, which were published in the journals of the Medical Service of the German armed forces *Wehrmedizinische Mitteilungen*, which became the *Wehrmedizinische Monatsschrift* in 1966 [291, 306–310].

It should be noted, however, that unit medical records and statistics on communicable diseases – similar to documents of the Army Veterinary Service – were lost or destroyed in the last two years of the war during the retreat [263].

During World War II, the U.S. military reported approximately 6 million cases of infectious and parasitic diseases, including 1,250,846 sexually transmitted diseases, 4,196,093 respiratory infections, 403,689 cases of malaria, 1,193 cases of typhoid and paratyphoid fever, 83,371 cases of dysentery, and 22,032 cases of food poisoning [311]. No cases of anthrax were reported.

The same applies to the British General Hospitals in Northwestern Europe, which provided medical treatment to 28,048 patients between July and December 1944 [312].

Microbiological analyses of samples from 37 wounded soldiers from Normandy, Belgium and Holland identified *Clostridium* bacteria, coliform bacteria and staphylococci but no bacilli [312]. Green [157] reported that there were no cases of anthrax in the armed forces of the United Kingdom during World War II. One likely reason for this was the early administration of penicillin for the management of wounds. In the British Army, penicillin or penicillin sulphonamide powder was applied to fresh war wounds in a preventive manner in 1943 [312]. As of July 1944, the British and U.S. armed forces had unlimited quantities of penicillin so that the early preventive administration of penicillin to wounded soldiers became the method of choice [311, 312].

According to Czickeli [241], fourteen Romanian soldiers died in 1942 from a cholera-like disease that was later found to be intestinal anthrax. Later epidemiological and bacteriological investigations confirmed that they had eaten cooked meat of a sick sheep.

In an earlier incident, an explosive outbreak which occurred at a railroad station in Yaroslavl and lasted from 6 to 17 July 1927, showed how difficult it was to diagnose anthrax only on the basis of clinical signs and symptoms. Twenty-seven workers developed acute symptoms indicative of influenza or mild gastroenteritis and within a short time died from what was found to be intestinal anthrax [313]. This epidemic was probably not a unique event during prewar times. Only on the territory of the Soviet Union, 31,668 human anthrax cases occurred between 1924 and 1925 (Table 6) [28]. In spite of the existence of many anthrax foci and anthrax outbreaks in the Eastern theatre of war, Red Army Medical Service reports provide no evidence of anthrax cases in the military, in the Soviet civilian population, or in military and civilian animal populations. It should be noted, however, that there were no official reports of anthrax cases from 1936 to 1947 (see Table 7).

The only information on anthrax infections during the war was provided by Viskovskiy and Rozhdestvenskiy [314] in Volume III of the Soviet Medical Service Report. At the time of the Soviet attack on Romania in August 1944, the epidemic and epizootic situation was unsatisfactory when it came to anthrax (see Table 7) and was thus a threat to the armed forces [280]. As a result of a low level of veterinary police surveillance, this zoonotic disease was common in local animals. Accordingly, anthrax morbidity rates in humans were relatively high and varied between 0.5 and 1.6 cases per 10,000 population from 1931 to 1940 (mortality rate: 5.1–8.7%) and between 0.2 and 0.5 cases per 10,000 population from 1941 to 1945 (mortality rate: 5.4–9.4%) [280, 314].

For this reason, the Red Army Medical Service provided human vaccinations against anthrax in particular for cavalry units from July to August 1944. A total of 90,000 Army soldiers was immunised with a live non encapsulated spore vaccine (called STI), which had been developed by N. N. Ginsburg and A. I. Tamarin in 1942. As a result, anthrax outbreaks were prevented in vaccinated populations [280, 314]. This preventive measure proved valuable also later in the war when combat took place in Hungary, where a large number of anthrax cases were reported among the local population in 1944 [314].

Occurrence of anthrax after 1945

Regional and local wars. During the Korean War, 67% of all war wounds were contaminated with anaerobic organisms. Bacterial contamination and infections were an “integral part” of all war wounds [315]. Examinations of wounded soldiers showed, that, similar to the situation in World Wars I and II, besides of pieces of clothing and bone fragments different bacterial species were introduced into wounds via soil particles [316, 317]. The majority of these bacteria were anaerobic spore-forming organisms, micrococci and streptococci whose toxins enabled them to enter tissue rapidly [315]. In 46% of the cases, the injuries were found to be contaminated with *Clostridium* spp. during primary debridément [316].

Bacillus spp. were detected in fresh wounds in 9.5% of 42 patients in the summer of 1952 and in 61.6% of 112 patients in the winter of 1952 [271]. *B. anthracis*, however, was not explicitly mentioned. Early debridement and the administration of penicillin and streptomycin led to a drastic reduction in the number of bacteriologically confirmed cases.

Other military medical reports on infectious diseases and wound infections in armed forces that participated in the wars in Korea and Vietnam do not contain data on anthrax [316, 318–323]. Between 1965 and 1968, approximately 500,000 U.S. troops were deployed to Vietnam. From 1966 to 1967, there were approximately 217,407 admissions to medical treatment facilities. Of these, approximately 70% were for communicable diseases [323]. Diarrheal diseases, respiratory diseases, malaria, skin diseases, and fevers of unknown origin accounted for 60% of these cases [323].

Palinkas et al. [322] reported that the total number of first hospitalisations among U.S. Marines was 192,654 in Vietnam between 1965 and 1971. Of these, 31,777 received treatment for infective and parasitic diseases and 16,113 for diseases of the skin and subcutaneous tissue.

According to Hardaway [324], 3.9% of the 17,726 U.S. soldiers who were wounded in Vietnam had acute wound infections. Initial wound management consisted of debridément in 80.5% and the topical application of antibiotics in 70%. Wound infections were present in 7.8% of the 24,742 soldiers who were hospitalised for maxillofacial injuries in 1968 [325]. In none of these cases did microbiological tests detect *B. anthracis*.

Between 1 January 1967 and 31 March 1968, Matsumoto et al. [319] analysed 1,531 cultures from wounds that had been swabbed immediately after U.S. soldiers had been wounded in Vietnam. Whereas 204 cultures showed no growth, 1,327 were positive. Of the 17 identified bacterial species, *S. aureus*, *Pseudomonas aeruginosa* and *Escherichia coli* were most commonly seen. *Bacillus* species, which are typical soil organisms, were not detected.

Similar results were reported by Kovaric et al. [326] who conducted a bacteriologic survey on 85 Vietnamese and 25 American soldiers who were treated for war wounds in a hospital in Vietnam from May to June 1967. No *Bacillus* species were found in the 78 samples that showed bacterial growth. Among the organisms that Tong [327] isolated from 63 fresh wounds of 30 injured U.S. Marines were commensals of human skin (*Staphylococcus epidermidis*) and organisms that are commonly found in moist environments such as *Mimea-Herellea* (probably *Acinetobacter* spp.), *Enterobacter*, and *B. subtilis*.

The immediate topical application of antibiotics made it possible to extend the infection-free period prior to debridément and to effectively reduce wound infection rates [318, 326, 328]. This would explain why *Bacillus* species were less frequently isolated from fresh wounds in the Vietnam War although these organisms were ubiquitous in soil. Matsumoto et al. [318], for example, detected apathogenic *Bacillus* species, such as *B. subtilis*, *B. mycoides*, *B. cereus* and *B. pumilus*, but no causative agents of anthrax in soil samples from areas where U.S. ground forces were engaged in combat.

In the Yom Kippur War in 1973, 22% of the 420 soldiers who had sustained injuries (mostly from high-velocity missiles) or burns were found to have developed an infection although they had received penicillin on the battlefield within 30–60 minutes after injury [329]. Anthrax infections were not reported.

Unusual epidemics of anthrax occurred in the Rhodesian Bush War between 1978 and 1980. Approximately one million cattle were reported to have died [37]. The epidemic involved a total of 10,738 human cases with 182 fatalities. All of the cases were among blacks living in rural areas known as Tribal Trust Lands, now known as Zimbabwe [37]. White settlers, their livestock, and members of the Rhodesian Army were not affected. There is some suspicion even today that this was a biological attack involving anthrax spores which the Rhodesian Army targeted at animals belonging to the black population [37]. In the 1970s, the white government maintained a limited biological weapons programme at the University of Rhodesia and planned to place anthrax spores and other organisms in cigarettes and chocolate in order to eliminate leaders in the liberation war [37, 330].

One reason for the massive spread of anthrax at that time was probably that the rural medical and veterinary system had collapsed and veterinary control measures were no longer provided. People were forced by hunger and malnutrition to eat sick animals that were slaughtered out of necessity and to use infected animal products. Safe drinking water was extremely scarce for both humans and animals [331].

All three forms of anthrax were observed [37, 238]. Clinically, cutaneous anthrax acquired by direct contact with sick animals and infectious animal tissue was the predominant manifestation of illness [37]. Other causes of infection were the bites of blood-feeding insects (especially stable flies and horseflies) and scratching with fingernails that harboured infectious blood or contaminated soil particles [37]. This latter route of transmission had already been described by Lindtrop in 1927 [28].

Wilson et al. [238] reported that the epidemic in the Tribal Trust Lands lasted until December 1984 and caused 17,199 human cases including over 200 fatalities. The manifestation rate was 0.43% in the overall Tribal Trust Land population of approximately four million or 2.1% in the rural farming population of 800,000 [238]. According to Fleischer (personal communication 2013), who provided treatment to more than 600 patients with cutaneous anthrax at that time, all patients were known to have had contact with animals. To his knowledge, there were no cases of infection caused by exposure to possibly contaminated soil.

During the Bosnian War, 4,545 patients were treated at the university hospital of Osijek from May 1991 to November 1992. Most of their injuries had been caused by explosive devices, firearm bullets, and blunt objects. Superficial aerobic wound infections exclusively were seen in 1.7% of patients [332].

Of the nearly two million personnel assigned to military service in Iraq and Afghanistan between 2005 and 2009, those who were wounded sustained more than 29,000 injuries. Improvised explosive devices (IED) caused 74% of the injuries [333]. From April 2010 to October 2013 alone, 902 of 15,504 Polish ISAF members underwent inpatient treatment for injury or sickness [333].

None of the above-mentioned or other military medical publications on Operation Desert Shield and Operation Desert Storm in Iraq, Operation Iraqi Freedom, Operation Restore Hope in Somalia, or Operation Joint Guard in Bosnia provided evidence of anthrax cases [334, 335]. The same applies to military operations of the armed forces of the United Kingdom from 1994 to 2014 [157].

Zouris et al. [336] analysed the records of 13,071 casualties of the U.S. Marine Corps and the U.S. Army during the Operation Iraqi Freedom Major Combat Phase (OIF-1, spring of 2003) and Stability Phase (OIF-2, spring of 2004) on the basis of the International Classification of Diseases (ICD-9). Of the 13,071 casualties, 3,263 were wounded in action (WIA) casualties and 9,808 were disease and nonbattle injury (DNBI) casualties [336]. The percentage of patients with infectious diseases ranged between 0.9 and 2.1%. Data on the spectrum of infectious agents are not available.

Aerobic cultures that were obtained immediately after injury from 61 separate wounds from 49 casualties in the spring of 2004 and that were analysed for the detection of aerobic bacteria provided no evidence of *Bacillus* species [337]. The bacteria most commonly isolated were skin-commensal organisms, i.e. different coagulase-negative staphylococci (CNS) species (32 cases) and *S. aureus* (4 cases).

Similar results were reported by Yun et al. [338] who retrospectively analysed bacterial cultures obtained from U.S. troops in Iraq between August 2003 and July 2004. A total of 176 isolates were recovered from U.S. patients (102 wound, 10 blood, 24 sputum, and 40 urine samples). The predominant bacterial isolates were coagulase-negative staphylococci (CNS) (34%), *S. aureus* (26%), and *Streptococcus* species (11%). Wounds were apparently contaminated with soil-borne bacteria only in rare cases. In both studies, *B. anthracis* was not identified.

Anthrax in armed forces of post-war Germany. Anthrax played only a minor role in post-war Germany. In the former German Democratic Republic (GDR), a mere 20 cases were reported from 1951 to 1958 [60]. Surprisingly, Sinnecker [339] did not deal with the occurrence and epidemiological features of anthrax in his monograph on general epidemiology whereas he addressed several other zoonotic diseases such as tularaemia, rickettsial diseases and salmonellosis.

In the Federal Republic of Germany, 77 anthrax cases were reported between 1949 and 1957. Of these, 30 cases were industrial anthrax [60]. The Robert Koch Institute registered the last case of cutaneous anthrax in 1994 and six cases of injection anthrax from 2009 to 2012 [340].

During the Cold War, no anthrax cases were recorded in the National People's Army (*Nationale Volksarmee*) and the Border Troops (*Grenztruppen*) of the GDR. At least, no case reports were published in the *Zeitschrift für Militärmedizin*, the journal of military medicine of East Germany (volumes 1958–1990).

Clinical aspects of anthrax and *B. anthracis* as a potential biological agent were briefly discussed only in a volume on military internal medicine (*Innere Militärmedizin*). It was published in 1984 as part of a series of manuals on military medicine (*Militärmedizin*). No information on anthrax, however, was available in the volumes on preventive health protection (*Vorbeugender Gesundheitsschutz*) (1972) and military hygiene and field epidemiology (*Militärhygiene und Feldepidemiologie*) (1987).

The analysis of European natural foci of zoonotic diseases, such as anthrax, was a major research topic among the military medical services of the Warsaw Treaty member states from 1970 to 1988 [341]. This included the occurrence of active anthrax soil foci on the European territory of the former USSR, which were predominantly found in marshes, black-coloured soil (chernozem), and alluvial soil [341]. The highest morbidity rates were seen in large cattles in the north western and in sheep and goats in the southern Soviet Union.

Anthrax soil foci and stationary anthrax sites that were unfavourable to livestock (stationary unfavourable sites – SUS) were classified as active, relapse active or non-active. Active and relapse active sites (approximately 20–25% of all SUS) were defined as places where anthrax occurred in animals at periodic intervals (every five to ten years) [341].

The risk of anthrax was assumed to rise in disaster settings, e.g. earthquakes or floods, and military exercises or wars [138].

Likewise, a higher anthrax risk was believed to be associated with the building of trenches, shelters or camps, the processing of dead animals and the slaughtering of sick animals in contaminated areas. Strict compliance with veterinary, occupational and food hygiene regulations and the vaccination of persons at a risk of occupational exposure to anthrax were therefore required [138]. For this purpose and in order to protect soldiers against potential biological attacks with anthrax spores, the Soviet live vaccines STI and GNKI prepared from the attenuated unencapsulated Shuya-15 strain [38] were available to the armed forces of the Warsaw Treaty (Pact) member states in a lyophilised state. The East German armed forces, for example, stored sufficient amounts of vaccines for its personnel in the Central Supply Depot near Spechthausen (Brandenburg) until 1990.

A search of the journals of the German military medical service (*Wehrmedizinische Mitteilungen*, *Wehrmedizinische Monatsschrift* and *Wehrmedizin*, which became *Wehrmedizin und Wehrpharmazie* in 1969) showed that in the *Bundeswehr* (German armed forces), too, no cases of anthrax have occurred since its founding in 1956 until to the present day. This applies to both the Federal Republic of Germany and anthrax endemic regions to which the *Bundeswehr* has been deployed. Latter include e.g. Turkey, Somalia, the Balkans, Afghanistan, Mali, Syria, Iraq and Sudan, where German troops took part in UN missions, disaster relief and NATO operations [282, 334, 335].

Frickmann et al. [342] analysed the infectious diseases for which military personnel who took part in the European Union Training Mission in Mali (EUTM Mali) sought medical care from 2013 to 2017. The total number of medical consultations was 9,805. The majority of infectious diseases were gastrointestinal and respiratory infections without pulmonary or systemic complications. There was no evidence of anthrax infections.

As a rule, military surgeons of the *Bundeswehr* Medical Service assume all gunshot injuries to be contaminated and to require surgical debridément, open wound management, and single-shot antibiotic therapy [343]. On the basis of this approach, wound infections caused by micro-organisms that are introduced into wounds are extremely rare.

The prevention of zoonotic diseases in the *Bundeswehr* is an integral part of preventive health care that is based on the German Animal Health Act (*Tiergesundheitsgesetz*), the Regulation on Notifiable Epizootic Diseases (*Tierseuchenanzeigeverordnung*), the German Protection against Infection Act (*Infektionsschutzgesetz*), and the Food Law (*Lebensmittelgesetz*). In accordance with this system of rules, suspect cases and clinical cases of anthrax and deaths from anthrax are notifiable upon suspicion in animals and notifiable upon diagnosis in humans.

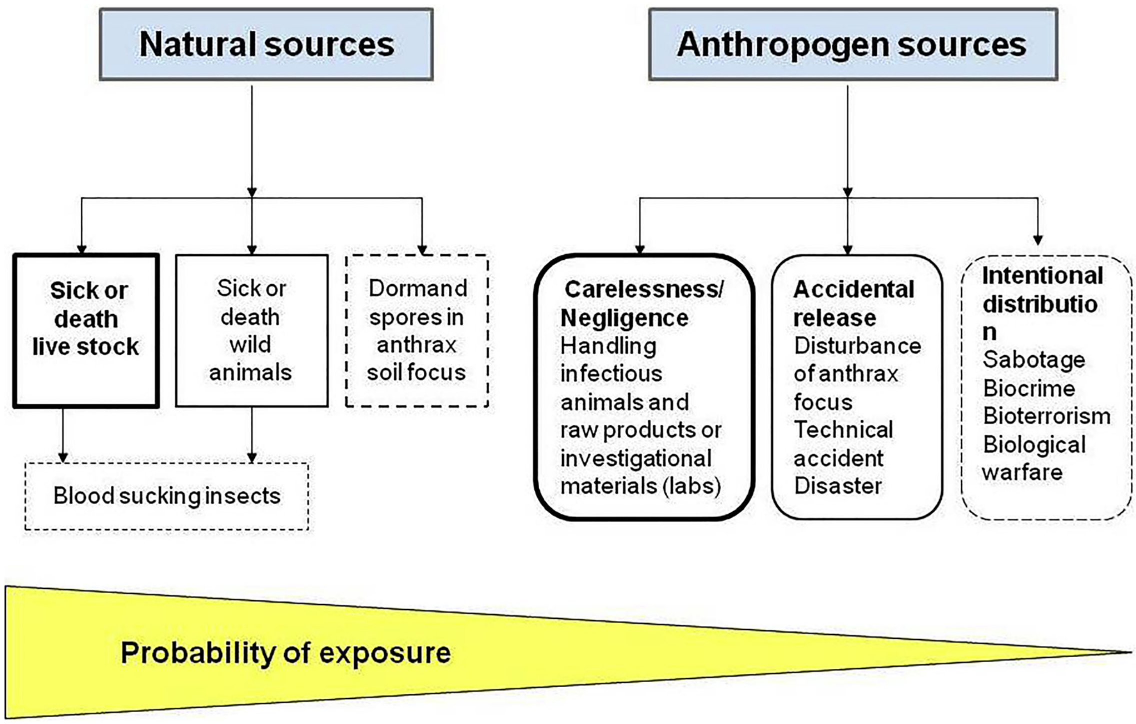

Fig. 5. Sources of contamination of the environment with spores of *B. anthracis*

The Veterinary Service of the Bundeswehr is responsible for the surveillance of epizootic and zoonotic diseases and the analysis of food, animal, environmental and water samples both in Germany and during deployments abroad [344]. A major objective is to prevent the introduction and spread of epizootic diseases during the redeployment of personnel and material. Further details are specified in Number 503 of Type A1 General Publication (*Zentralvorschrift*) A1-843/0-4011: *"Animals, animal parts and objects that can carry infectious substances must not be imported."* These requirements are translated into military orders during deployments and military personnel are informed in accordance with Annex 8.3 of the aforementioned General Publication (personal communication with Schotte, 2018).

But, there is a lack of historical data on past or present anthrax outbreaks in endemic areas of deployment as a result of missing or incomplete reports to the OIE and a large number of unreported cases (personal communication with Schotte, 2018). For this reason, it is difficult to assess the probable risk of infection objectively and to determine appropriate preventive measures. Such measures would be necessary only if an outbreak occurred among animals in deployment or assembly areas of military personnel.

When military personnel are deployed to endemic anthrax areas, they receive relevant information on nations and, if required, are informed about risks associated with animal products of unknown origin, e.g. meat, sausages, leather products or shaving brushes (personal communication with Buchner and Morwinsky, 2018).

In Germany, activities involving soil disturbance or the construction of canals or other structures are subject to the Occupational Safety and Health Act (*Arbeitsschutzgesetz*), the Biological Agents Ordinance (*Biostoffverordnung*) and the Accident Prevention Regulations (*Unfallverhütungsvorschriften*) of the responsible professional associations. These provisions also apply to the *Bundeswehr*. Before special engineer units perform construction work or other activities involving soil disturbance, a hazard analysis is conducted in order to assess possible health risks caused, for example, by explosive ordnance, noxious chemical substances (heavy metals), or hantaviruses. Special attention is paid to exposure to dust contaminated with faeces and the associated potential risks of skin and airway infection or irritation during military operations abroad (personal communication with Densow, 2018). Potential exposure to soil-borne anthrax spores is not specifically mentioned.

CONCLUSIONS

Apart from the relatively low infectivity for humans, there are a number of factors that may explain why only very few cases of soil associated anthrax in humans were registered [28, 40, 49, 61, 156, 157, 209, 345–349]:

Small size and number of active anthrax soil foci, and animals that died of anthrax (depending on the season and weather conditions) in an endemic combat area, and thus a low probability of the release of spores and exposure in association with combat situations

"Dilution" and distribution of spores in anthrax soil foci by agricultural activities and decrease of spore concentration by antagonistic soil microbial activities

“Dilution” of spores as a result of the impact of bombs, grenades or mines when large amounts of soil from different layers are blasted into the air and mix with spores
Thermal inactivation of spores by explosions
Inactivation of free deposited spores by UV light of sun
Attachment of spores to the soil matrix (e.g. clay, bentonite, humus particles) and formation of large complexes with soil and dust particles preventing inhalation in deeper air ways
Number of spores on or in contaminated environmental media too low to cause infection

It should not be underestimated, however, especially during World Wars I and II, the incidence of anthrax in enzootic areas decreased among domestic animals as a result of the reduction of animal populations (combat-related deaths and injuries, diseases, confiscation of animals by occupiers, mass slaughtering of animals as a result of an increased need for meat among soldiers and the population, shortage of feed, less breeding, and others).

Moreover, the import and use of animals and raw products from endemic areas were restricted for several years because of blockades.

As a result, there was a decrease in the incidence of agricultural and industrial anthrax cases and probably in the contamination of soil and waters with spores since the processing of infected raw materials was almost completely discontinued.

Weekly reports by the World Health Organization (WHO) and the World Organisation for Animal Health [164] show that active anthrax foci exist in some regions of deployment. Before military contingents are deployed to such regions, relevant information must be obtained although the risk of infection through soil or water potentially contaminated with spores appears to be extremely low (Fig. 5). This precaution is justified since former Commonwealth of Independent States (CIS) member states continuously monitor the epizootic situation (e.g. number, location and activity) of anthrax foci and have established special biosafety rules for the use of these sites or SUS.

Health risks after contact with soil contaminated by infectious carcasses, blood or tissue or after exposure to infected raw animal material or infected animal products, however, cannot be ruled out and should be included in an epidemiological assessment of the situation in an endemic area of deployment.

Under present mission conditions, anthrax as a zoonotic disease has no military medical impact [351]. Nethertheless, military personnel must be informed of potential infection risks in highly endemic areas of deployment where the carcasses of animals that died of anthrax are not buried appropriately and the organs and tissues of animals infected with anthrax are processed or otherwise used.

Soil, buildings, sewage reservoirs and land-near water bodies affected by wastewater discharges can be assumed to be associated with a low probability of spore contamination if infected animal skins from endemic regions have been processed at these sites in the past.

Anthrax spores are likely limited to the vicinity of tanneries, storage facilities for animal products, slaughterhouses, rendering facilities, knackeries, animal burial sites and animal graves if they are not transported via soil water to other areas by heavy rain. If wells, roads or canals must be constructed at these sites or other activities involving the movement of soil must be performed and if there is evidence of potential contamination, a biological hazard analysis must be performed. The same applies to activities during which the soil is disrupted and carcasses or parts of animals or animal processing wastes are dug up. In these cases, a higher risk of exposure must be assumed. If justified, microbiological investigations can be necessary to detect spores in soil.

It should be noted that the increase in mean global temperatures in the northern hemisphere in the 21st century can favour the reactivation and spread of spores of *B. anthracis* [352]. The anthrax situation among domestic and wild animals and the population in endemic areas of deployment should therefore be analysed prospectively and, where necessary, actively clarified and monitored during deployment. For this purpose, available GEOSYS data and registers of anthrax soil foci can be used, or specific registers should be established on the basis of country reports that are submitted to the OIE and WHO. When anthrax cases occur among animal populations in endemic areas of deployment and are likely to lead to environmental spore contamination, soil areas or objects should be microbiologically tested for anthrax prior to their being used for military purposes. Isolates of *B. anthracis* should be genotyped with a view to differentiating between wild-type and vaccine strains. Knowledge of the epizootic or epidemic background and the characteristics of endemic *B. anthracis* strains is particularly important in the case of unusual anthrax outbreaks. Based on this knowledge, it is possible to determine whether an outbreak is a natural or man-made incident (e.g. a bioterrorist attack) and whether it has been caused by a strain that is atypical for a region.

For this purpose, there should be a continuous exchange of information and data between the medical services of allied nations using, for example, the NATO Deployment Health Surveillance Capability (DHSC). In addition, it is important to ensure interdisciplinary cooperation within the medical service (veterinary service, occupational safety and health protection, biological medical defence, medical intelligence, etc.) and with CBRN (chemical, biological, radiological, nuclear) defence forces, the geoinformation service, and military units (e.g. special engineer units).

If residual animal material (e.g. skins, fur, hair or bristles) is detected after attacks involving the use of improvised explosive devices (IEDs) in endemic areas, it should be examined for the presence of anthrax spores and casualties should be monitored for signs of infection (Fig. 5).

As a result of the rarity of anthrax in Central Europe, physicians are no longer completely familiar with the clinical picture of the disease. There is a risk that single cases or index cases will be detected too late in natural outbreaks or bioterrorist attacks. For this reason, it is important to know the routes of transmission, the forms of infection, clinical signs and symptoms, and the differential diagnosis of anthrax and to identify potential sources of exposure on the basis of past medical history. If a severe case of anthrax occurs despite precautions, a multi-disciplinary approach to diagnosis and intensive medical care is imperative.

So far there is no scientific evidence proving for soil-borne anthrax in military animals and soldiers even in case of intensive exposure during heavy disturbance of soil structure in known endemic areas.

In summary, the few available reports on civilian anthrax cases after exposure to soil-borne or dust-borne spores suggest that this route of transmission is of very low epidemiological significance. That is supported by the fact that the sources or vehicles of infection could not be ascertained in many of the cases described.

The literature review presented here shows that the risk of infection through soil or water potentially contaminated with spores is extremely low in anthrax regions (Fig. 5). In highly endemic areas of deployment, however, carcasses of animals that died of anthrax are often simply buried and infected animals and animal material are processed and otherwise used. For this reason, there is a certain risk of infection in the case of contact with soil from recent burial sites of infected animals and with products made of infected or contaminated raw animal material. Such health risks should be included in an assessment of the epidemiological situation in any endemic area of deployment and military personnel should be informed accordingly.

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ABBREVIATIONS

°C	degree centigrade
B.	*Bacillus*
BIG	Prof. Burmeier Ingenieurgesellschaft mbH
canSNP	canonical single nucleotide polymorphism
CBRN	chemical, bacteriological, radiological, nuclear
CIS	Commonwealth of Independent States
cm	centimetre
CNS	coagulase-negative staphylococci
DHSC	Deployment Health Surveillance Capability
DNBI	disease and nonbattle injury
EF	oedema factor
e.g.	for example
EUTM	European Union Training Mission
Fig	figure
GIS	geographic information system
km^2	squre kilometres
ICD	International Classification of Diseases
IED	improvised explosive device;
LF	lethal factor
µm	micrometer
NATO	Northern Atlantic Treaty Organization
OIE	Office Internationale des Epizooties
OIF	Operation Iraqi Freedom
PA	protective antigen
SAA	stationary anthrax-affected area
SNP	single nucleotide polymorphism
SUS	stationary unfavourable by anthrax sites
TNF	tumour necrosis factor
U.S.	United States
WHO	World Health Organization
WIA	wounded in action

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1556/1886.2020.00008.

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Supplementary material 1: Summary of soil-borne and air-borne risks of anthrax infection

Potential hazards associated with anthrax soil foci

In theory, anthrax foci can pose a potential risk of infection to animals and humans if sufficient amounts of virulent spores are present in the soil even after an extended period of time. In addition, these spores must move from deep soil layers to the soil surface in order to cause exposure (contact, inhalation, ingestion).

Spores can be released from soil foci as a result of heavy rainfall or flooding of pastures near the banks of waters [137-140]. Spores can escape during soil disturbances associated with the construction of wells and water pipes to water troughs in pastures with animal burial sites as well as during activities involving the movement of soil at animal burial sites or at watercourses downstream from former tanneries or rendering facilities [4, 7, 28, 49, 139, 141, 142].

Studies in endemic anthrax areas in Africa suggest that, at the onset of the rainy season, spores from animal carcasses or burial sites are swept down to lower lying areas with intense grass growth, where they aggregate especially around plant roots [31, 57].

Extrem weather variations increase the epizootic activity of anthrax outbreaks. As example, in the South Omo region of Ethiopia anthrax outbreaks in livestock and the local population occurred in 2006 after a heavy flood and 2016 - 2017 during long lasting drought periods [143].

The extent to which anthrax spores persist and spread in soil depends on adhesion to soil particles, the type, matrix and biological parameters of soil, rainfall and the flow properties of soil water [31, 144].

Precipitation data for the endemic Kars region in northeast Turkey from 2008 to 2009 show how rainfall patterns influence the concentration of spores in soils. The highest concentrations of spores were measured in May, i.e. when the heaviest rainfalls occurred [145].

There are hints indicating that some bacilli do not form spores but can survive in the soil and multiply [146]. Manchee et al. [135] reported that the addition of calf blood or rabbit faecal pellets to spore-contaminated soil cores led to an increase in the concentration of anthrax spores under laboratory conditions (incubation for 7 days at 37 °C and 22 °C respectively). It is not clear whether this also applies to the setting of infectious animal carcasses buried in soil.

Hypotheses (“incubator area”, microevolution) concerning the germination, multiplication and sporulation under favourable conditions of pH, temperature and humidity in certain types of soil or in free-living amoebas are, however, a matter of controversy [30, 31, 43, 57, 147, 148-150].

It has also been hypothesised that mechanical aggregation of spores around roots and in the rhizosphere of grass [151] can result in increased concentrations of anthrax spores. This appears to be the case, for example, when pastures and fields are flooded with contaminated surface water or the discharges of sick animals [7, 57]. Anthrax spores are easily transported by rain or surface water from anthrax carcasses because they have a high hydrophobicity and low electronegativity [152, 153, 154].

An understanding of the soil life cycle of *B. anthracis* is of military medical interest when animals that died of anthrax were only buried and not burnt in some enzootic areas of deployment [6, 155]. Secondary growth in soil and local increases in spore concentrations in the vicinity of animal burial sites would pose a potential hazard to military personnel.

This appears not to apply to tropical endemic areas. Investigations into an anthrax outbreak in Etosha National Park (Africa) showed that the highest levels of spores were found in the soil and in regenerating grasses in the direct vicinity of animal carcasses only during the first two years. This period was associated with the highest probability of new anthrax cases, though only in animals [27, 57].

In African savannas, spores in dust or in the soil appear to present no increased risk of infection for humans in endemic areas of outbreaks of anthrax among animals [27, 31, 43]. Despite unprotected contact with infected carcasses (transport, burning, blood or tissue sampling) or exposure to spore-containing dust and flies, anthrax cases among rangers, hunters and veterinarians were never reported in Etosha National Park, Namibia, or Krüger National Park, South Africa [6]. The same applies to safari participants who were exposed to dust when traveling in open vehicles through potentially contaminated areas.

Even during epizootics and incidents of massive contamination of soil and water, the majority of spores get probably inactivated depending on initial concentrations, temperature, moisture, ultraviolet radiation, pH, and accompanying microflora [156]. This is one of the reasons, beside of the relatively high infectious doses, why human infection resulting from contaminated soil or the inhalation of dust is rather unlikely [157]. In studies on dust bathing herbivores in Etosha National Park, the highest concentrations of anthrax spores were found around and under an anthrax carcass where the soil was massively contaminated with blood, intestinal contents, and tissue fluids [40]. In the presence of blood proteins (e.g. albumin), anthrax spores form a complex with soil particles and become firmly attached to the soil matrix. As a result, most spores are not released as infected dust [40]. For this reason, anthrax cases among animals that dust bathed in the vicinity of such sites were very rare [40]. When, however, spore-laden dust particles are raised into the air, particles with a diameter of more than 5 µm sediment relatively quickly and become attached to the soil. When the dry season begins after the rainy season, new infections can occur even many years later in animals that graze at old carcass sites although decreased levels of spores may be present [57].

In temperate zones, too, animal burial sites or undetected anthrax carcasses are usually scattered in pastures and the majority of anthrax spores persist in close vicinity to carcasses left on the ground or buried at these sites [7, 39, 57, 136, 157]. On Gruinard Island, virulent *B. anthracis* spores were detected in the top 6 cm of the soil after more than 35 years [135].

As a result of the melting of snow, long periods of rainfall or floods, spores at old burial sites of animals may be brought to the surface from deeper soil layers and into ground and surface water. From there, they can be carried to distant places [28, 38, 139, 141].

In 2008 and 2009, Sahin et al. [145] detected the highest concentrations of spores (2.5–1.24 x 10^8 spores/g of soil) in anthrax carcass burial sites in northeast Turkey after heavy rainfalls, which usually occur in May. The decomposition of animal carcasses often causes the ground to sink and the higher humidity in this sink leads to an increased growth of plants. When spores reach the surface, they can infect animals that graze at these sites.

Optimum conditions for the survival of spores are found in forest steppes, woodland, peatlands, marshes, and black-coloured soil with an alkaline pH (7.2–7.4), a moisture content of 50–70 %, temperatures ranging from 10 °C to 45 °C, and a high content of organic matter [38, 43, 140, 158].

Grazing animals are often found at places where spores had been brought to the surface by rodents building burrow systems [59]. The detection of anthrax-infected rodents in soil foci in outbreaks in Kazakhstan suggests that rodents may be a further silent reservoir of *B. anthracis* [59]. Rodent ectoparasites such as ticks may transmit anthrax bacilli to wild animals and grazers [59].

The present review is based on a variety of German- and English-language monographs, textbooks, manuals and studies on microbiology, hygiene, internal medicine, infectious disease medicine, and veterinary medicine and WHO manuals from 1956 to 2020. These publications report no cases or only rare suspect cases in which spore-containing soil was implicated as the vehicle of infection for natural anthrax infections in humans. Based on available evidence, the authors believe that humans are at risk of infection only if they have contact with animals infected with anthrax, infectious animal carcasses and products, or spore-containing industrial wastes, and contaminated environmental media [6, 7, 28, 41, 60, 61, 90].

Spores were found to be virulent in dried soil that had been stored for as many as sixty years [54]. Anthrax cases occurred among horses in a stable that had been built on the site of a former tannery and the soil had been disrupted through digging [159]. In another case, a cow was infected with spores that had survived for 24 years in the soil of a ditch [160]. In 1913, von

Gonzenbach [28] detected viable anthrax spores and the remains of animal carcasses in a Swiss village in the soil of a former rendering facility that had been abandoned six years before. The place was covered with rubble and earth and construction work was prohibited at this site with a view to ruling out any risk of infection.

Descotes and Joubert [161] described an anthrax outbreak in 1977 in Savoy (France), where six animal cases and four human cases of anthrax were reported. Drilling operations associated with the construction of the Lyon-Chambéry motorway and the drainage of a former animal burial site were believed to be the cause of the outbreak. Forty-four years before, anthrax carcasses had been buried at this place, which was later used as grazing land.

In 2001, an outbreak of anthrax was detected in a Swedish nature reserve among cattle that had obviously been exposed to spores originating from a 70-year-old anthrax carcass burial site [51]. Two other incidences of epizootic anthrax in Swedish cattle were reported in 2008 and 2011 and were also probably caused by the accidental disturbance of old burial sites of anthrax carcasses [52]. When anthrax spores are deposited on grass, hay or straw, the use of these feedstuffs can cause what may be termed stable-related anthrax [142].

Likewise, sporadic outbreaks in cattle were observed in endemic regions in France. For example, an outbreak occurred among cattle in the Moselle region in July and August 2008 and was probably caused by the flooding of old anthrax carcass burial sites [162]. In December of the same year in the Moselle department, three people required inpatient treatment for cutaneous anthrax after a home slaughter in late November [163].

After the revitalisation of the Moselle River in northeast France, anthrax cases were again reported in 2016 and 2017 in the Moselle department in cattle that had grazed on pastureland where anthrax cases had occurred earlier [164].

Future climate changes will likely alter soil and water environments as well as the flora and fauna of regions [165]. In an ecosystem, conditions that are more favourable for *B. anthracis* may lead to an activation of old soil foci and an increased spread of spores through new animate and inanimate factors and may pose a hazard to humans as well as wild and domestic animals. This can be illustrated by an example. Anthrax epizootics occurred in reindeer in the Siberian Yamal-Nenets tundra region in 2016. Prior to this incident, there had been no outbreaks for several decades. Approximately 2400 reindeer died, 115 humans were infected, and one child died. The outbreak is believed to have been caused by an anthrax carcass burial site in permafrost soil which was more than 70 years old and had thawed as a result of abnormally warm summer temperatures [166].

In 2009, an outbreak of anthrax was reported among cattle in the Rosenheim district (Bavaria) after contaminated soil had been moved from a construction site to grazing land (, [167].

Until the 1980s, spores on hay and other feeds or imported feeds caused approximately 100 outbreaks every year in animal populations in Britain [7].

In Germany, too, sporadic animal cases continue to occur occasionally as a result of the flooding and contamination of pastureland alongside streams and rivers into which spore-containing tannery wastewater had been discharged [7, 49]. This applies, for example, to outbreaks that affected cattle in the Elbe valley near Magdeburg in Saxony-Anhalt in 2012 and in Burgenland in 2014 [139, 141].

Turnbull [27] estimated that there is one human cutaneous anthrax case per ten anthrax livestock carcasses. On the basis of this correlation, the number of human anthrax cases in highly endemic countries should be higher than that officially reported [168]. In Turkey, for example, 6721 human cases and only 4039 animal cases were registered between 1970 and 1981 [168]. During the same period, 54 human and 228 animals were infected with anthrax in Germany. It is noteworthy that the number of cases decreased every year [168]. From 1991 to 1995, three sporadic new outbreaks were reported on farms and one to three human anthrax cases per year [114].

In the European Union (EU), outbreaks in animal populations are rarely associated with human anthrax cases. Contact with infected animals continues to be the most common source of infection and usually leads to cutaneous anthrax [169].

The incidence of this zoonotic disease is decreasing. Twenty-seven EU/EEA member states reported an average annual number of 47 confirmed cases from 1997 to 2006 and only 31 sporadic cases from 2012 to 2016 [169].

Risk of acquiring anthrax through direct contact with soil

Anthrax is a natural disease that occurs in niches. Since it depends on a variety of different environmental factors, it is limited to the place where it occurred [6, 170-172]. As a result of the rapid course of disease in highly susceptible animals, this zoonotic disease is usually not spread over great distances [2].

There is a close correlation between the stability and activity of anthrax foci and the type of soil (woodland and black-coloured soil, neutral to moderately alkaline soil, calcium content), moisture (50–70 %), amount of precipitation (dispersal of spores from the soil), temperature (10–45 ºC), and the type and intensity of vegetation [31, 140, 158, 173].

For centuries, the territory of the former Soviet Union and its successor states has included regions with soil and climatic conditions that are favourable for the long-term survival of anthrax spores and the persistence of active anthrax foci [3, 43, 140]. In Kazakhstan, for example, such foci exist on pastures where animal carcasses have decomposed or were buried or at sites located in close vicinity to slaughterhouses, animal markets, rivers or lakes [140, 173].

In the Russian-language literature, spore-containing media such as soil, dust and water have long been reported to be natural factors or vehicles of transmission of anthrax bacilli and can pose a risk to occupationally exposed people [36, 77, 174-176].

Drankin and Malafeeva [38] believe that anthrax infections can result from direct contact with soil, for example through walking barefoot on contaminated soil, gardening, and digging up old animal burial places. A number of Soviet authors reported that, in the 1960s, between 3 % and 10 % of infections were caused in a similar manner in the Volgograd Oblast, in Kirghizia and

Transcaucasia [38].

According to Sklyarov [177], more than 270 anthrax stationary unfavourable sites (SUS) existed from 1895 to 1914 in the Stavropol Governorate, where 15,578 cattle and 4636 humans became infected with anthrax. Between 1946 and 1961, the number of anthrax cases decreased from 954 to 24 animal cases and from 45 to 6 human cases. The infection was transmitted by direct contact with sick animals, animal hides, skins and meat as well as carcasses (66.8 %), shaving brushes (0.9 %), and soil (2.8 %) [177]. Cutaneous anthrax accounted for 94.2 % of the cases and inhalation anthrax for only 0.3 %. Most anthrax outbreaks occurred among private animal keepers who secretly slaughtered sick animals without a previous veterinary inspection and processed the meat for their own consumption or for sale. Moreover, the animals were not adequately registered and vaccinated for reasons of cost and the soil at the SUS had been heavily contaminated with anthrax spores in the past [177]. The largest outbreak of anthrax in domestic animals in the past forty years occurred in the Stavropol district in 1976 [36].

It is generally believed that all activities that bring viable spores to the surface of the soil and water pose a potential risk of infection to humans and animals [36]. For this reason, persons engaged in construction, excavation, agricultural or hydrotechnical work have an occupational risk of infection [35, 36, 64, 77, 140, 165, 174-176, 178].

The Russian Federation and some other successor states of the Soviet Union continue to keep systematic registers of anthrax foci (including animal burial sites and animal graves), anthrax stationary unfavourable sites (SUS) and stationary anthrax-affected areas (SAA) using a geographic information system (GIS) [64]. These registers contain data on the concentrations of anthrax spores in the soil and the use of the sites in order to continuously monitor enzootic and endemic activity [64, 65, 122, 140, 179-182]. These data are used for biological hazard analyses and assessments of the risk of exposure before roads, railway lines or irrigation systems are built. Appropriate measures are then taken to protect construction workers from infection and to prevent the activation of dormant anthrax soil foci by fencing off animal burial sites, moving dangerous objects, reorienting canals and railway lines, and similar procedures [36, 64, 77, 140]. In Kazakhstan, this has long been common practice when roads are constructed or other construction work involving the movement of soil is performed in highly endemic anthrax regions. No cases of anthrax caused by contact with spore-containing soil have thus far been reported. “Participation in earthwork or other work associated with soil” is a criterion for the clinical diagnosis of a “probable” anthrax case [64].

One reason why anthrax spores have been present for a long time in the soils of the former Soviet Union is that carcasses and slaughterhouse waste from anthrax-infected animals were not burned but buried in animal waste pits or biothermal pits until this was prohibited by the government in 1953 [140].

Anthrax outbreaks were often caused by the secret and uncontrolled home slaughtering of sick animals and the sale of meat from these animals without an appropriate veterinary certificate. Moreover, butchers and meat companies accepted, processed and sold this meat [38, 64]. As a result, soil was repeatedly contaminated, old anthrax soil foci continued to exist, and new foci developed [177].

Soil-borne infections were suspected in an outbreak in a sovkhoz in the Stavropol district, where cutaneous anthrax was detected in five patients who had not been occupationally exposed to animals [38, 183]. This suspicion was not confirmed since epidemiological history showed that the patients had had contact with infected beef.

Between 1900 and 2003, a total of 35,585 SUS with animal burial sites and animal graves and more than 70,000 human anthrax cases (including 31,668 cases from 1924 to 1925 alone) were registered on the territory of the Russian Federation [28, 78, 122, 184]. There were approximately 35,000 anthrax burial sites; only 8000 of these sites, however, had been bacteriologically analysed [122].

Most SUS were found in the southern Privolzhsky District (Chuvashia and Kirov areas: 12,731 SUS) and in the Central District (Moscow area: 9732 SUS) [122]. SUS and associated anthrax soil foci were a permanent potential risk of infection for domestic animals and humans until the 1950s. For example, the highest anthrax activity was reported in the Krasnodar region in southern Russia from 1936 to 1955 [65]. This can be explained by the geological situation and favourable climatic and soil conditions [35, 77].

Until 2010, a total of 5608 SUS were identified in the Siberian Federal District and were associated with old and new anthrax soil foci [184].

Cherkasskiy [185] reported that, to his knowledge, there were 2086 sites in the Ural region (Kurgan, Sverdlovsk, Tumen, Chelyabinsk, Yamalo-Nenetskaya, and Hanti-Mansiyskaya national districts) that had a history of anthrax and were therefore permanently labelled as “anthrax sites”. Owing to a lack of studies, however, there is no information on whether viable and virulent anthrax spores are still present at these sites. Between 1991 and 2000, anthrax infections in animals were reported at only four sites [185].

According to the occurrence of anthrax Vassiliev et al. [178] differentiated Southern territories of the USSR in four risk groups. The Republic of Tartastan, the Ul`janovsk, Penzensk, Saratov und Samarsk Oblasts showed high risk whereas the Orenburg Oblast and the Republic of Bashkortastan exhibited the highest risk.

In the 1990s, the risk of anthrax was also high or even very high in the Kirov, Ulyanovsk, Penza, Saratov, Samara and Orenburg regions and in the Republics of Mordovia, Tatarstan and Bashkortostan [77]. During this period, a total of 1000 stable anthrax foci were detected in southern Russia and humans accounted for 80 % of all anthrax cases [186].

For this reason, stationary unfavourable sites and anthrax foci are permanently monitored and land development and construction projects in these areas are subject to special safety regulations [122]. Recent studies involving sites where infected animals had been buried between 1933 and 1957 showed that no new human anthrax cases had occurred [122].

In the early 2000s, more than 75,000 natural anthrax foci were registered in CIS member states [158].

In Ukraine, there were approximately 11,000 permanent anthrax foci (PAF) in the past decade [63]. The occurrence of PAF correlates with soil type and acidity. The largest number of PAF was reported between 1946 and 1970 in forest steppes, followed by steppes, foothills and forests. During this period, 68.3 % of cattle (especially privately owned cattle), 19.5 % of small ruminants, 10.15 % of pigs and 2.4 % of horses were infected with anthrax. Between 1920 and 1970, and thus presumably during World War II, there were anthrax outbreaks among animals in about 50 % of the places where earlier anthrax cases had occurred. The majority of outbreaks were observed in areas with neutral soil. Most recurrent epizootics were reported during the first five years. After more than 26 years, they occurred more rarely. Only isolated cases have been reported since the introduction of annual cattle vaccinations [63]. There is no evidence of human cases caused by contact with soil in these anthrax foci.

In 1997, Juzvik and Agapov [187] reported that 97 % of anthrax patients in the Chitinsk Oblast and in the Republic of Buryatia became infected when they processed infected animals and 1 % when they came into contact with soil that had been contaminated when sick animals had been cut up. As a result, new anthrax foci and SUS developed at these sites. In the 1990s, there were 367 SUS in 29 raions in the Chitinsk Oblast. For this reason, the epizootic situation was judged as unfavourable with respect to anthrax [187].

In Georgia, a total of 161 anthrax cases allegedly caused by contact with spore-containing soil or grass were reported between 2000 and 2005 [180, 188]. According to further studies by Kracalik et al. [181, 182] which covered the period from 2006 to 2009, 27 of 252 patients with anthrax reported that they had become infected when working in the fields (sowing and harvesting). The authors point out, however, that this mode of transmission was insufficiently documented. In addition, these patients may have wished to hide the fact that they were infected when slaughtering sick animals.

Similar motives may be behind a number of soil-related anthrax cases that were reported in the Soviet medical literature [189].

In the Republic of Kazakhstan, a total of 1786 stationary anthrax-affected areas (SAA) (less than 20 active ones) and 2616 anthrax soil foci were registered between 1948 and 2016 and led to disease in 25,313 animals and 1907 humans [64, 190]. In a recent outbreak in 2016, *B. anthracis* (including atypical strains) was detected in 0.2–1.7 % of soil samples. Aikimbayev [64] reported that anthrax soil foci covered a total area of 2136.54 km² and sporadic cases occurred every year.

In September 2018, a man died of anthrax in a hospital in Ust-Kamenogorsk. An old soil focus, where an anthrax carcass had been buried in 1972, was reported to be the source of infection [80].

There may, however, have been other sources of infection since spores can be ingested along with vegetables grown in contaminated soil [64].

In 2018, there were still 1778 SAA and 2249 soil foci in Kazakhstan [59]. For this reason, biosafety measures must be followed during activities involving the movement of soil at anthrax soil foci and SUS in Kazakhstan [176].

In the Kyrgyz Republic, anthrax is of veterinary and economic importance. Permanent anthrax soil foci still exist. Most animals are slaughtered at home. When animals are slaughtered and meat products are sold, veterinary and hygiene rules are not met and the veterinary service is not informed [191].

In Mongolia, 289 anthrax cases were officially registered between 1978 and 2015. Men of working age, especially shepherds (52 %) and miners (10.4 %) were mostly affected [192]. The majority of infections were associated with the slaughtering of sick animals and the processing of their infectious tissues. Twelve cases of anthrax (4.2 %) were caused by contact with “infectious soil” during agricultural and mining activities. For this reason, risks of infection associated with these types of work will be further investigated. One question to be addressed is whether the soil was contaminated by spores from old burial sites of anthrax carcasses or from animals that died or were slaughtered at the site.

Li et al. [193] analyzing anthrax in China between 1955 and 2014 found, that since the 1960ies the anthrax incidence steadily decreased. Due to strict sanitary measures in the fur and wool manufactories and improved medical care after 1980 almost no cases of industrial anthrax was seen in large cities. But in rural areas agricultural anthrax manifesting in 98 % in its cutaneous form continues to occur mainly in farmers and herdsmen, which handled sick or dead animals and infectious animal products, respectively. Soil as source of infection has not been reported.
In Poland, anthrax foci (“damned pastures”) were found in three regions during the 1980s and 1990s, i.e. in southern Poland in the Carpathian Mountains (Krakow, Tarnow and Bielsko-Biala districts), in central Poland (Kielce and Zamosc districts), and in the plains of northern Poland (Bydgoszcz and Lomza districts). A total of 26 anthrax cases in animals but no human cases were reported [194].
According to experienced specialists in tropical medicine at the Bernhard Nocht Institute for Tropical Medicine in Hamburg and at the Medical Mission Hospital in Würzburg, whose focus of work has for decades been on tropical regions, there are no known cases of anthrax caused by spore-containing soil (personal communication with Racz, Burchard and Fleischer, 2013).
Likewise, the source of infection or the inoculation incident remained unknown in the case of a malnourished child with cutaneous anthrax in Niger, where further cases occurred during a famine. The child’s medical history revealed no contact with animals (personal communication with Kitz and Fleischer, 2013).
In Western European regions, there are only a few reports of possible anthrax cases caused by contact with soil. In an analysis of the risk of acquiring anthrax from soil and wastewater from former tanneries in Neumünster, Germany, BIG (Prof. Burmeier Ingenieurgesellschaft mbH) [49] reported the case of a gardener with cutaneous anthrax. In 1954, the gardener became probably infected by contact with soil when working at the site of a leather factory that had been closed down in 1929. The exact route of infection, however, remained unclear. In a further anecdotal case report, BIG [49] described a patient who, in the 1950s, probably became infected at the site

where an anthrax (cattle) carcass had been buried [49].

Breathnach et al. [113] reported the case of a 63-year-old casual labourer who, in 1995, developed cutaneous anthrax on his chest after having worked in the ventilation shaft of a London bank for only one day. Initially, the disease was attributed to a sting or bite or spore-containing dust. These potential causes of infection were, however, ruled out. The source of infection was found to be infectious hides. A week before, the patient had worked in a leather firm where his duties involved lifting hides. Because of the heat, he had removed his shirt while working. As a casual labourer, he had not been vaccinated against anthrax. Several similar cases of cutaneous anthrax occurred in Germany among dockers, who carried imported hides on their backs.

Figure: A docker presenting with cutaneous anthrax. Photography: Courtesy of Professor Dr. Gerd Burchard, Bernhard Nocht Institute for Tropical Medicine, Hamburg, 2014.

In 2009, human remains were found during tunnelling work on the London Crossrail project at a 488-year-old mass burial site suspected of containing anthrax victims. There were fears that anthrax spores had been released but no evidence was found [195].

Similar concerns were raised in England in 2017, when construction work was planned at the site of former mass animal graves [166].

Between 2006 and 2009, 13 cases of cutaneous anthrax were reported by five EU countries [196]. Some cases were reported to have been the result of a possible contamination of skin lesions with soil-borne anthrax spores. There was, however, no supporting microbiological evidence.

Drankin and Malafeeva [38] reported that infections could occur in endemic areas as a result of contact with what may be termed “field bones” from anthrax carcasses which were found in pastures or landfills. According to Hugh-Jones [189], there are only a few confirmed cases of soil-related human cases of anthrax. These cases were individuals who had salvaged steel from a derelict Soviet automobile factory and dug through a cattle grave. All of them developed cutaneous anthrax.

From a military medical perspective, it is interesting to note that little or no mention is made of anthrax in armed forces in the medical war reports and publications on infectious diseases in times of war which were analysed here.

Intense fighting destroyed or adversely affected the structure and properties of the soil of anthrax foci especially during World War I, the Russian Civil War, and World War II. The construction of field fortifications extending over thousands of kilometres, military manœuvres involving combat vehicles, and millions of explosions of mines, bombs and grenades could have disturbed the soil of anthrax foci or other potentially contaminated areas (e.g. rendering facilities, knackeries, tanneries, or places where animal hides, hair, wool or bones were produced or stored), as a result of which spore-containing soil or dust particles may have been raised into the air.

Despite the large number and density of troops in World War I and II fortifications and offensive operations, e.g. at Stalingrad or the Kursk salient, neither military animals nor soldiers became infected with anthrax. At least, no such cases among military personnel or the local population were mentioned in reports from the medical and veterinary services of the armies involved.

What, then, are possible reasons for the absence of outbreaks of anthrax?

When anthrax carcasses are appropriately buried and disinfected, spore concentrations decrease in animal burial sites over the years and anthrax foci become inactive, which may also be the result of competition from soil microflora [28, 185].

In the former USSR, sowing with a wide variety of crop plants was effective in reducing spores in anthrax foci [173]. According to the regulations of the veterinary service in Germany, grasslands can be used again for grazing five years after an anthrax case had occurred [49].

It is doubtful whether the density of animal burial sites and their spore load in a combat area can reach levels sufficient to contaminate projectiles or grenade or bomb fragments with spore-containing soil and to allow high enough doses of agents to be introduced into wounds [157]. Moreover, large numbers of spores are likely damaged or destroyed by the heat that is released when projectiles or grenades are launched or bombs explode.

In earlier wars, infections by opportunistic and pathogenic staphylococci and streptococci commonly present on human skin and mucosa usually manifested as abscesses and phlegmons or compartment syndrome and decisively influenced the local wound situation. In such cases, a simultaneous anthrax infection may not even have been suspected. It may be assumed that the numbers of anthrax spores that entered wounds were much lower than those of other aerobic bacteria (especially streptococci and staphylococci) and anaerobic bacteria ubiquitously in the soil (especially the causative agents of gas oedema and gangrene). Animal experiments quoted by Sobernheim [28] demonstrated that these bacteria could multiply more readily than anthrax bacilli in deeper tissue layers (e.g. muscles). In other animal investigations quoted by Sobernheim [28] *Pseudomonas aeruginosa* (pyocyanin), streptococci, staphylococci, *Klebsiella* *pneumoniae* and apathogenic bacilli were described to be antagonistic to *B. anthracis* resulting in less severe anthrax infections.

Since no cases of “wound anthrax” were registered even before the use of antibiotics, *B. anthracis* apparently played no role as a causative agent of wound infections. As mentioned before, the primary treatment of wounded soldiers included the early administration of penicillin in the late stages of World War II. This and an early debridément of wounds may have suppressed the development of an anthrax infection [157]. The successful use of penicillin in treating anthrax was described for the first time in England in 1944 [61].

Moreover, humans are moderately susceptible to *B. anthracis* [6]. Schlottau [49, 197] reported that the number of animal hides that were imported from endemic areas to Germany was approximately four million in 1910. The number of human anthrax cases, however, was relatively small. Most commonly affected were workers who had been exposed to anthrax spores for decades in tanneries and in the wool, upholstery, leather, soap and textile industries and had come into contact with infected skins, hides, furs, wool or bones as well as with contaminated dust and surfaces [49, 60, 93, 111].

If individuals become infected at all, most apparently have subclinical or no symptoms and acquire specific immunity that largely prevents further anthrax infections [96, 117, 198, 199].

In studies involving 271 volunteers from the endemic Kars region in northeast Turkey, 15 people without a history of anthrax had antibodies to PA and LF [118]. One person came from a village in which two soil samples were found to contain anthrax spores (10^3/g). In a second study of 64 workers with no previous anthrax disease, six people had toxin-specific antibodies. Two of these six people belonged to a group of 11 workers whose work involved the use of construction equipment for the movement of soil at a spore-contaminated site (10^2 spores/g) where three infected animals had been buried [118].

Cordeiro et al. [119] also assumed that mild infections that are not diagnosed as anthrax can occur in enzootic areas in Portugal.

Humans may have a certain species-specific tolerance to naturally occurring spores. This would explain why there are relatively few epidemiologically and microbiologically confirmed cases of anthrax among miners and canal, road and other construction workers in countries with a large number of active anthrax foci and settlements that are unfavourable with respect to anthrax. The anthrax outbreaks in a Swiss textile factory between 1977 and 1981 [111] and cases of injection anthrax in Western Europe show, however, that this disease is not easy to diagnose on clinical grounds (see Table 2) and that atypical or subclinical cases can therefore go undetected [72].

Available studies as well as our own search do not provide evidence as to whether inapparent anthrax infections occurred among soldiers who took part in combat in endemic areas.

The previously mentioned cases of injection anthrax cannot be simply compared with wound infections associated with war injuries. When heroin was injected, virulent anthrax spores did not originate from soil but from animals (hides, skins) and a possible contamination of heroin with spore-containing dust during packaging and transportation could not be investigated.

It should be further noted that drug users often have multiple morbidities and thus a higher susceptibility to infection as otherwise healthy soldiers.

During World Wars I and II, surgical wound management alone which at that time consisted in debridément, antiseptic wound irrigation and dressings, and leaving the wound open, may have suppressed anthrax infections. The situation further improved during later wars when antibiotics were topically applied at an early stage.

It is only of theoretic interest if plasmid-free spores in anthrax foci might contribute to the absence of soil-related anthrax in human. Afanasev et al. [200] analysed 30 strains of *B. anthracis* collected in Siberia and the Far East between 1959 and 2012. These strains were isolated from 8 patients, 13 domestic animals, 9 environmental samples (soil), and 4 vaccine strains. Eight isolates, including all vaccine strains, had no pXO2 plasmid and one was plasmid-free.

Sahin et al. [145] investigated in 2008 and 2009 soil samples from animal burial sites in 25 villages in an endemic region of northeast Turkey. In 13 villages, pXO2-deficient isolates were obtained at 23 sites with a high level of spore contamination. Reduced capsule formation was detected in 11 *B. anthracis* strains*.* But, as seen with anthrax outbreaks of susceptible animals at animal carcass sites, presence of small quantities of plasmid-free strains do not exclude a natural infection, because the majority of spores present in naturally contaminated soil would still possess both plasmids and, hence, are virulent.

On the whole, available data suggest that soil-borne anthrax spores are unlikely to be the cause of primary wound infections. There is some uncertainty, however, as to whether this also applies to deep soft-tissue processes that are difficult to diagnose.

No definitive conclusions can be drawn at this stage as to whether deep tissue infections following war injuries were caused by *B. anthracis*. It is doubtful whether bioforensic analyses of war-related wound specimens can retrospectively detect pathogen DNA and provide the required evidence in the absence of epidemiological, clinical or pathomorphological indicators of anthrax (personal communication with Hörmannsdörfer, 2014). It is unlikely that analyses of tissue samples are successful in the case of patients who received penicillin and streptomycin during primary wound management. This applies to injured members of the British and U.S. military forces at least in the late stages of World War II. Since then, antibiotic therapy has been a standard treatment for injuries sustained in armed conflicts.

Analyses of soil samples collected at former tanneries in Neumünster (Schleswig-Holstein, Germany) reveal only trace levels of anthrax spores [49]. Since no cases of anthrax had been reported among workers at these tanneries, the risk of direct infection from spore-contaminated soil was assessed as low in a hazard analysis. This is supported by the fact that only very few cases of anthrax after probable contact with soil or soil-like materials (e.g. sludge) were documented in Germany between the end of the 19th century and 1989 [49].

According to available annual epidemiological reports on infectious diseases and a publication by the Robert Koch Institute in Berlin [201], there were no typical cases of anthrax or wound infections in Germany suggesting that spore-contaminated soil or grass were vehicles of transmission of *B. anthracis*. For this reason, the risk of such infections appears to be extremely low. This was also the opinion of experts from the City of Munich Department of Environment and Health (personal communication with Graf, 2014) and the Bavarian Health Office (personal communication with Hörmannsdörfer, 2014) since no cases of anthrax after direct contact with soil had been reported to these authorities in the past. The Hazardous Substances Department of the Construction Professional Association in Munich also had no information on anthrax cases among construction workers in Bavaria in the past (personal communication with Feige-Munzig, 2014). The same applies to the *Bundeswehr*. According to available data, there have been no reports of anthrax cases among military personnel or animals in Germany or in countries of deployment (personal communicatin with Schotte, Buchner, Morwinsky, and Densow, 2018). The *Bundeswehr* Veterinary Service reports that analyses of the enzootic and epidemic situation in countries of deployment also cover anthrax. As mentioned above, deployed military personnel are informed about possible risks of exposure if required from an epidemiological perspective (personal communicatin with Buchner, 2018).

In Germany, according to the guideline 90/679/EWG of the European Community, the Civil Engineering Professional Association requires that workers must be protected from infection with soil-borne pathogens (biosafety level 2) during activities involving the movement of soil. These pathogens include *Clostridium* (tetanus, gas gangrene) and *B. anthracis* spores [124]. As a result, health authorities usually request property developers to assess the soil for the presence of anthrax spores before any soil movement of a potentially contaminated site begins. This precaution is taken because the presence of spores is assumed to present a possible risk of infection. Minimal quantities of spores per cm^3 of soil, which, however, may be too low to cause an infection, can be detected using modern molecular diagnostic techniques.

Risk of anthrax following inhalation of soil-borne spores

A case of inhalation anthrax was reported in the United States in the 1950s. The patient was a football player who may have contracted the disease from contaminated playing-field soil [68]. In 2004, a worker developed inhalation anthrax in Canada after having transported bison that had died of anthrax to an animal burial site [202].

Between 2011 and 2014, three patients were treated for suspected inhalation anthrax in Canada and the United States. In the Canadian case, the disease was believed to have been caused by spore-laden dust that the patient may have inhaled when he used a bulldozer to bury buffalo that had died of anthrax [203].

The other two patients had travelled through the southern part of the United States for an extended period of time [204, 205]. One patient was a member of the British armed forces who had been vaccinated against anthrax and who, in 2012, had travelled by car through Florida two weeks before he was admitted to hospital with severe sudden-onset central chest pain at rest, nausea and haematemesis. A retrospective diagnosis of inhalation anthrax was made on the basis of the serological results. Time, place and type of exposure, however, remained unknown [116, 157, 205].

Airborne transmission of naturally occurring anthrax spores appears to cause disease in humans extremely rarely.

Only a few virulent spores are probably needed to cause cutaneous anthrax [77]. By contrast, recorded inhalation LD_{50}s, most of which are based on experiments on non-human primates, range from 2500 (8000), 10,000 (20,000) to 50,000 and 500,000 to 760,000 spores [66, 68, 77, 206-210]. Animal testing on chimpanzees showed that the doses needed to cause airborne infection varied between 32,000 and 66,500 spores [87, 88]. Exposure to finely dispersed aerosols (particle diameter < 5 µm) that can penetrate deep into the lungs is unlikely to occur under natural conditions. In contrast, so called “weapons-grade” spores of highly virulent *B. anthracis* strains with low electrostatic surface charge and the above mentioned particle range offers high volatility and stability in the air. Following inhalation the lethal dose of aerosols containing such spores may be many fold lower [210, 211]. LD_{50} values of fewer than 100 spores were calculated on the basis of data from the attacks with powders of “high-grade” anthrax spores in the United States in 2001 and from the Sverdlovsk outbreak in 1979 [210]. Meselson [66, 68] estimated that a dose of fewer than nine spores may have caused infection in strongly exposed persons at a ceramics factory in Sverdlovsk though the actual number and concentration of spores released is not known.

In the case of naturally occurring spores, however, a much higher dose is likely needed to cause infection even in highly susceptible herbivores as an anthrax outbreak in Upper Bavaria in 2009 suggests [141]. After one cow died in a stable during an outbreak scenario on pasture, *B. anthracis* spores were detected in stable dust. Since the diagnosis was only made at autopsy, the owner of the animals had been exposed to spore-laden dust over several days but did not develop cutaneous or inhalation anthrax.

Between 1871 and 1910, the German Reich imported approximately four million animal hides every year from endemic regions [49]. According to Schlottau [197], 30 % of the sheep and goat skins that were imported from Yugoslavia in the 1930s and approximately 44 % of the sheep skins that came from Turkey, India and Morocco in the 1950s were contaminated with anthrax spores. This means that several thousand workers in factories that processed potentially infected raw animal products had been at risk every day for decades. Despite this occupational exposure, no cases of inhalation anthrax were reported in Germany in the 20th century [49]. Whether the inhaled dose or the virulence of the spores was too low to cause infection or whether the particles were too large is unknown.

Natural anthrax spores attach to surfaces, stick together and tend to form clumps with diameters above 5 µm by means of adhesion (van der Waals) forces [209, 212]. If distributed by dust or aerosols these particles will be too large and heavy topenetrate into the lungs and cannot be deposited into alveolar spaces [40, 87, 88, 157, 212-214]. Moreover, the concentration of spores dormant for long times in the soil is generally too low to cause airborne infections, because spores underly progressing degradation by physical, chemical and biological factors [156, 209, 215].

If spore-laden soil and dust particles were spread by the airborne route during military activities involving the movement of soil (engineering, vehicle movements, or explosions), it would be unlikely that doses are high enough to cause apparent infections. This assumption is supported by the extremely rare number of cases of naturally occurring inhalation anthrax.

Retrospective epidemiological studies of 41 anthrax cases that were reported in the United States between 1950 and 2001 showed that 24 infections involved an agricultural setting, 11 infections (including cases of inhalation anthrax) occurred in textile mills, and 5 infections were caused by contact with contaminated animal products and bones [87, 88, 216]. In one instance, the source of infection was not determined.

From 1900 to 1976, only 18 cases of occupationally acquired inhalation anthrax (woolsorters' disease) were reported in the United States among tanners and workers in goat-hair mills and wool factories [87, 88, 217]. In 117 industrial cases of anthrax which occurred between 1933 and 1955, only one patient was diagnosed with inhalation anthrax at post-mortem [218, 219].

In the mid-1950s, the public health service and the U.S. Army conducted a study at the Sackville Woolen Mills (Pennsylvania, United States) which resulted in the recovery of anthrax spores from air samples and dust collected from machinery, walls and floors as well as from the clothing and body surfaces of workers [220]. The risk of infection at these mills had been known even before this study. When in 1933 six workers and one child contracted anthrax, the 200 residents of the village were evacuated. The village thereafter ceased to exist [220]. Until the closure of the factory in the late 1950s, workers continued to contract anthrax at an average rate of about five cases a year [220].

In the Philadelphia region, there were 150 wool-processing factories with more than 7500 workers who were exposed to anthrax spores in potentially infectious raw wool and aerosols every day for many years and who often sustained injuries at work [93, 218, 220]. Between 1948 and 1959, a total of 105 anthrax cases were recorded in this region [92, 93, 221]. In three of seven cases that were not linked to occupational exposure, inhalation of spore-laden dust from nearby factories was assumed to be the cause of infection [92, 218]. It remained unclear why factory workers did not develop inhalation anthrax and why there was only a small number of cutaneous anthrax cases given the large number of workers and the long duration of exposure. The annual average number of anthrax cases was 10 of a total of 7500 workers, which corresponds to a manifestation rate of only approximately 0.13 % in the Philadelphia region. The development of airborne infections depends on the virulence of the *B. anthracis* strain, the concentration of spores and the size of particles in the inhaled aerosol, the duration of exposure, the retention of spores in the alveolar space, the rate and depth of breathing, and the type of inhalation (nose or mouth breathing) and the susceptibility of the host.

The relevance of these factors is supported by an unusual anthrax outbreak in Sverdlovsk (now Yekaterinburg) in the former USSR [66]. On 2 April 1979, an aerosol of anthrax spores was accidentally released from a military research facility. This led to an explosive epidemic ending on 17 May. The diagnosis of anthrax was confirmed as late as 12 April, i.e. when the outbreak reached its peak. Approximately 96 people developed cutaneous and inhalation anthrax [68, 89]. Most of the persons who became ill were workers at a nearby ceramics factory who performed hard physical outdoor labour [68]. In the immediate vicinity of the military facility, approximately 5000 unprotected people had been exposed in indoor or outdoor environments for several hours to the primary airborne cloud of spores. Second exposure perhaps occurred by contact to spores deposited on roads, trees and buildings or raised in the air with dust during cleaning activities in the following two to three weeks [66, 68]. Potentially contaminated roads, buildings and trees were then partially decontaminated and more than 80 % of the approximately 50,000 at-risk individuals were vaccinated against anthrax and treated with antibiotics [68]. In the end, anthrax manifested itself at a comparatively low rate of ca. 0.2 % of exposed persons [67, 68]. Since a large part of the city was contaminated by high virulent anthrax spores, the number of cases could have been much higher.

A similar situation occurred in the United States in the autumn of 2001, when mailed letters filled with “weapon grade” anthrax spores infected 22 people and killed five of them [67, 68]. Mainly people with special predisposition had been affected. Two major mail distribution centres were contaminated with spores as well and several postal workers contracted cutaneous or inhalation anthrax [68, 222-224]. On 12 October 2001, the anthrax letter that was addressed to Senator Daschle was processed at the Brentwood mail facility (Washington, DC). Four employees of the mail facility developed inhalation anthrax between 19 and 21 October. Laboratory tests confirmed the diagnosis on 21 October [68]. The facility was closed on the evening of 21 October but the staff did not receive detailed information and were not treated with antibiotics before 22 October. As a result, approximately 2000 unprotected employees were exposed to secondary aerosols of spores and contaminated surfaces for a period of two to six days, which is the normal incubation period for inhalation anthrax. There were, however, no further anthrax cases and the estimated attack rate (approximately 0.2 %) was relatively low, too.

In both events, infection appears to be favoured by certain predisposing factors such as an age of more than 40 years, underlying conditions such as inherited or acquired immune defects (ionising radiation, glucocorticoids, cytotoxic agents), diabetes, and a low-protein diet [6, 193, 225, 226]. The average age of patients was 45 years during the Sverdlovsk outbreak and the anthrax letter attacks of October 2001 [68, 227]. As a result of their occupational exposure, men were more commonly affected than women in both incidents. In the former USSR, occupational and non-occupational anthrax occurred predominantly in men who were older than 30 years of age [38]. In generally, anthrax can affect people of all ages if they have sufficient contact with infectious material [79, 228].

Previous damage to the lungs from infections, heavy smoking, noxious chemical substances or silicosis can help spores enter the human body and germinate [6, 28, 68, 92, 229]. Genetic factors too can influence individual susceptibility to disease [230]. Investigations quoted by Sobernheim [28] showed, that predators with a common infection in a zoo, overtired oxes and carnivores and rodents that received neither meat, nor vitamins, nor water oxen exhibited a higher susceptibility to anthrax. Chronic administration of alcohol to dogs, rabbits, guinea pigs, pigeons and chickens have been described to result in considerably lower resistance [28].

It is likely that weakened local tissue defence (injection damage) and multiple morbidities may have favoured the development of anthrax infection in intravenous drug users.

Some infections appear to cause no or only subclinical symptoms and therefore may go undetected and unreported [72, 79]. This applies for example to workers who, without proper precautions, were exposed to anthrax spores for decades in environments heavily contaminated with spores, e.g. in goat-hair or wool mills [60, 84, 92, 97, 111]. Anthrax spores were recovered from the nose and pharynx of these workers who, however, had no signs or symptoms of disease [38, 92].

For this reason, Dahlgren et al. [38, 231] estimated that an unvaccinated worker can inhale approximately 1300 anthrax spores over an eight-hour shift without ill effect. This is supported by retrospective studies on workers in factories processing animal hair, wool or leather contaminated with anthrax spores. Some of the tested individuals had antibodies to *B. anthracis* and/or a positive skin test to anthraxin [38, 61, 111, 198, 199, 232].

It can be assumed that inhalation anthrax develops only after the inhalation of very large numbers of spores and that the majority of infections are therefore clinically inapparent [92, 111].

Following the introduction of mandatory vaccination with the anthrax vaccine adsorbed (AVA), the last occupational case of anthrax in the United States was diagnosed in 1976 [233].

Since then, isolated cases of inhalation anthrax have been reported in the United States and Britain in drum makers or individuals who produced or played drums made from goat hides that were contaminated with anthrax spores and that had been illegally imported from epizootic regions in Africa [68, 72, 73, 115, 234]. It should be noted that no other drummers or potentially exposed individuals developed an infection although they had been exposed repeatedly for several hours at the site where contamination had been detected [73, 81].

Occasional cases of inhalation anthrax are still reported among gardeners using imported fertilisers that contain spore-contaminated felt or bone, hoof or horn meal [60, 68, 97, 235, 236].

In the 1950s, anthrax occurred in workers who were exposed to spore-containing dust when they were producing bone meal [38]. Between 1960-1966 in England and Wales, 10 of 70 anthrax cases with contact to bone meal had been reported [97]. Taking the import of hundreds of tons of potentially contaminated animal raw materials per year into account, the authors assumed a very low risk of infection.

The high environmental persistence of anthrax spores – they can survive in enclosed spaces for up to 70 years – necessitated time-consuming and expensive decontamination measures for the complete removal of these special preparations of spores [68, 237]. The public and the users of the buildings and rooms would not have accepted even minimal levels of residual contamination [237].

The presence of an effective health system allowed the two above-mentioned anthrax outbreaks to be detected and controlled at an early stage.

By contrast, the anthrax epidemics during the Rhodesian War were associated with considerably higher manifestation rates (between 0.43 % and 2.1 %) in the affected African population [238]. This was mainly attributable to the intensive handling of infected animals, carcasses and tissues and the consumption of infected animal products [37, 238].

Data on these three epidemics probably do not include cases that, because of the low infectivity of anthrax spores in humans, were associated with subclinical or inapparent symptoms and were therefore not recorded [27, 238].

This assumption is supported by the fact that spores were detected in the nose and pharynx of clinically healthy workers in heavily contaminated textile mills and in the Hamilton postal service facility in New Jersey in 2001 [61, 68]. The relatively low number of cases in the United Kingdom in the 1960s, when many hundreds of tons of potentially contaminated bone meal were imported from endemic countries and were widely used for commercial and private horticultural purposes, also appears to be consistent with the low infectivity of anthrax organisms for humans [97].

It is difficult to make a valid assessment of the real risks associated with anthrax exposures. There are no reliable data on the doses of airborne anthrax spores or spores on surfaces in indoor or outdoor environments which cause infections [237]. Moreover, environmental media such as soil and water may contain natural background levels of anthrax spores whose potential of infection has never been reliably assessed. As a result, it is difficult to demand that environmental media show no spore growth on any sample, which, for example, applies to indoor locations in the United States [237]. Following the Amerithrax attacks in 2001, there was no guarantee that total decontamination could be achieved even if a maximum amount of resources was used [239, 240].

Prior to the beginning of construction work Silman et al. [240] recommend analysis of environmental samples for the presence of anthrax spores if buildings were involved in “white powder” incidents and sites with a high likelihood of historical contamination (previous tannery sites, abattoirs and old buildings with horse-hair plasters) will be used.