

Observing tuberculosis and brucellosis in the Austrian Avar population

By

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Ethics Statement

This research paper involves the use of human remains and minimally destructive methods. It is known that without these individuals, advancing research on the related topics would not be possible. All research on human remains was conducted with permission from the Naturhistorisches Museum Wien and Museen der Stadt Wien. There is an acknowledgment of these individuals, the research conducted, and knowledge provided by these methods. It is a privilege to gain understanding from this process and previously conducted projects involving individuals from our past.

Abstract

The Avar people were a semi-nomadic population from medieval Eurasia who migrated from the Eastern Asian Steppes to Western European countries that are modernly known as Hungary, Croatia, Slovakia, Serbia, Czech Republic, Romania and Austria. The objectives of this research are to 1) understand the experience of tuberculosis and brucellosis in the Avar population from medieval Austria, 2) gain insight into related lifestyle and cultural practices that had an impact on population health, and 3) address the challenges of skeletal diagnosis between tuberculosis and brucellosis in the hopes of advancing methodology. It is hypothesized that 1) given the high transmission rates of tuberculosis and its confirmed presence in medieval Europe, a frequency of tuberculosis at 17% or greater would be expected in the medieval Avar population (Pedersen et al., 2019), 2) given the lower transmission rates of brucellosis than tuberculosis and its rare observation in archaeological contexts, a lower frequency of brucellosis in comparison to tuberculosis would be expected in the medieval Avar population (Bendrey et al., 2020; D'Anastasio et al., 2010), and 3) given that brucellosis is more common in populations with ties to husbandry and farming given its zoonotic origin, brucellosis is expected to be observed in this population (Fournie et al., 2017; McKeown, 2009; Moreno, 2014; Zuckerman et al., 2014).

Data for the project was based on a visual osteological analysis complemented by radiographic and photographic images, as well as a Fisher's exact test based on pathological scoring. Pathological scoring and biological profiles were completed on the skeletal remains of Avar individuals who are a part of the Bruckneudorf collection at the Naturhistorisches Museum and the Hirschstetten collection in the City Archaeology Department at the Museen der Stadt Wien in Vienna. Results suggest that there is a connection between animals, people, and the environment. The frequency of tuberculosis within the studied population being 35.58% and the

frequency of brucellosis being nearly 7.40% could be attributed to different Avar lifestyle factors such as increased husbandry, unique utilization of horses in battle, increasing contacts with migration, nomadism to sedentarism, and even housing structures. Results suggest alignment with all three hypotheses. Concluding remarks found that the Fisher's exact test used to determine frequency of tuberculosis would work best when paired with a proteomic or aDNA component to further strengthen both the claim for diagnosis and the validity of the model. Additionally, the use of the biocultural, multidisciplinary, and one health approaches should be implemented in further paleopathological research projects, and these guidelines need to be developed in a way that allows paleopathologists and bioarcheologists to address the osteological paradox in their framework.

Key words: Tuberculosis, Brucellosis, Skeletal Analysis, Radiographs, Pathology, Biocultural, One Health, Disease, Infectious, Eurasia, Austria, Horseback, Differential Diagnosis

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1.0 Introduction

The Avar people were a semi-nomadic population from medieval Eurasia who migrated from the Eastern Asian Steppes to Western European countries that are modernly known as Hungary, Croatia, Slovakia, Serbia, Czech Republic, Romania and Austria (Csáky et al., 2020; Daim, 2003; Kardaras, 2018; Pohl, 2018; Vidal-Ronchas et al., 2019). Their population thrived in a seat of power from the 6th century to the 9th century C.E. due to their formidable warriors, unique riding equipment, and well-designed weaponry (Daim, 2003; Kardaras, 2018; Pohl, 2018; Preiser-Kapeller, 2018; Saag & Staniuk, 2022). Towards the beginning of the 9th century most of Central Europe was taken over by the Franks, including known Avar settlements (Gnecchi-Ruscone et al., 2022; Kardaras, 2018; Pohl, 2018). Over the course of three centuries, the Avars transitioned from a nomadic lifestyle to a sedentary one, which included increasing animal husbandry practices and contact with new populations (Daim, 2003; Kardaras, 2018; Meinel et al., 2010; Pohl, 2018; Preiser-Kapeller, 2018).

Factors such as the state of the physical environment, proximity, diet, access to medical care, wealth, and social interactions can impact the spread of infectious disease within a community (Lönnroth et al., 2009; World Health Organization, 2024). The previously mentioned changes in Avar lifestyle would predictably have an impact on the spread of infectious disease within their sedentary groups. Due to their pre-recorded presence in early medieval populations, brucellosis and tuberculosis will be the subject of this research project (Bendrey et al., 2020; Corthals et al., 2012; Waldron, 2008).

1.1 Objectives

The objectives of this research are to 1) understand the experience of tuberculosis and brucellosis in the Avar population from medieval Austria, 2) gain insight into related lifestyle and cultural practices that had an impact on population health, and 3) address the challenges of skeletal diagnosis between tuberculosis and brucellosis in the hopes of advancing methodology. Using multiple methodologies, this research will gain new information on positively identifying infectious diseases and provide new avenues for understanding the correlation to modern health. Testing will include three separate research methods such as traditional differential diagnosis, probabilistic lesion analysis, and x-ray imaging. These data will be evaluated using the combined theoretical perspectives of a biocultural and One Health approach. This will draw connections between humans, animals, and the environment.

In examining this topic, the project will look at a series of questions: What is the frequency of tuberculosis versus brucellosis in this population? Will the use of different diagnostic techniques make it possible to positively identify brucellosis versus tuberculosis? What effect could community lifestyle have on the spread of infectious disease in this population? It is hypothesized that:

- 1) Given the high transmission rates of tuberculosis and its confirmed presence in medieval Europe, a frequency of tuberculosis at 17% or less would be expected in the medieval Avar population (Pedersen et al., 2019).
 - a. Pedersen et al., (2019) found a 17% frequency in a later medieval Danish population, a similar or greater frequency would be expected in this population given the population density of the Danish population in comparison to the Avar population.

- b. This hypothesis would be supported if the Fisher's exact test on frequency of tuberculosis in this population totaled 17% or greater.
- c. The null hypothesis is that high transmission rates of tuberculosis and its presence in medieval Europe would not affect the Avar population and therefore there would be no observation of tuberculosis.
- d. The null hypothesis cannot be rejected if the Fisher's Exact test on tuberculosis had a p-value > 0.05 , as this suggests that results are not statistically significant (more on this in section 3.3) (Boldsen, 2005; Pedersen, 2016).

2) Given the lower transmission rates of brucellosis than tuberculosis and its rare identification in archaeological contexts, a lower frequency of brucellosis in comparison to tuberculosis would be expected in the medieval Avar population (Bendrey et al., 2020; D'Anastasio et al., 2010).

- a. This hypothesis would be supported if there are fewer observed cases of brucellosis than tuberculosis.
- b. The null hypothesis is that low transmission rates of brucellosis and its rare identification would have no effect on the medieval Avar population and therefore there would be a higher or equal frequency of brucellosis than tuberculosis.

3) Given that brucellosis is more common in populations with ties to husbandry and farming given its zoonotic origin, brucellosis is expected to be identified in this population (Fournie et al., 2017; McKeown, 2009; Moreno, 2014; Zuckerman et al., 2014).

- a. This hypothesis would be supported if there are any signs of brucellosis observed in this population.
- b. The null hypothesis is that zoonotic ties in this population would have no effect on brucellosis transmission, so brucellosis would not be identified in this population.

1.2 Significance

The project stands to gain further insight into tuberculosis and brucellosis, which are previously known to be misidentified for each other in archaeological contexts (Bendrey et al., 2020; Guo et al., 2021). In applying both a biocultural and a One Health perspective approach, this research will also show the benefits of considering environmental factors in infectious disease research from past populations. Additionally, this project will develop a further understanding of the Avar populations and their experience with tuberculosis and brucellosis, which has not yet been a subject of study.

2.0 Literature Review

Avars settled in the Carpathian Basin, located in central Europe, after 568 C.E. They quickly became a strong geopolitical power that was ruled by a Khaganate, referring to a population ruled by a single leader or a Khan (Csáky et al., 2020; Daim, 2003; Gneccchi-Ruscone et al., 2022; Kardaras, 2018; Pohl, 2018; Vidal-Ronchas et al., 2019). The Avars believed in shamanism and gods but were converted to Christianity shortly after their migration to Europe (Pohl, 2018). It is rare for long-distance migration to have occurred at this time; however, the

Avar population was an exception (Gnecchi-Ruscone et al., 2022; Khazanov, 1978; Savelyev & Jeong, 2020). Though their exact origin has been largely debated, it is suggested that the group comes from Eastern Asia thanks to modern genomic research (Csáky et al., 2020; Gnecchi-Ruscone et al., 2022; Gnecchi-Ruscone et al., 2024; Maróti et al., 2022; Savelyev & Jeong, 2020). It is possible the Avars had a stronger ability to complete such a long-distance move due to their previously nomadic lifestyle and horseback riding practices. Though they adjusted to settling in a new area, the Avar maintained their social and political structures.

The Avar population, much like many others in the 6th-9th century C.E., maintained a hierarchical social structure (Daim, 2003). According to research from Csáky et al. (2020), Avar elites inherited power and wealth through paternal lineage. It is also noted that kinship ties were of higher importance in nomadic societies than settled societies. Results suggest that Avar elites had not mixed with other local populations for nearly a century after their arrival to the basin around 600 C.E. and maintained a closed society, even keeping marriages internal to the Avar populations. Towards the latter half of their rule, the Avar population did intermix with other groups. Over the centuries, they often found themselves allies and/or enemies to the Slavs, Persians, Gepids, Lombards, and the Franks (Kardaras 2018; Pohl, 2018). They were also allied with the Byzantine Empire for some time and often fought battles on their behalf, until eventually becoming enemies. The Siege of Constantinople in 626 C.E. would have brought them into contact with most of the Byzantine and Sassanid Empire (Kardaras, 2018; Preiser & Kapeller, 2018; Pohl, 2018; Vidal-Ronchas et al., 2019). The Avar were well known for their abilities in battle given the equipment and techniques that were introduced by them to Europe. In large part, this is owed to their use of horses equipped with armor in battle, their introduction of stirrups which allowed for more comfortable riding and easier saddling, and their introduction of

mounted archers (Daim, 2003; Fields, 2006; Ivantchik, 2004). Many elite members of society even elected to be buried with their horses either in whole or part, to set themselves apart from non-elites (Saag & Staniuk, 2022).

Data suggests that settlement and agricultural activity among the Avar began to increase toward the mid-8th century (Preiser-Kapeller, 2018). As a previously nomadic society, they would have to adapt to a new ecological and economic environment to become sedentary (Khazanov, 1978). Vidal-Ronchas et al. (2019) successfully completed isotope analysis on dentine and enamel collected from several Avar burials within the Nuštar cemetery in Croatia. This determined no dietary differences based on age, sex, or amongst elites and non-elites, revealing social homogenization. They also found that much of the Avar diet consisted of cattle, pigs, sheep, goats, and poultry, reasonably concluding that these were commonly farmed animals among their population based on bones recovered from the site. Results suggest that the population relied more on terrestrial plants than animal-based protein; however, there is evidence of a higher frequency in cattle, sheep, and goat consumption than pigs and poultry. Additionally, there was some speculation that results could be interpreted as a higher consumption of horses and deer than other animals. This is significant given the implications that increased contact with farmed animals could have on the spread of disease within Avar populations (Fleming et al., 2021).

2.1 Medieval Paleoepidemiology

Paleoepidemiology is the study of disease and health in past populations to examine the transmission, origin, and effects on different populations to aid in modern prevention and treatment (Dutour, 2008). The medieval period took place long before germ theory was

discovered and before the term epidemiology was even coined (Conrad & Wujastyk, 2017). In fact, germ theory was not founded until the 19th century C.E. by Louis Pasteur (Susser & Stein, 2009; Tibayrenc, 2007). Germ theory is the idea that diseases are caused by microorganisms known as pathogens or germs, also referred to as the ‘agent’. It is with this knowledge that we can use the sociological and environmental background from the Avar population to look at tuberculosis and brucellosis while considering the complexities of variation in socio-economic and environmental dynamics as conclusions are drawn (Preiser-Kapeller, 2018). Of the infectious diseases that exist today, most are caused by bacterial or viral agents (Fleming et al., 2021). Both brucellosis and tuberculosis are bacterial diseases (Aufderheide & Rodriguez-Martin, 2014; Ortner 2008; Rogers, 2011).

Developing medicine and advanced research suppresses fear of disease outbreak among modern western populations, although healthcare workers face new concerns as bacteria change and become drug resistant, making new outbreaks more plausible (Roberts & Brickley, 2019; Susser & Stein, 2009). According to a Global Tuberculosis Report released in November of 2024, tuberculosis was still one of the leading causes of death from a single infectious agent, having affected 10 million people that year worldwide. Brucellosis is also one of the leading zoonotic diseases worldwide, with as many as 5-12.5 million cases reported each year (Dawood et al., 2023). Though tuberculosis and brucellosis can both be traced back to well over 2 thousand years ago, they still pose a threat (Graham & McAdam, 2018; Pappas et al., 2006; Roberts & Buikstra, 2020). This leads us to consider: What threat might they have posed in a time without modern medicine or preventative measures?

The transmission pathway is the way in which the agent is introduced to the host. Environment is that which affects either the host or the agent in terms of transmission. Common

transmission pathways of a pathogen include respiratory or droplet transmission, airborne transmission, and contact transmission. Contact transmission occurs in one of three ways: person-to-person contact, animal-to-person contact, or environmental contact (Roberts & Brickley, 2019; Fleming et al., 2021). This knowledge is valuable because some infectious agents, such as tuberculosis, can survive for long periods in several environments including in water, in food, and on hands or surfaces (fomites) (Fleming et al., 2021; Tibayrenc, 2007). Some of the environmental factors that can influence pathogen survival include climate, temperature and humidity (Fleming et al., 2021; Green, 2018; Kramer & Assidian, 2014; Mathema et al., 2017). For this reason, these transmission pathways are most effective in colder weather as colder weather tends to draw populations indoors and to congregate in confined spaces for warmth (Green, 2018; Ortner & Aufderheide, 1991).

Additionally, the survival time of a virus or bacteria tends to be longer in warmer or more humid conditions like an indoor environment (Kramer & Assidian, 2014). For many nomadic tribes, population groups were kept small so crowding may have been minimal (Fleming et al., 2021). Typical housing structures would have been huts during the sedentary or middle-to-late Avar period, creating a more confined space ideal for bacterial survival (Daim, 2003; Penz & Lehofer, 2023; Wright, 2016). Population density can also be considered a crucial factor when looking at conditions for transmission, as more people and more contacts also mean more potential carriers (Ortner & Aufderheide, 1991; Tibayrenc, 2007). Furthermore, herd immunity can help prevent the spread of communicable diseases in a population. Tuberculosis is often used as an example of ‘social diseases’ and requires preventative measures (Lönnroth et al., 2009). Additional environmental risk factors for both tuberculosis and brucellosis must be considered.

Contact with most livestock brings an increased risk for both brucellosis and bovine tuberculosis (Conrad & Wujastyk, 2017; D’Anastasio et al., 2011; Fleming et al., 2021). There is often correlation to the domestication of cattle, horses, pigs, goats, sheep, and dogs with the increased presence of infectious disease (D’Anastasio et al., 2011). This is significant as cattle are commonly linked to bovine tuberculosis and brucellosis can be linked to any of the previously listed animals (Rogers, 2011). Additionally, horseback riding allows for larger herding groups of cattle and sheep which also increases the number of potential carriers (Anthony, 2007). Given the common horseback riding among the Avar and a high level of husbandry, we would expect to see an increase in carriers amongst their population as well.

Transmission of brucellosis is caused by unpasteurized milk from livestock. Most consumed milk would have been unpasteurized in the medieval period given that pasteurization would not have been standard practice until William Dewes, Louis Pasteur, and Soxhlet developed the idea in the 19th century (Holsinger, Rajkowski, & 1997; Lucey, 2015). According to Mia et al. (2022), those who work with animals would find themselves at greater risk for transmission of the disease, even in a modern population. In a research study, they found 14-19% pooled prevalence of both bovine tuberculosis and brucellosis among modern livestock occupation groups such as veterinarians, farmers, and slaughterhouse workers.

2.2 One health, Biocultural, & Multidisciplinary Framework

According to Leatherman & Hoke (2017), a biocultural approach is essential to closing the distance between the biological and socio-cultural understanding of humans within the discipline of anthropology. This provides a fuller scope of the intimate connections between people and the environment. Through a multidisciplinary approach, academics stand to gain a

new perspective on old methodologies (Tibayrenc, 2007). The framework centered around a biocultural approach is that of observing the interconnected components of the physical body and environment, thus increasing both understanding and knowledge in research.

Taking the biocultural approach means defining social constructs, determining a method of feasible and reasonable measurement for such constructs, and considering more than one of many socio-cultural factors (Khongsdier, 2007). Despite the tangled web of connecting ideologies and the complications a biocultural approach brings into the framework; it does open the door for multidisciplinary collaboration. Similar to the biocultural approach, the One Health Perspective concerns itself with connecting animals, people, and environment (Bendrey et al., 2020). According to Lebov et al. (2017), the necessity for a multidisciplinary research approach to understand environmental connections to health has never been greater. One Health involves the implementation of knowledge from experts in multiple disciplines to gain a full perspective when looking at health and disease. According to Bendrey et al. (2020), to build a One Health perspective framework, research projects must consider the relationship between exposure sources and direct questions with an aim to understand their ramifications. Additionally, the project would involve collaboration and the use of relevant literature to provide a full scope of interpretation. Recommendations also imply the need for analytical methods that can navigate intricate data structures due to the complexity added by using secondary methodologies.

2.3 Burial Goods in Context

Burial goods often provide context clues to lifestyle and cultures of different populations. They can be crucial in terms of burial dating, determining culture of origin, providing information on social structure or familial relations; they can tell us something about individual

burials, and so much more (Martin et al., 2013). This can play a significant role in a biocultural approach as it assists in piecing together aspects of life and death. One of the foremost goals of all anthropological research is to interpret findings and see what they can tell us about past human populations. Burial items add another piece to the puzzle. An excellent example of this comes from Allison et al. (1972), who wrote about a burial of a mummified child between 8-10 years old who was suspected of having a nearly life-long battle with tuberculosis. A radiograph on the spine revealed Pott's disease.

Analysis on the mummified lungs showed serious necrosis on multiple internal organs, the worst of which stemmed from the lungs bearing small white tubercles typical of tuberculosis. This was further strengthened when they discovered one of the many burial goods was a cushion that they suspected was designated to alleviate pain from the child's back due to vertebral destruction. This is an excellent example of a biocultural approach because they combined archaeological site finds with the biological aspects of the study. While the use of radiographic imaging confirmed the child had tuberculosis, the finding of the pillow was fundamental in understanding that it was a long-term battle with the illness. This highlights the significance in considering environmental components, allowing researchers to understand the experience of past populations.

The Avar population has been known to bury their deceased with various goods; these goods often provide the necessary evidence to identify burials from the Avar population. Some of these goods include weapons or military equipment, jewelry, textiles, belts, horse harnesses, riding equipment, pottery, and horses or other animals (Csáky et al., 2020; Daim, 2003; Gneccchi-Ruscione et al., 2024; Kardaras, 2018; Young, 1978). These archaeological finds, much like any other, are often interpreted in study. Things like jewelry, textiles, and material goods are known

to be a symbol of social status, often used to indicate elite members of a population (Csáky et al., 2020). Identification of social status may help indicate whether different individuals are affected differently by disease based on said status.

Additionally, the symbolisms associated with these goods may suggest specific trade relations. For example, the Christian cross and shaman symbolisms have been discovered in Avar burials and suggests the Avars were either influenced by the Byzantines or traded with them (Kardaras, 2018). Trade means further contact with other populations, providing another potential avenue for disease transmission. According to Preiser-Kapeller (2018, p. 6), “The emergence of slow-wheel-turned pottery in the Middle Avar period reflects a change in the organization of pottery production, which was most likely connected to other economic changes in the Avar Khaganate that are less readily detectable by archaeological methods.” Economic transition may also have something to do with an increase in trade and thus an increase in contacts. Finally, archaeological finds include signs of wood and materials known to be used for tents, which are also associated with Avar lifestyle and have connections to disease transmission in terms of both contact and airborne transmission (see more on this in section 2.1) (Daim, 2003).

Often Avar burials, or “horseman graves” are buried with their harness, including the bridle, saddle, and stirrups, as well as their belt and weaponry such as bows, arrowheads, single-edge swords, and scabbards (Csáky et al., 2020; Daim, 2003; Gneccchi-Ruscone et al., 2024; Kardaras, 2018). Mounts might also contain silver, gold, or have intricate decoration, suggesting the burial as elite (Csáky et al., 2020). Archaeological discovery of these graves provided the basis of understanding the Avars history in battle. It is also known that a select few of these burials include coinciding animal burials, on some occasions to further classify social status. Placement of animals, animal skins, or horses also offer potential implications of disease

transmission within the population. These burials would suggest strong ties to animals. As already known from Vidal-Ronchas et al. (2019), typical diet includes horses, cattle, sheep, poultry, pigs, goats, and on rare occasion, dogs or deer. Each of these animals is known to be associated with either tuberculosis and/or brucellosis. The significance of the breadth of knowledge gained from burial goods allows for better application of the One Health, Multidisciplinary, and biocultural approaches. One health requires the investigation of people, animals, environment, and their interconnection. To understand this connection, an analysis of findings must be made to gain perspective on potential socio-economic or cultural factors that have the potential to affect the spread of disease.

2.4 Tuberculosis

Tuberculosis is caused by specific species of the bacterium known as *Mycobacterium* and is divided into two categories known as Nontuberculosis Mycobacteria or Mycobacteria other than tuberculosis (NTM or MOTT) and *Mycobacterium tuberculosis* complex (MTBC) (Lewin & Schäfer, 2019). The MTBC is a grouping of *Mycobacterium* species that cause tuberculosis infection and consists of *M. tuberculosis* (MTB), *M. bovis*, *M. africanum*, *M. microti*, *M. canettii*, *M. pinnipedii*, and *M. caprae* (Lewin & Schäfer, 2019; Roberts & Manchester, 2010; Zhang et al., 2022). *M. tuberculosis*, *M. canettii* and *M. africanum* are primarily human pathogens, while the remainder of the *Mycobacterium tuberculosis* complex are mainly animal pathogens (Godreuil, Tazi, & Bañuls, 2007). *M. canettii* and *M. africanum* are typically found in certain parts of Africa and would have been rare to see in a medieval Euro-Asian population. *M. microti* causes tuberculosis in rodents, has been found in Europe and North America, and rarely infects humans (Zhang et al., 2022). *M. pinnipedii* causes tuberculosis in seals, walruses, sea lions, and

other pinnipeds. *M. pinnipedii* is also typically found in coastal areas and rarely infects humans. *M. caprae* causes tuberculosis in goats and sheep which means it can be found in any geographical region they inhabit and can infect humans but is less common than *M. bovis* (Zhang et al., 2022). The two main tuberculosis causing bacteria are *M. bovis* and *M. tuberculosis*, the latter being the origin of its common name. *M. bovis* is the most significant of the zoonotic pathogens as other species are less likely to infect humans (Nardell, 2025). Zoonotic infection of *M. bovis* can be transmitted from dozens of animals but is most usually transmitted from cattle via consumed unpasteurized dairy products or airborne bacteria. *M. tuberculosis* makes up 98% of human tuberculosis cases and is typically transmitted through person-to-person contact but can occasionally also be transmitted through animal-to-person contact (Lin & Desmond, 2014; Rogers, 2011; Zhang et al., 2022).

MTB (*M. tuberculosis*) are typically transmitted from sputum, spit, or other bodily fluids (CDCTB, 2022; Nardell, 2025). It can be spread from sneezing or any droplet forming activity but is most often spread through coughing, which creates droplets that remain airborne for several hours and are then inhaled. Although droplets can land and contaminate surfaces, they are often difficult to resuspend and reach airways, making surface contamination less likely to facilitate spread (Nardell, 2025). Symptoms of MTB in humans often include chest pain, fatigue, fever, chills, and most frequently coughing up blood (hemoptysis) or sputum (CDCTB, 2022; Churchyard et al., 2017). MTB is primarily a respiratory infection, often known as pulmonary tuberculosis. This is because *Mycobacterium* are aerobes, and oxygen would have the best supply in the lungs (Nardell, 2025). However, it can be heterogeneous and spread through the blood via the vascular system, this is known as systemic miliary tuberculosis (Bóna, 2014; Nardell, 2025; Rogers, 2011). This means that once MTB is transmitted, it can spread to the

kidney, spine, and brain (CDCTB, 2022). This is also known as extrapulmonary tuberculosis. This dissemination through the body is what typically affects soft or skeletal tissue and is the primary cause of skeletal lesions (Aufderheide & Rodriguez-Martin, 2014; Bóna, 2014). One of the complexities of MTB is that it also can lead to different presentations of infection including primary infection, latent infection, and active infection.

As outlined in Nardell (2025), primary infection is a stage of MTB and occurs upon initial transmission of the *Mycobacterium*; this is typically the first exposure of the individual to the disease. However, this does not necessarily mean that the disease is active, if the individual immune system can fight off bacteria. The latent infection stage is called such because though the bacteria has been transmitted, it does not transform into disease as it is contained inside a granuloma. Latent tuberculosis infection means the bacteria have been introduced to the body but cannot be spread to others, it does not show signs of active disease and is not actively attacking the body. This is because the bacteria are not actively growing despite being present and the disease can self-resolve without treatment over time. Active tuberculosis occurs when the immune system cannot stop the *Mycobacterium* and it begins to multiply. Active tuberculosis means an individual can spread the disease to others and is experiencing symptoms. Reinfection is when a new strain of the disease is transmitted into the same individual. The disease is less likely to be active in this phase due to the prior introduction of the bacteria to the immune system (Aufderheide & Rodriguez-Martin, 2014; Ortner, 2008). However, tuberculosis can enter a reactivation phase in which the disease is no longer latent, causing active pulmonary tuberculosis. Active pulmonary tuberculosis, is when the individual is highly contagious and chronic tuberculosis development becomes possible. It is notable that these stages of tuberculosis are non-linear, and some may be experienced simultaneously (Godreuil, Tazi, & Bañuls; 2007).

While tuberculosis can be deadly, it is also survivable, though living with tuberculosis long term leads to more complicated side effects (CDCTB, 2022). Duration of disease is dependent on both the host and the bacteria but can range from months to years (Churchyard et al., 2017). Long-term or chronic tuberculosis can affect the vertebral region by causing skeletal lesions, most commonly affecting the thoracic and lumbar areas. This could be due to the amount of trabecular bone or its volume of arterial blood supply. Roberts & Brickley (2019) report that only 3-5% of those infected with tuberculosis that remains untreated experience skeletal involvement. In clinical research by Garg & Somvanchi (2011), they report that 10% of extrapulmonary tuberculosis cases have skeletal involvement, and that of those cases, approximately 50% involve the spine.

2.4.1 Paleopathology of Tuberculosis

Diagnostic features of tuberculosis outlined by Aufderheide & Rodriguez-Martin (2014) include: age of death for individuals, lesion morphology, lesion location, and extra-vertebral location. It is possible in most cases for lesions to centralize to the vertebral body, this is likely due to the arterial connections with trabecular bone in the vertebral columns and can also lead to presentation of enlarged vascular foramina in the anterior portion of the vertebrae (Baker et al., 2015; Coqueueqnoit et al., 2015; Waldron, 2008). Tuberculosis vertebral lesions often appear nearly perfectly circular in nature and often also present as resorptive and fragile, with an almost “Swiss cheese” like appearance (Arriaza et al., 1995; Aufderheide & Rodriguez-Martin, 2014; Baker et al., 2015; Kelley & El-Najjar, 1980; Mays et al., 2001; Pálfi et al., 2015). Additional porosity of the vertebral column is apparent, especially in the thoracic and lumbar areas. Lytic lesions are centralized in the lower thoracic and upper lumbar area, though the cervical vertebrae

can be affected (Arriaza et al., 1995; Baker et al., 2015; Kelley & El-Najjar, 1980; Ortner, 2008). There can also be fusion between multiple vertebral bodies. Furthermore, the vertebral collapse combined with vertebral fusion creates an extremely curved appearance known as kyphosis and obtaining an acute angle (Allison et al., 1972; Buikstra, 1976; Li et al., 2019; Ortner, 2008; Ortner & Putschar, 1981; Waldron, 2008). This phenomenon is also known as Pott's disease, an indicator that is specific to tuberculosis (Allison et al., 1972; Coqueueqnoit et al., 2015; Pálfi et al., 2015; Papa et al., 2023; Rivas-Garcia et al., 2013; Teschler-Nicola et al., 2015; Tuli, 2013).

Beyond the vertebrae, the second largest indicator of tuberculosis is the ribs. There is a tendency to observe rib enlargement, new bone formation on the visceral portion of the rib, periosteal new bone formation also on the visceral portion of the rib, and rib lesions (Aufderheide & Rodriguez-Martin, 2014; Kelley & El-Najjar, 1980; Matos & Santos, 2006; Mays et al., 2002; Ortner, 2008; Roberts & Brickley, 2019; Santos & Roberts, 2006; Teschler-Nicola et al., 2015). Nearly 9% of individuals with pulmonary tuberculosis have rib lesions (Aufderheide & Rodriguez-Martin, 2014). There are additionally affected elements including the pelvis and long bones. The pelvis is affected in 20% of tuberculosis cases with skeletal involvement (Aufderheide & Rodriguez-Martin, 2014). The lateral body of the ilium, acetabular fossa, and iliac auricular surface of the pelvis can have clusters of deep pits and abscesses (Aufderheide & Rodriguez-Martin, 2014; Coqueueqnoit et al., 2015; Pedersen, 2019b; Kelley & El-Najjar, 1980; Ortner & Putschar, 1981; Roberts & Brickley, 2019).

On the long bones, the olecranon process of the ulna, head of the femur, greater trochanter of the proximal femur, articular surface of the distal femur, intercondylar area of the proximal tibia, condylar area of the distal humerus, articular surface of the distal humerus, and radial tuberosity of the proximal radius can all present with pits or cavities as well (Arriaza et al.,

1995; Aufderheide & Rodriguez-Martin, 2014; Baker et al., 2015; Pedersen et al., 2019b; Kelley & El-Najjar, 1980; Masiu et al., 2023; Ortner & Putschar, 1981; Roberts & Brickley, 2019). Skeletal tuberculosis that affects the knee is seen in 16% of cases and skeletal tuberculosis that affects the elbow is seen in 5% of cases. Additionally, lytic lesions on the manubrium and scapula are found in 2% of cases, though they are uncommon and more likely to affect children (Aufderheide & Rodriguez-Martin, 2014). Tuberculosis dactylitis, which affects the phalanges of the hands and feet as well as the wrists, is also seen more often in children and only found in 4-7% of cases with skeletal involvement. The most uncommon features are those that can affect the cranium, as they make up less than 1% of cases (Aufderheide & Rodriguez-Martin, 2014). These features are characterized by similar pits or cavities along the anterior, middle or posterior cranial fossa (Masiu et al., 2023; Ortner & Putschar, 1981; Pálfi et al., 2015). Finally, tuberculosis of the joints is uncommon and causes erosion of the surrounding bone. It would be typical to see this effect the epiphysis of the long bones, joints in the hip, or the hands and feet as previously listed. These indicators are more common in children than adults and given selection criteria for the study, are expected to be less common (Aufderheide & Rodriguez-Martin, 2014; Ortner & Putschar, 1981).

2.5 Brucellosis

Brucellosis is the most common and one of the most dangerous zoonotic diseases transmitted today (Bendrey et al., 2020; Chelli Bouaziz et al., 2021; Dawood et al., 2023). Unlike most infectious diseases, brucellosis is also known to primarily affect young and middle-aged adults as opposed to infants and the elderly, who tend to be more vulnerable to disease (Chelli Bouaziz et al., 2021). It is often signified by symptoms including fever, sweating, headaches,

body pains and aches, fatigue, anorexia, malaise, and swelling of the organs (Dawood et al., 2023; Pradeepkiran, 2021). These symptoms are often chronic and can last for years (Dawood et al., 2023). The disease often spreads throughout the body haematogenously to the reticuloendothelial system and nearly every organ can be affected (Chelli Bouaziz et al., 2021; D'anastasio et al., 2011; Mays, 2009). However, brucellosis can be unpredictable as individuals who contract the disease may be asymptomatic and the symptoms may appear or disappear unexpectedly overtime due to repeat exposure to the bacteria, much like tuberculosis (Zhen et al., 2013).

Brucellosis is typically caused by the bacteria *Brucella*, of which any species can affect human populations (including *B. netomae*, *B. ovis*, *B. ceti*, *B. pinnipedialis*), and *B. microti*, but the four main species are: *B. melitensis*, *B. abortus*, *B. canis* and *B. suis* (Aufderheide & Rodriguez-Martin, 2014; Bendrey et al., 2020; D'anastasio et al., 2011; Dawood et al., 2023). *B. melitensis* is typically transmitted through infected goat milk, *B. abortus* is often transmitted from contact with cattle or horses, *B. canis* is usually transmitted from contact with dogs, and *B. suis* is usually transmitted through infected pig meat or through an open wound from direct contact with contaminated animal tissue (Aufderheide & Rodriguez-Martin, 2014; Chelli Bouaziz et al., 2021; D'anastasio et al., 2011; Ortner, 2008; Pradeepkiran, 2021). Human-to-human transmission is rare (Mays, 2009). Unpasteurized milk consumption is the most common transmission method to humans, but cuts and abrasions that come into contact with infected animals are notable as well (Aufderheide & Rodriguez-Martin, 2014; Bendrey et al., 2020; D'anastasio et al., 2011; Fournié et al., 2017; Pradeepkiran, 2021).

Fournié et al. (2017) found that goat pasturing was a major contributing factor to the spread of brucellosis and stated that the change from a hunter-gatherer lifestyle to animal

domestication played a large role in increasing disease transmission. Due to the close association between humans and large herds that is observed with husbandry lifestyle, an ideal environment is created for the spreading of bacteria. It is hypothesized that brucellosis infections escalated in the early stages of animal domestication (McKeown, 2009; Moreno, 2014; Zuckerman et al., 2014). In considering population dynamics and conducting a sensitivity analysis through simulated scenarios, Fournié et al. (2017) found that it was reasonable to conclude the emergence of livestock-related, zoonotic diseases likely occurred in the Near East. They also found further validation for the theory that animal domestication played a large role in the rise of zoonotic infection. Despite the strong foundation for potentially identifying the origin of brucellosis, it is still rarely identified in archaeological records (Bendrey et al., 2020). The *Brucella* bacteria retain life in the immune system, before spreading to the spine where it primarily affects the lumbar system (Bendrey et al., 2020; Glasgow, 1976). Though skeletal pathology typically presents in 10% of brucellosis cases, some studies have reported up to 70-75% of brucellosis cases having skeletal involvement (Aufderheide & Rodriguez-Martin, 2014). This could be attributed to misdiagnosis or some studies on skeletal brucellosis could be looking at populations where the disease is endemic.

2.5.1 Paleopathology of Brucellosis

Similar to tuberculosis, vertebral lesions often occur in groups and in several vertebrae. Vertebral degradation is centered in the lumbar region (60%), primarily affecting the fourth and fifth lumbar vertebrae, rarely affecting the thoracic (19%) or cervical (12%) vertebrae (Aufderheide & Rodriguez-Martin, 2014; Chelli Bouaziz et al., 2021, D'Anastasio et al., 2011; Jones, 2019; Mays, 2009). Its unique identifier being the 'parrots beak' feature on the affected

vertebrae and appearance of the vertebrae would be similar to that of degenerative disorders (Chelli Bouaziz et al., 2021; Jones, 2019; Ortner, 2008; Tuli, 2019). This often presents with osteophytes on the anterior-superior portion of the vertebrae (Chelli Bouaziz et al., 2021; Jones, 2019; Mays, 2009; Ortner, 2008). Additional erosion on the superior and inferior corners of the vertebral body is consistent with brucellosis as well as height loss of the intervertebral disc (Jones, 2019). This is likely due to the rich blood supply at the discovertebral junction (Chelli Bouaziz et al., 2021; D'Anastasio et al., 2011). Though skeletal brucellosis can be traced back to the Middle Bronze Age, it remains under-studied in comparison to tuberculosis (Chelli Bouaziz et al., 2021).

Other signs of skeletal brucellosis can include arthritis, spondylodiscitis, bursitis, tenosynovitis, osteomyelitis, or Pedro Pons' (Aufderheide & Rodriguez-Martin, 2014; Chelli Bouaziz et al., 2021; D'Anastasio et al., 2011). Pedro Pons' sign is a sclerotic curvature in the anterosuperior angle of the lumbar region and is specific to brucellosis. This sclerotic formation is accompanied by a hemi-ring, a crescent shaped bone formation that can be dense and cover the anterosuperior somatic angle both inferiorly and posteriorly, surrounding an area of osteolysis. This is likely caused by the trabecular-arterial network within the spine and the ossification center of the anterior body (D'Anastasio et al., 2021; Mays, 2009). Skeletal involvement can be dependent on age, often presenting as spinal in elderly and jointly in children and young adults (Chelli Bouaziz et al., 2021). Brucellosis may affect the hips, joints, and long bones, though this is rare, and flat bones are least often affected (Aufderheide & Rodriguez-Martin, 2014; Ortner & Putschar, 1981).

2.6 Differential Diagnosis

Brucellosis and tuberculosis can present similarly in terms of symptoms (Table 3) and skeletal pathology. This is likely because the two are so alike in terms of clinical presentation, dissemination in the body, delivering agent, transmission pathways, and occasionally similar demographic patterns. Unlike tuberculosis, however, transmission of brucellosis is more commonly animal-to-person and rarely person-to-person (Bendrey et al., 2020; Chelli Bouaziz et al., 2021). These similarities of activity in the body are the likely cause of their similar presentations in the skeleton.

Table 1. A comparison of brucellosis and tuberculosis

Tuberculosis	Both	Brucellosis
- Transmission: Person-to-person & Person-to-animal (predominantly Person-to-person) - Majority Strains Affecting Human Populations: <i>M. bovis</i> and <i>M. tuberculosis</i> - Transmission Pathways: Airborne / Droplet / Respiratory / Contact / Unpasteurized milk or meat consumption / Sputum or Contact / Infected host - Symptoms: Coughing, sputum, chest pain, & other respiratory complications - Can be active or inactive (latent)	- Symptoms: Fever, fatigue, body aches, chills & sweating - Disease-causing organism: Bacteria - Affects major organs - Demography: Can both be transmitted zoonotically	- Transmission: Person-to-animal & Person-to person (predominantly Person-to-animal) - Majority Strains Affecting Human Populations: <i>B. melitensis</i>, <i>B. abortus</i>, and <i>B. suis</i> - Transmission Pathways: Unpasteurized milk/meat consumption or contact with farmed animals - Symptoms: Organ swelling, anorexia, headaches & malaise

Regardless of the differences between brucellosis and tuberculosis, they are difficult to distinguish from one another based on skeletal diagnosis (Bendrey et al., 2020; Guo et al., 2021; Ortner & Putschar, 1981). Distinguishing brucellosis from tuberculosis is challenging, in part,

because the most common diagnostic skeletal feature of both are lesions in the vertebrae of the spine (Aufderheide & Rodriguez-Martin, 2014; Chelli Bouaziz et al., 2021; D’Anastasio et al., 2011). The vertebral destruction typically observed in tuberculosis and brucellosis occurs on both the inferoanterior and superoanterior surfaces of the vertebral body (Jones, 2019; Tuli, 2019; Waldron, 2008). However, tuberculosis tends to be more centralized in both the thoracic lumbar areas and brucellosis tends to be more centralized in the lumbar area than the thoracic (Aufderheide & Rodriguez-Martin, 2014).

Modern technology like MRIs or radiographic imaging has, of course, made clinical diagnosis easier (Chhem et al., 2008; Guo et al., 2021; Villa et al., 2019). However, modern methods of identification often involve soft tissue or fluid samples (Dawood et al., 2023; Mateos et al., 2020; Queipo-Ortuño et al., 2009). This is a factor that has also presented itself in archaeological research projects as some have successfully distinguished brucellosis from tuberculosis using soft tissue samples (Arriaza et al., 1995; Corthals et al., 2012; Crube’zy et al., 1998; Mays et al., 2001; Zink et al., 2007). However, the proposed project will focus on bone tissue, which has also found success in other projects (Boros-Major et al., 2011; Pedersen et al., 2019a; Kay et al., 2014; Li et al., 2019; Masiu et al., 2023; Matos & Santos, 2006; Mays et al., 2001; Mutolo et al., 2012).

Guo et al. (2021) conducted MRI mapping on skeletal lesions from brucellosis and tuberculosis, which found that brucellosis had significantly less severe vertebral degradation, osteonecrosis, posterior vertebral convex deformity, and abscess scope than tuberculosis (Chelli Bouaziz et al., 2021; D’Anastasio et al., 2011). However, tuberculosis causes paravertebral abscesses, vertebral collapse, vertebral fusion, kyphosis, and it frequently affects the ribs unlike brucellosis (Aufderheide & Rodriguez-Martin, 2014). The lack of identifiable rib features can be

attributed to brucellosis not being a respiratory disease like tuberculosis (Matos & Santos, 2006; Pradeepkiran, 2021). Additionally, brucellosis simultaneously demonstrates a destructive and reparative process, whereas tuberculosis is only destructive (Guo et al., 2021; Jones, 2019). According to Waldron (2008), “There is an attempt at repair early in the course of the disease and new bone formation is a feature of brucellosis while radiographs of affected vertebrae show dense sclerosis around and beneath lesions, an important point that may be used to differentiate brucellosis from tuberculosis” (p. 96). There was also higher vertebral hyperplasia (bone enlargement) due to increased tissue multiplication in brucellosis than tuberculosis.

Though uncommon, both brucellosis and tuberculosis can be mistaken for or diagnosed as pyogenic osteomyelitis, actinomycosis, arthritis, coccidioidomycosis, blastomycosis, metastatic tumors, and pyogenic spondylitis as shown in Table 2 (Aufderheide & Rodriguez-Martin, 2014; Buikstra, 1976; D’Anastasio et al., 2011; Ortner, 2008; Pálfi et al., 2015). The misdiagnosis is perpetuated by the bias of tuberculosis focused studies and concerns over a lack of adequate and well-defined diagnostic features (Bóna et al., 2014). Pyogenic osteomyelitis can be differentiated from tuberculosis as it is not nearly as destructive to the vertebrae, involves no gibbus formation (acute spinal angle), does not include sequestrum of lytic lesions, and more often affects the spinous process or neural arch than the anterior portion of the vertebrae (Aufderheide & Rodriguez-Martin, 2014; Buikstra, 1976; Ortner, 2008; Ortner & Putschar, 1981; Pálfi et al., 2015). Actinomycosis more often involves the mandible, which is not a typical skeletal component of tuberculosis and osseous inclusion in actinomycosis is rare. Arthritis tends to be bilateral as opposed to tuberculosis, which tends to be unilateral, and it more frequently affects the joints (Aufderheide & Rodriguez-Martin, 2014; Buikstra, 1976; Ortner, 2008; Ortner & Putschar, 1981; Pálfi et al., 2015).

Blastomycosis and coccidiomycosis both involve posterior elements of the vertebrae as opposed to the anterior elements commonly observed with tuberculosis. Metastatic tumors result in a more obtuse gibbus formation as opposed to the acute one displayed in tuberculosis and typically involves more than two continuous vertebrae. With pyogenic spondylitis, rarefaction is common, but cysts or lesions are not (Aufderheide & Rodriguez-Martin, 2014; Buikstra, 1976; Ortner, 2008; Ortner & Putschar, 1981; Pálfi et al., 2015). However, additional considerations for coinfection must be considered in cases where identifiable features do overlap with multiple diseases. Skeletal morphology may be difficult to decipher; it is for this reason that strict diagnostic parameters will be followed based on founding literature.

Table 2. Differential diagnosis of skeletal pathologies (Aufderheide & Rodriguez Martin, 2014; Buikstra, 1976; Ortner, 2008)

Pathology	Appearance
Actinomycosis	Resorptive lesions commonly seen in the mandible, more often affecting the head and neck areas of the body. Though it can affect the vertebrae, it is rare and is typically seen in the neural arch as well as the vertebral body in the thoracic and lumbar region. Ribs can also be affected but it is rare.
Arthritis (Nonspecific)	Most frequently affects the joints, hands, and feet. Has a symmetrical appearance. Cervical region of the vertebral column most affected, though different types of arthritis can affect different regions. Typically seen with aging in older individuals.

Blastomycosis	Vertebral and rib lesions are observed, typically observed in the posterior portion of the spine often affecting the neural arch. The skull, tibia, and short bones of the hands and feet are also usually involved.
Brucellosis	Typical features such as the parrot's beak, and destruction to the inferior and superior portions of the ventral margin. Signs of repair are expected (more features listed in 2.5.1).
Coccidioidomycosis	Any skeletal involvement is rare but would commonly affect the spine, ribs, long bones, and skull. Spinal involvement usually affects any region but typically observed in the posterior portion similar to Actinomycosis and Blastomycosis.
Malignant or Metastatic Tumors	Tends to have a more obtuse gibbus formation, and affects multiple, noncontinuous vertebrae. The neural arch and ribs would have lesions.
Tuberculosis	Typically observed in the vertebral bodies with destructive lesions in the vertebral body. Typically affects the thoracic and lumbar portions. May also be seen with kyphosis (Pott's), creating an acute spinal angle and vertebral fusion. (more features listed in section 2.4.1).
Pyogenic Osteomyelitis (Nonspecific)	Typically observed with one or more cloacae (lesions), sequestered bone, and/or involucrum. Its primary locations stem from the marrow in bone. Mostly seen in the long bones, but can affect the vertebrae.
Pyogenic Spondylitis (Nonspecific)	Cyst formation in the vertebrae is not common, but rarefaction (loss of density) is. It can cause vertebral destruction, height loss, and kyphosis. Does not typically affect other areas of the body (i.e. ribs, hips, etc.).

2.7 Osteological Paradox

In 1992, Wood et al. wrote of the ‘osteological paradox’ to highlight the challenges with the standardized analytical practices in paleopathology and paleodemography. The challenges include hidden heterogeneity in frailty, selective mortality, and demographic nonstationary. Hidden heterogeneity in frailty acknowledges the fact that different individuals will vary in susceptibility to diseases or stressors, thus making them unequal in risk of death. Selective mortality acknowledges that data taken only from the deceased are a biased representation of past populations. Demographic nonstationary acknowledges that a cemetery may be from a population that migrated and lost individuals on the journey who are therefore not represented or experienced fertility and mortality changes, also limiting our perception of their story (Dewitte & Stojanowski, 2015; Wood et al. 1992). This is significant because each of these challenges relate to the Avar population given that they are known to have migrated and the sole focus of the project is to gain insight on the experience of tuberculosis and brucellosis in this population from skeletal data.

The osteological paradox acknowledges that a lack of pathology observed in the skeleton is not a complete indicator of health as 1) not all diseases have skeletal involvement, 2) not all individuals experience a disease the same way and, 3) some individuals may have lived longer with the disease than others. It is recognized that in paleopathology there is minimal representation of individual health in comparison to the population (Dewitte & Stojanowski, 2015; Siek, 2013; Wood et al., 1992). It is important to note here that the osteological paradox must be considered in reporting as this refers to the dynamic of using observation-based diagnostics in the skeletal appearance and labeling of individuals as ‘healthy’ versus ‘diseased’ (Dewitte & Stojanowski, 2015; Wood et al., 1992).

For example, an individual skeleton may appear ‘normal’, with no pathological signs of infection despite having been infected, which would be the case if an individual died shortly after infection. We cannot then automatically label this individual ‘healthy’ simply because their skeleton lacks pathological indicators (Wood et al., 1992). While both brucellosis and tuberculosis can be chronic, there are many cases where the disease advances rapidly and there is no skeletal involvement (Buzgan et al., 2010; Donoghue, 2011; Donoghue et al., 2015). Additionally, we must consider the possibility of coinfection (Bendrey et al., 2019). Although an individual shows signs of having had tuberculosis in the skeleton, they may still have also been infected with brucellosis. In this case, differential diagnosis may be impossible from a macroscopic view. Simultaneously, the osteological paradox states an overreliance on skeletal lesions as confirmation of disease or infection (Dewitte & Stojanowski, 2015; Wood et al., 1992). This includes the paleopathological interpretations on lesions in bone.

An easy assumption to make when lesions are observed is an increased risk in individual susceptibility or increased frequency of a disease within a population. This is not, however, accounting for the previously highlighted considerations when looking solely at skeletal-based data. For example, lesions in the skeleton can be benign and do not necessarily indicate an active illness or disease (Hakim et al., 2015). Skeletal lesions are open to interpretation at the discretion of the researcher, historically known to lead to the conclusion that skeletal lesions are associated with poor health. The osteological paradox addresses this assumption with the understanding that the prevalence of lesions does not mean a prevalence of disease within a population and that skeletal evidence is only paradoxical if single skeletal indicators are used to infer the health status of said population (Goodman, 1993; Merrett, 2004; Wood et al., 1992).

While skeletal lesions may not suggest that an individual was unhealthy, lesions are still often considered common indicators used to diagnose diseases like tuberculosis and brucellosis. This further prompts the inquiry: What do we consider “healthy” and how do we prevent this concept from leading to grand conclusions? This debate has become polarized since the World Health Organization released their definition of ‘health’ in 1948 stating it as, “a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity” (pg. 16). This definition suggests that if we are not ‘completely’ healthy then most people would be considered unhealthy most of the time. Additionally, it emphasizes concerns that have changed, evolved, or shifted in the last nearly 75 years (Dewitte & Stojanowski, 2015; Huber et al., 2011; Jadad & O’Grady, 2008; Temple & Goodman, 2014).

3.0 Methods & Materials:

Data for the project is based on a visual osteological analysis complemented by radiographic and photographic images, as well as a statistical probability model based on pathological scoring. Pathological scoring and biological profiles were completed on the remains of Avar individuals that are a part of the Bruckneudorf collection at the Naturhistorisches Museum and the Hirschstetten collection from City Archaeology Department at the Museen der Stadt Wien. The statistical probability analysis using a Fisher’s exact test was based on an existing sensitivity and specificity scale in relation to tuberculosis (Pedersen et al., 2016; Pedersen et al., 2019a; Pedersen et al., 2019b).

3.1 Materials: Skeletal Sample

The sample size includes 54 individuals from the Hirschstetten (22 individuals) and Bruckneudorf (32 individuals) cemeteries. The Hirschstetten cemetery was recently excavated in Fall 2022 – Fall 2023 after being discovered during the process of construction and city development in Vienna. The site is located in the Franz-Fellner Gasse area of Vienna's 22nd district (see Figure 1) and burials have been dated to the late Avar period (680/710-822 C.E.) based on burial goods (Penz & Lehofer, 2023). Excavations uncovered 205 individuals who have hardly been studied given the site's recent excavation. Preservation was described as "moderately good" given grave disturbances with construction, unfavorable soil conditions, and groundwater fluctuation which led to many missing, fragmented, or damaged grave components (Penz & Lehofer, 2023). Additional records on burial sites and grave goods have been made available for Hirschstetten. The Bruckneudorf site was excavated in 2003-2005 and the collection has remained housed at the Naturhistorisches Museum since. The site is located 40 km southeast of Vienna (see Figure 1) and the burials have been dated to the middle/late Avar period from 7th-8th century C.E. The collection consists of 412 individuals total and have overall been "well preserved" with minimal fragmentation and many complete skeletons including skulls (Pany-Kucera & Wiltchke-Schrotta, 2023). Burial records were not available for study on the Bruckneudorf individuals.

Figure 1. Map of Vienna Highlighting Archaeological sites of Hirschstetten and Bruckneudorf (OpenStreetMaps, 2025, August 27)



3.2 Materials: Imaging

The osteological methodology for this project was minimally invasive and required photographic and radiographic imaging equipment as individuals were mainly studied macroscopically. The method required lab space for macroscopic study and access to adult skeletal remains. This took place at the Naturhistorisches Museum and Novetus Archaeological Trust. Any additional methodologies were dependent on permissions through the NHM and Museen der Stadt Wien. For the differential diagnosis evaluation, both radiographic and photographic images were taken. Radiographic and imaging techniques provide another means of observing osteological findings and are commonly used methods for diagnosis by both

paleopathologists and doctors (Aufderheide & Rodriguez-Martin, 2014; Baker et al., 2015; Chhem et al., 2008; Coqueugniot et al., 2015; Irede et al., 2024; Mays et al., 2007; Mutolo et al., 2012; Pálfi et al., 2015; Villa et al., 2019).

Both imaging techniques play a beneficial role in observing skeletal remains up close, proving an avenue to study structural bone changes and allow for easier pathological diagnosis. Clear radiographic and photographic images were taken with an emphasis on any features that were used to flag a potential diagnosis of pathology. Relevant photographs were taken using a Canon DSLR camera and lighting setup. Individuals suspected of having tuberculosis or brucellosis based on diagnostic features also underwent radiographic imaging using a Gierth HF200a on pathological vertebrae. This provided an internal view of the relevant vertebrae and allowed for appropriate comparison of lesions in the vertebral body and other diagnostic features previously listed in literature review (see section 2.4.1). For the purpose of this project, the log linear model under the One Health approach will build the structure of statistical data interpretation as it is best used when examining a variable relationship that examines three or more factors and their inter-dependencies. The alternative was a principal component analysis that allows researchers to make a linear correlation between factors under consideration, but this could limit the project's focus as it condenses potential contributing variables as opposed to focusing on connections (Lebov et al., 2017).

3.3 Methods: Skeletal Sample

All individuals included in the study were 16 years of age or older due to the higher risk of death before skeletal involvement in individuals under the age of 16, as per Pedersen, (2016). Information on sex, age, pathological signs and burial records were collected. Sex and age are

estimated using traditional methodology and modern methodology in accordance with feature scoring. For sex estimation, individuals were graded on a scale of 1-5, with 1 being scored as female and 5 being scored as male. Determining biological sex of each recorded individual meant scoring both pelvic and skull features. For pelvic features, the subpubic concavity, medial aspect of the pubic symphysis, ventral arc, and sciatic notch were scored (Klaes et al., 2012; Walker, 2005). For skull features, the nuchal crest, mastoid process, supraorbital margin, supraorbital ridge, and mental eminence were also scored (Buikstra & Ubelaker, 1994; Walker, 2008; White et al., 2011). The scores between all methods were averaged for reporting. Age estimation for younger individuals (ages 16-24 years old) was scored via dental eruption and epiphyseal growth sites (Cardoso, 2008; Schaefer, 2008; Schaefer, Black, & Scheuer, 2009; Ubelaker, 1979; Webb & Suchey, 1985).

Age estimation for older individuals (ages 24+) was scored for the surface of the pubic symphysis and auricular surface of the ilium (Brooks & Suchey, 1990; Lovejoy et al., 1985; Todd, 1923). All individuals were also scored and run through the transition analysis statistical program to calculate age estimation, version 3 (Milner et al., 2021). Of all individuals studied between both collections, there was an nearly equal number of individuals identified as biological males (24) or females (23), with only seven individuals being listed as unknown as shown below in Table 3. Individual age scores were recorded on a point estimate and given a minimum and maximum age at death (Christensen et al., 2014; Milner & Boldsen, 2012). Individual age scores using transition analysis had differing error ranges which are available with the transitional analysis reports. Ages reported in Table 3 were listed within 10-year age ranges for greater accuracy in reporting and to accommodate error ranges (Buckberry, 2015).

Table 3. Demographic Data of Studied Individuals

Data	Number of Individuals	Frequency (% of sample)
Biological Sex		
Male	24	44.44
Female	23	42.59
Unknown	7	12.96
Age at Death		
18-25	3	5.56
26-35	4	7.41
36-45	13	24.07
46-55	14	25.93
56-65	10	18.52
65+	10	18.52

3.4 Methods: Paleopathological Analysis of Tuberculosis

Eight indicators of tuberculosis included in statistical analysis will be considered according to the sensitivity and specificity scale on a range of absent (0) to present (1) and centered towards the ribs, vertebrae, pelvis and long bones. The indicators and matching descriptions as listed in Table 4, are from Pedersen et al. (2019b, Table 3).

Table 4. Recorded indicators scored for tuberculosis (Pedersen, 2019b, Table 3)

Indicator	Location	Description
RIB1	Visceral surface of ribs	Small nodules and rough texture > 5 cm
RIB2	Visceral surface of ribs	Two or more pieces of ribs larger than 5 cm have: • Superficial bone proliferation covering more than 5 cm • One or more bean-shaped lytic lesions measuring more than 5 mm in diameter
VEN1	Ventral portion of thoracic and lumbar vertebrae	Three or more large cavities with a roughly circular shape and rounded edges each measuring at least 3 mm in diameter
VEN2	Ventral portion of thoracic and lumbar vertebrae	Two or more thoracic or lumbar vertebrae have a proliferation of bone with a woven appearance that covers 50% of the bone's surface
BOD	Lateral body of ilium between the lower gluteal line and upper acetabular margin	Three or more large pits with a roughly circular shape and rounded edges each measuring more than 3 mm • Proliferation of bone with a woven structure is present on at least 50% of the bone's surface
ACE2	Articular surface of the acetabulum	Two or more deep cavities in the acetabular fossa, each measuring more than 3 mm or covering more than 50% of the area, with

		borders having the appearance of a woven structure with dense trabeculae
ILI	Iliac auricular surfaces	Clustered pits or large cavities in two or more areas, each measuring more than 3 mm, or in one area measuring more than 10 mm
PU	Olecranon process of proximal ulna.	Clustered pits or large cavities are present on the olecranon process in two or more areas, each measuring more than 3 mm, or in one area measuring more than 10 mm

RIB1 presents as small, rough nodules on the visceral surface of the ribs. RIB2 presents as perforated, woven bone, or lytic lesions also on the visceral surface of the ribs. VEN1 presents as large circular pits on the ventral aspect of the vertebral body in either the thoracic or lumbar region. VEN2 presents as perforated or woven bone also on the ventral aspect of the vertebral body in either the thoracic or lumbar region. According to Pedersen (2016, p. 53), RIB2 and VEN features were statistically strong indicators of tuberculosis, “The presence of RIB2 lesion provided a 59.7% probability of a valid TB-diagnosis. The absence of a lesion here provided a 3.2% probability of TB. For VEN the presence provided a 58.1% probability of a valid diagnosis and the probability of TB when absence of lesion was 4.8%.” More on this topic can be found in Pedersen (2016), as these probabilities are the foundation for sensitivity and specificity numbers used for analysis.

BOD presents as multiple pits or cavities clustered together on the articular surface of the acetabulum. ACE presents as pits or deep cavities on the iliac auricular surface of the os coxae. PU presents as erosion, pits, or cavities on the olecranon process of the proximal ulna. Though

not included in the statistical analysis, additional features had to be considered per findings in Section 2.4.1.

3.5 Methods: Statistical Analysis of Tuberculosis

The statistical analysis selected for this project is attributed to the Fisher's exact test used in Pedersen et al., (2016; 2019a; 2019b). This method builds on the statistical model built by Boldsen (2001a; 2005) on leprosy. Statistics were completed with the use of SPSS, version 29 and mapped using Desmos, version 7.37.0. Priors for statistical calculations were based on the Terry and Bass collections used in Pedersen et al., (2016; 2019a; 2019b) to create the sensitivity and specificity scale. There were 240 individuals from the Terry collection at the Smithsonian dated from the 1920s-1950s who had tuberculosis documented as their cause of death in medical records and 240 individuals from the Bass collection dated to the 1980s who had no signs of tuberculosis or any pulmonary related condition. Both collections are from U.S. populations. The Terry collection was used as an experimental group and Bass was used as a control group (Pedersen et al., 2016; 2019a; 2019b).

Sensitivity and specificity were used to determine the likelihood that a specific lesion could be an indicator of tuberculosis. Sensitivity determines a true positive by calculating the probability that an individual would have a scorable lesion given that the individual had tuberculosis. Specificity determines a true negative by calculating the probability that an individual would not have a scorable lesion given that the individual did not have tuberculosis (Pedersen et al. 2016; 2019a). Though many scorable lesions are considered, only 8 are determined to be statistically significant (Pedersen et al., 2016; 2019a; 2019b). Sensitivity and

specificity measures have already been provided in Pedersen et al., (2019b, p. 95) and are shown below in Table 5.

Table 5. Sensitivity and Specificity Numbers used for Statistical Analysis of tuberculosis (Pedersen, 2019b, p. 95, Table 3)

Lesion	Sensitivity	Specificity
RIB1	0.400	0.416
RIB2	0.337	0.987
VEN1	0.208	0.962
VEN2	0.533	0.959
BOD	0.332	0.949
ACE2	0.420	0.935
ILI	0.296	0.942
PU	0.092	0.983

Pedersen's study was based on an archaeological collection of 713 skeletons from the Ribe cemetery which dates back to 800-1800 C.E. Denmark (2016). This analysis had multiple steps starting with 1) computing the log-likelihood ratio based on the presence or absence of the 8 tuberculosis indicators using the equation shown in Figure 2 (Pedersen, 2019, Equation 1), then 2) finding the simulated positive mean and simulated negative mean using scores from the log-likelihood ratio as pictured in the equations shown in Figure 3 (Boldsen, 2005, Equation 2 & 3), then 3) calculating the mean and variance of data from previous equations to determine the p-

value or significance and the prevalence of the disease using the equations shown in Figure 4 (Pedersen, 2019, Equation 2, 3 & 4). Prevalence will conclude how frequent or common tuberculosis was within the studied population.

Figure 2. Application of the statistical model to calculate the likelihood of an individual having tuberculosis at death (Pedersen, 2019, Equation 1)

$$t_k = \sum_{j=1}^8 \ln \left(\frac{sens_j^{\Delta jk} \cdot (1 - sens_j)^{1-\Delta jk}}{spe_j^{1-\Delta jk} \cdot (1 - spe_j)^{\Delta jk}} \right)$$

Key for Equation

- t_k - Probability of tuberculosis
- Δjk – Sum of lesion scores
- 8 – Number of scored indicators
- $sens$ – Sensitivity: Probability of having an indicator lesion and disease of interest
- spe – Specificity: Probability of having neither indicator lesion nor the disease

Figure 3. Application of the statistical model to calculate the likelihood of an individual having tuberculosis at death given lesion presence or did not have tuberculosis given lesion absence (Boldsen, 2005, Equation 2 & 3)

$$t^+_k = \sum_{j=1}^8 \ln(sens_j^{\Delta jk} \cdot (1 - sens_j)^{(1-\Delta jk)})$$

$$t^-_k = \sum_{j=1}^8 \ln(spe_j^{1-\Delta jk} \cdot (1 - spe_j)^{\Delta jk})$$

Key for Equation

- t^+_k - Probability of tuberculosis at death given lesion presence

- t_k^- - Probability of not having tuberculosis at death given lesion absence
- Δjk – Sum of lesion scores
- 8 – Number of scored indicators
- $sens$ – Sensitivity: Probability of having an indicator lesion and disease of interest
- spe – Specificity: Probability of having neither indicator lesion nor the disease

Figure 4. Application of the statistical model to calculate frequency of tuberculosis at death (or prevalence) in a population (Pedersen, 2019, Equation 2, 3 & 4)

$$t_0 = p \cdot t_+ + (1 - p) \cdot t_-$$

Or (to solve for p)

$$p = \frac{t_0 - t_-}{t_+ - t_-}$$

$$S_0^2 = p \cdot s_+^2 + (1 - p) \cdot s_-^2 + p \cdot (1 - p) \cdot (t_+ - t_-)^2$$

Or (to solve for p)

$$p = \frac{[(s_+^2 - s_-^2) + (t_+ - t_-)^2] \pm \sqrt{[(s_+^2 - s_-^2) + (t_+ - t_-)^2]^2 - 4(t_+ - t_-)^2(-s_-^2 - s_0^2)}}{2(t_+ - t_-)^2}$$

$$f(p) = \left(\frac{t_0 - (p \cdot t_+ + (1 - p) \cdot t_-)}{se(t_0)} \right)^2 + \left(\frac{s_0^2 - (p \cdot s_+^2 + (1 - p) \cdot s_-^2 + p \cdot (1 - p) \cdot (t_+ - t_-)^2)}{se(s_0^2)} \right)^2$$

Key for Equations

- t_0 = Observed mean
- t_+ = Observed simulated positive mean
- t_- = Observed simulated negative mean
- S_0^2 = Observed variance
- s_+^2 = Observed positive variance
- s_-^2 = Observed negative variance
- se = Standard error (calculated using standard deviation divided by sample size squared)
- p = each of the values solved for in the first two equations
- $f(p)$ = how well tb frequency matches observed data

In statistics, a p-value is always a value in the range of 0-1 that quantifies the strength of evidence against the null hypothesis. This helps determine that the observation is not due to chance, in this case the observation of lesions related to tuberculosis (Glantz, 2012; Greenland et al., 2016). The p-value is derived from a t-statistic that derives data based on the statistical model built. This value was created in 1925 when Ronald Fisher developed a statistical model suggesting that the p-value could be used to represent significance (Glantz, 2012). For the purpose of this project, the p-value is set at $p < 0.05$ which would suggest statistical significance (Boldsen, 2005; Pedersen, 2016; Pedersen, 2019b).

3.6 Paleopathological Analysis of Brucellosis

Four indicators of brucellosis have been considered (Table 5). However, there is no sensitivity and specificity scale on brucellosis, making statistical analysis using the Fisher's exact test selected for tuberculosis unfeasible. Macroscopic methods for brucellosis will be

centered toward differential diagnosis and will be used to calculate suspected frequency of brucellosis at death.

Table 6. Recorded indicators scored for brucellosis (Aufderheide & Rodriguez-Martin; Chelli Bouaziz et al., 2021; D’Anastasio et al., 2011; Jones, 2019; Mays, 2009; Ortner, 2008; Tuli, 2019)

Indicator	Location	Description
VER1	Superior and Inferior surface of the lumbar vertebrae	Pits or cavities are present in two or more areas, each measuring more than 3 mm, or in one area measuring more than 10 mm
VER2	Superior and Inferior surface of the lumbar vertebrae	Signs of new bone growth / healing, degradation and destruction but with new bone growth
VER3	Anterosuperior & Anteroinferior surface of lumbar vertebrae	Osteophytes / “Parrots beak”

VER1 is presented as pits or cavities on the superior and inferior surfaces of the lumbar vertebrae (Aufderheide & Rodriguez-Martin, 2014; Chelli Bouaziz et al., 2021, D’Anastasio et al., 2011; Jones, 2019; Mays, 2009). VER2 is presented as both degradation and reparative bone growth on the superior and interior surfaces of the lumbar vertebrae (Aufderheide & Rodriguez-Martin, 2014; Chelli Bouaziz et al., 2021, D’Anastasio et al., 2011; Jones, 2019). VER3 presents as a unique form of osteophytic lipping known as the “parrot’s beak” which is present on both the anterosuperior surface of a lumbar vertebra and the anteriorinferior surface of the lumbar

vertebra directly above it in the spinal column (Chelli Bouaziz et al., 2021; Jones, 2019; Ortner, 2008; Tuli, 2019).

4.0 Tuberculosis & Case Studies

RIB1 was identified in 10 individuals making up 18.51% of the sample and RIB2 was seen more infrequently with 11.11% of the individuals (see Table 7).

Table 7. Calculated number of individuals with each diagnostic feature of tuberculosis

Indicator	# of individuals scored positive for indicator	Observed (% of sample)
RIB1	10	18.51
RIB2	6	11.11
VEN1	18	33.33
VEN2	23	42.59
BOD	20	37.03
ACE2	31	57.41
ILI	7	12.96
PU	1	1.85

Individuals with rib markers often had grooves on the inferior dorsal portion and woven bone on the shaft of the rib (see Figure 5). Proliferative lesions were observed most infrequently and location tended towards the head of the rib.

Figure 5. Rib observations of suspected tuberculosis; Top: Superior photographic view of the rib from individual 16 in the Hirschstetten collection (RIB1) Bottom: Inferior photographic view of the rib from NHMW-Anthro-Oste-866 (individual 27.309) in the Bruckneudorf collection (RIB2)



VEN1 was seen in 18 out of the 54 individuals making up exactly one third of the study. This was often presented as lytic or proliferative on the anterior portion of the vertebral body, namely in the lumbar and occasionally thoracic area. Some individuals had widened nutrient foramina, likely due to hypervascularization. In most severe cases, individuals had the “Swiss cheese like appearance” previously mentioned in section 2.4.1. This specific vertebral destruction was present in individual 27.484 from Bruckneudorf, as well as from individuals 5 and 84 from Hirschstetten as shown in Figure 6.

Figure 6. Vertebral observations of suspected tuberculosis; *Upper Left:* Superior photographic view of T12, L1, L2, & L3 from NHMW-Anthro-Oste-4266 (individual 27.484) in the Bruckneudorf collection, suspected diagnosis of tuberculosis; *Lower left:* Superior radiographic image of T12, L1, L2, & L3 from individual 27.484 in the Bruckneudorf collection; *Upper Right:* Anterior rotated photographic image of T12 from individual 5 in the Hirschstetten collection, showing lesions (VEN1); *Lower Right:* Anterior photographic image 2 of T12 from individual 4266 and from individual 5 in the Hirschstetten collection



The second most frequently recorded feature was VEN2, having affected 23 out of 54 individuals (see Table 5). This was approximately 42.59% of the individuals recorded in the study. There was extensive proliferation on both the anterosuperior and anteroinferior portion of the vertebral body. The most notably absent feature from the vertebral column in individuals was vertebral fusion and kyphosis as would be seen in Pott's disease. Only 2 individuals had any type of vertebral fusion and no more than 2 or 3 vertebrae were fused in either case. The BOD, ACE2, and ILI features of the pelvis were also quite prominent. 37.03% of the individuals were affected

by proliferation on the BOD, 57.41% by ACE2 and 12.96% by the ILI. The identified features are shown below in Figure 7.

Figure 7. Pelvic observations of suspected tuberculosis in NHMW-Anthro-Oste-4670 (individual 27.591) from the Bruckneudorf collection; *Left:* posterior photographic view of the left os coxa (ILI); *Top Right:* anterior photographic image of the auricular surface on left and right os coxa (BOD); *Lower Right:* superior photographic image of the acetabulum on the right os coxa (ACE2)



The PU feature did not appear in any individuals except one that was marked present, this was individual 5 from the Hirschstetten collection. Values for individual markers suggesting likelihood of tuberculosis are grouped as a) less than 1 mean tuberculosis unlikely, b) greater than or equal to -1 or less than one means tuberculosis is possible, and c) greater than or equal to 1 mean tuberculosis likely.

4.1 Tuberculosis Case Study 1

Tuberculosis case study I is on NHMW-Anthro-Oste-866 (individual 27.309) from Bruckneudorf. The individual was assessed to be a male between the ages of 45-55. The skeleton was fairly complete with the only things missing being fragments of the scapula, hands, feet, and a small portion of the sacrum. All cranial markers for tuberculosis were marked absent, however, the individual scored present for 8 indicators, 6 of which were included in the statistical analysis. These indicators included RIB2, VEN1, VEN2, BOD, ACE2, and ILI. Long bones had no indicators. Vertebrae, however, had the beginnings of lesions in the thoracic and lumbar area similar to what is depicted in Figure 6. This indicator was observed on T11-L3. Additionally, the body of the vertebrae was beginning to show signs of pathological degradation. The pelvis presented with woven bone in the acetabulum, pitting both on the iliac portions and the auricular surface. There was also periosteal new bone formation on more than one rib. The combination on these observations would suggest strong signs of the individual having had tuberculosis at the time of death. Values for individual markers suggesting likelihood of tuberculosis came to 1.99, further suggesting that tuberculosis is likely.

4.2 Tuberculosis Case Study 2

Tuberculosis case study II is on NHMW-Anthro-Oste-4266 (individual 27.484) from Bruckneudorf. The individual was assessed to be a male between the ages of 61-67. The skeleton was also fairly complete with the only things missing being fragments of the C5, hands, feet, and some surface damage to the left os coxa. All cranial markers for tuberculosis were marked absent, however, the individual scored present for 6 indicators, 5 of which were included in the statistical analysis. These indicators included RIB2, VEN1, VEN2, BOD, and ACE2. Long

bones had no indicators. Vertebrae, however, had the exact same lesions in the thoracic and lumbar area as is depicted in Figure 6. This indicator was observed on T10-L2. Additionally, the body of the vertebrae had extensive woven bone/new bone formation on the anterior portion. The pelvis presented with woven bone in the acetabulum, extreme pitting on the iliac portion, some pitting on the acetabulum and cavities on the auricular surface of both os coxa. There was also periosteal new bone formation on more than one rib. The combination on these observations would suggest strong signs of the individual having had tuberculosis at the time of death. Values for individual markers suggesting likelihood of tuberculosis came to 11.26, further suggesting that tuberculosis is likely.

4.3 Tuberculosis Case Study 3

Tuberculosis case study III is on Individual 16 from Hirschstetten. The individual was assessed to be a male between the ages of 47-52. Unfortunately, the preservation was poor, and the skeleton was very fragmented and incomplete. However, enough of the ribs, vertebrae and long bones were present for scoring. All cranial markers for tuberculosis were marked absent. However, the individual scored present for six indicators, five of which were included in the statistical analysis. ACE1 could not be scored due to breakage. Positive indicators included RIB1, RIB2, VEN2, ACE2, and PU. Lytic lesions were present in the thoracic and lumbar area as depicted in Figure 6. This indicator was observed on T6-L2. Additionally, the body of the vertebrae showed extreme signs of pathological degradation. Heavy remodeling was observed on the tibial shaft. Several ribs also presented with woven bone and vascular grooves along the inferior dorsal side of the ribs closest to the lung as shown in Figure 5. Signs in the pelvis were difficult to score due to fragmentation, but pitting was present in the acetabulum. The

combination on these observations would suggest strong signs of the individual having had tuberculosis at the time of death. Values for individual markers suggesting likelihood of tuberculosis came to 7.06, further suggesting that tuberculosis is likely.

4.4 Tuberculosis Case Study 4

Tuberculosis case study IV is on Individual 207 from Hirschstetten. Though sex could not be ascertained, the individual was estimated to be between the ages of 26-32. The skeleton was mostly incomplete with a greater scale of fragmentation. Only four indicators were scored as present, however, three indicators could not be scored at all due to breakage. Of the scored indicators, three marked as present were included in the statistical analysis. These indicators included RIB1, VEN1, & ACE2. Lytic lesions were present in the thoracic and lumbar vertebral area similar to depiction in Figure 6. This indicator was observed on 6 of the thoracic vertebrae and 1 lumbar vertebra, though breakage was significant and others could not be positively scored. Additionally, there were signs of vertebral fusion in the fragments of 2-3 thoracic vertebrae. The combination on these observations would suggest high likelihood of the individual having had tuberculosis at the time of death. Values for individual markers suggesting likelihood of tuberculosis came to 2.07, further suggesting that tuberculosis is likely.

4.5 Statistical Analysis of Tuberculosis

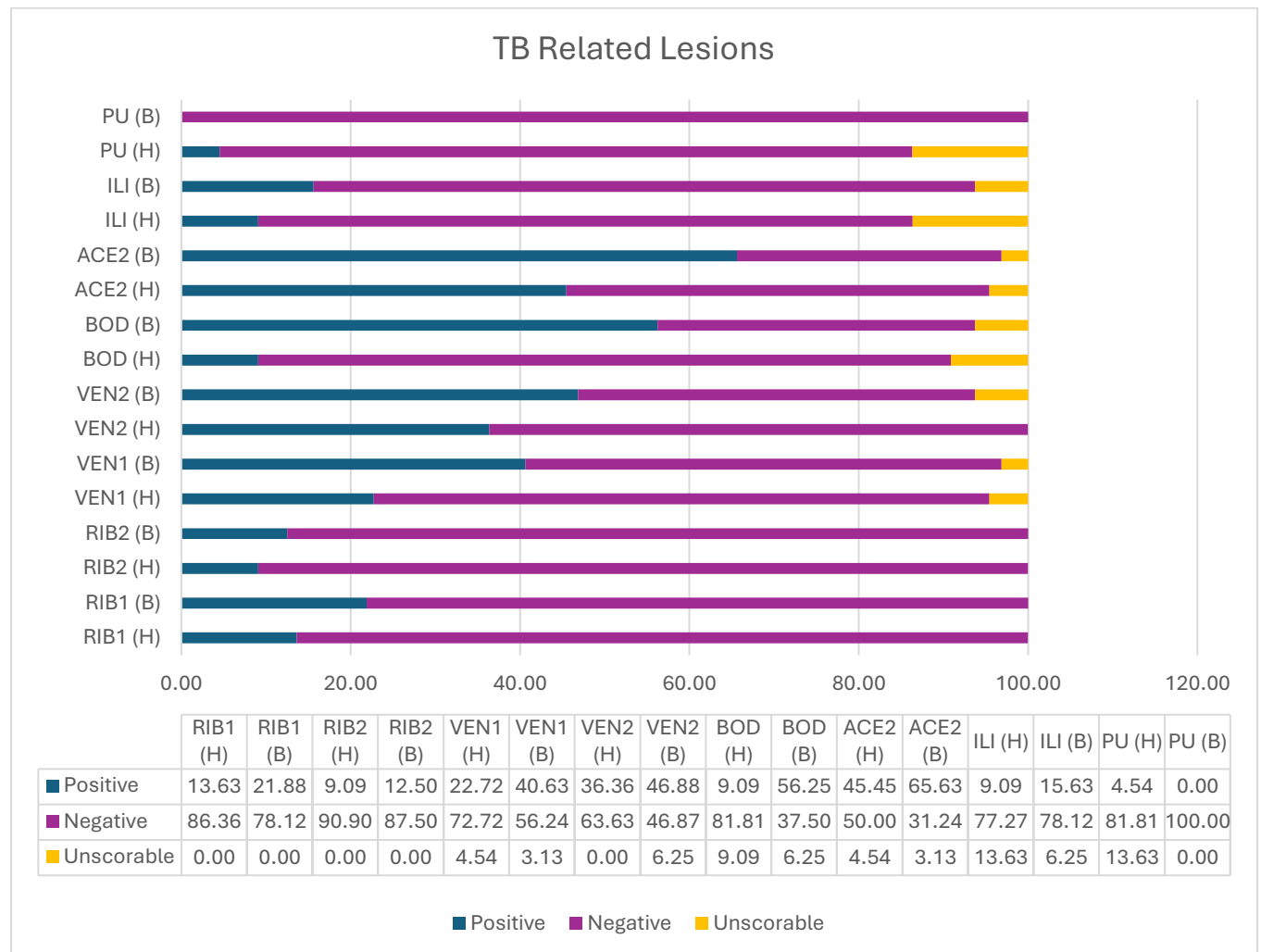
The output of calculated mean and variance is shown below in Table 8. These totals were used to solve for $f(p)$. The frequency of lesion patterns is shown below in Figure 8. Numbers reported are percentages based on the number of individuals who were marked present for each

indicator. This is to accurately reflect the distribution of lesions from each site given the difference in numbers of studied individuals: Bruckneudorf (32) and Hirshstetten (22). Frequency of tuberculosis at death (p) was 0.3558. Putting most likely prevalence at 35.58% with a 95% confidence interval of 16.70% - 37.60%. The p-value came out to 0.748 which is greater than 0.05 meaning it is not statistically significant. This tells us that null hypothesis one (that high transmission rates of tuberculosis and its presence in medieval Europe would not affect the Avar population and therefore there would be no observation of tuberculosis) cannot be rejected.

Table 8. Calculated mean and variance to estimate tuberculosis frequency

Descriptive Statistics						
	N (Sample Size)	Minimum	Maximum	Mean	Std. Deviation	Variance
Observed	54	-2.14	13.18	2.7145	3.9143	15.322
Simulated Positive	54	-2.89	9.36	3.3616	2.6625	7.089
Simulated Negative	54	-2.89	10.51	3.5216	3.0817	9.497

Figure 8. Frequency of lesion patterns between Bruckneudorf (B) and Hirschstetten (H)



5.0 Brucellosis & Case Studies

Of the 54 individuals studied, only four were suspected of having brucellosis. This would suggest that approximately 7.41% of the studied individuals had brucellosis. Individuals suspected of brucellosis often had extreme ventral margin lipping, simultaneous degradation and reparation on the antero-superior margin, and/or the ‘Parrot’s beak’. Each of these features were scored as shown below in Figure 9 and are as seen below in Figure 10.

Figure 9. Scoring of brucellosis indicators between Bruckneudorf (B) and Hirschstetten (H)

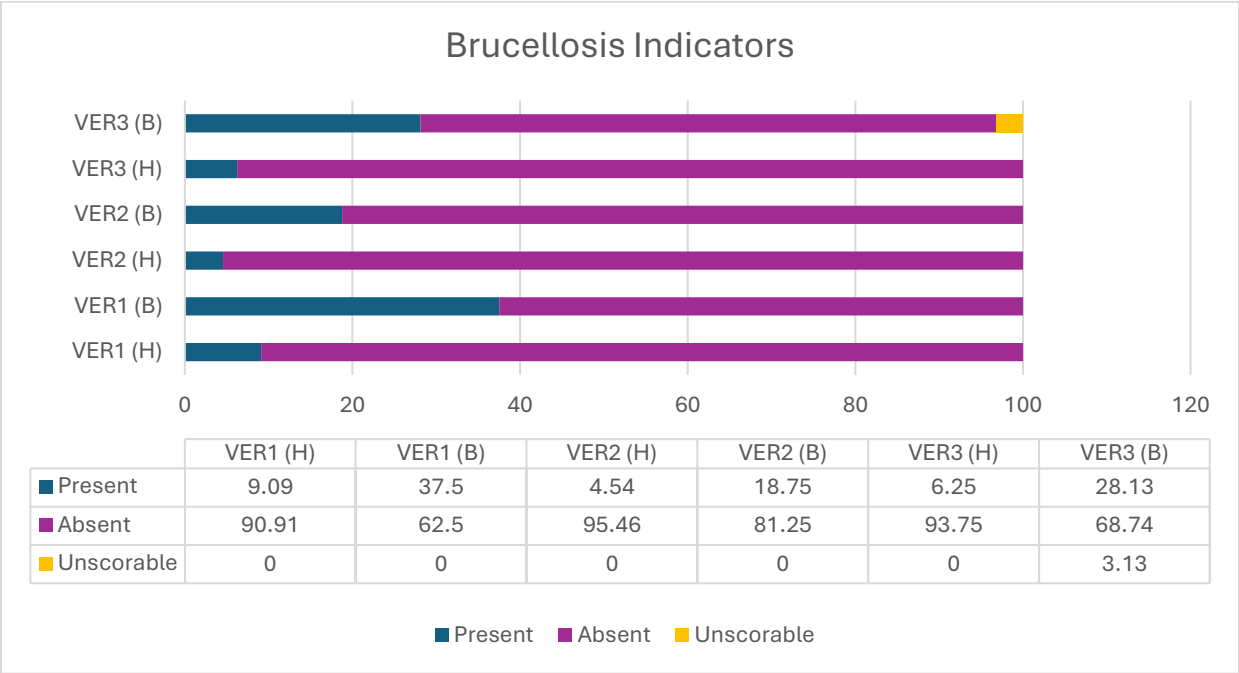
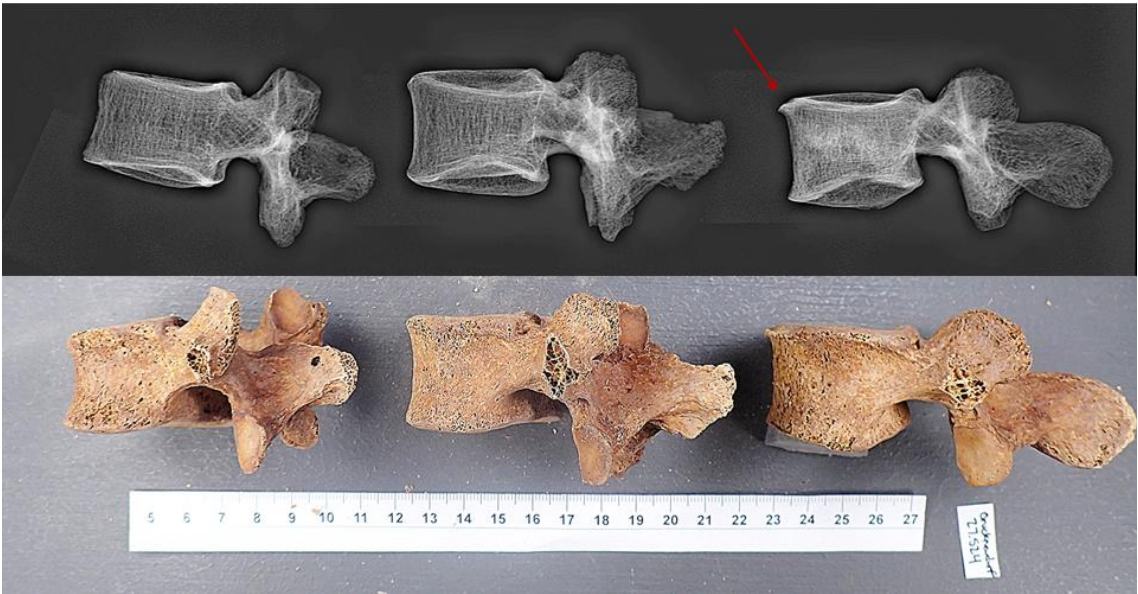


Figure 10. Feature observation on individuals suspected of having brucellosis; Top: radiographic image of Bruckneudorf NHMW-Anthro-Oste-4318 (individual 27.524), L2, L3, & L4 from a left lateral view, clearly highlighting the ‘parrot’s beak’, this individual scored for both tuberculosis and brucellosis, unknown diagnosis; Bottom: photographic image of Bruckneudorf NHMW-Anthro-Oste-4318 (individual 27.524), L2, L3, & L4 from a left lateral view, clearly highlighting the ‘parrot’s beak’



5.1 Brucellosis Case Study 1

Brucellosis case study I is on NHMW-Anthro-Oste-905-2 (individual 27.334) from Bruckneudorf. Sex could not be ascertained, but age was estimated to be between 35-45 years old. The skeleton was very well preserved; the only missing components included fragments of both scapula and the ischial portion of the left os coxa. Three out of the four indicators were scored as present. These indicators included VEN1, VEN2, & VEN3. The anterosuperior portion of lumbar vertebrae has erosion as seen in Figure 11 and described in Mays (2007) and ventral margin lipping. The combination on these observations would suggest high likelihood of the individual having had brucellosis at the time of death.

Figure 11. Feature observation on individuals suspected of having brucellosis; Top: radiographic image of Bruckneudorf NHMW-Anthro-Oste-905-2, L3, L4, & L5 from a left lateral view, clearly highlighting the anterosuperior vertebral destruction; Bottom: photographic image of Bruckneudorf NHMW-Anthro-Oste-905-2 individual 27.334, L3, L4, & L5 superior view, clearly highlighting the anterosuperior vertebral destruction



6.0 Discussion

This project had three objectives: 1) understand the experience of tuberculosis and brucellosis in the Avar population from medieval Austria, 2) gain insight into related lifestyle and cultural practices that had an impact on population health, and 3) address the challenges of skeletal diagnosis between tuberculosis and brucellosis in the hopes of advancing methodology. Ultimately, these objectives would also promote how and why to incorporate multidisciplinary, biocultural, and One Health approaches into paleopathological research. While each objective was met, there are some concerns about the resulting data including the outcome and use of the statistical model, challenges with differential diagnosis, and guidelines for the biocultural, multidisciplinary, and One Health approaches. These concerns stemmed from a limited timeframe for sampling leading to a smaller data set and unforeseen obstacles with analyses.

6.1 Statistical Analysis of Tuberculosis

Results suggest that there is a high prevalence of tuberculosis at death for 35.58% of the studied individuals. The prevalence for tuberculosis at death was 17% in the medieval sample from Pedersen (2016). Pedersen's prevalence did change drastically based on how individuals were divided up for testing including by site, time period, and biological sex, each of which had variable prevalence numbers. This prevalence is also quite different from the prevalence found between Bruckneudorf and Hirschstetten. However, Masiu et al., (2023) using both the same Fisher's exact test and sensitivity/specificity scale, reported a 55% prevalence for tuberculosis at death in their South African sample from the pre-antibiotic era (1950s). It is possible that these differences in prevalence are a result of a difference between populations, difference of time period, difference of region, or even difference of sample size. Additionally, while most of the

individuals in the study were selected at random, some of the individuals from Bruckneudorf that were selected for study had been marked for potential tuberculosis or brucellosis by the staff at the Naturhistorisches Museum and were therefore included in scoring. This prior knowledge should be considered when interpreting statistical values as they may have been affected.

Though results seem to suggest a higher frequency of tuberculosis in alignment with hypothesis one, components of the statistical analysis should be examined given that the null hypothesis could not be rejected. For one, priors selected for the statistical portion of the project may be considered a biased sample. The Terry collection and Bass collection contain individuals from over 10 centuries past the Avar population. These collections stem from a time that is post-germ theory and in a time of modern epidemiology studies. The individuals housed in both Terry and Bass would have also had access to newer western medicine than the Avars. This is concerning because lesion or even tuberculosis frequency in this population could be misrepresentative of another population, making their sensitivity and specificity results questionable (Byers & Roberts, 2003). Another factor to consider would be the statistical model used to calculate the prevalence of tuberculosis.

The p-value and its significance have been debated for over 65 years (Bakan, 1966; Lakens, 2021; Meehl, 1978; Nunnally, 1960; Rozeboom, 1960). The American Statistical Association itself advocates for “moving the world beyond $p < 0.05$ ” (Wasserstein & Lazar, 2016). The use of the p-value in statistical models such as the t-tests, chi squared test, or regression model have been criticized for multiple reasons. The largest of which are the consistent misinterpretation of the p-value and the overreliance on a value that takes a ‘reverse psychology’ approach to statistical testing (Greenland, 2017; Lakens, 2021; Wellek, 2017).

This debate stems from the approach to probability models like Fisher's. The development of such models is experimental, and many published works have been brought into question for finding that a substantial percentage of research projects using this analysis are not reproducible (Wellek, 2017). Some journals have even banned the use of such statistical models, creating an "unnecessary crisis" according to some (Greenland et al., 2016; Lakens, 2021). The difficult part is determining if this is truly a concern with the approach, the way it is reported, or rather the reliance on a single number to confirm findings, preventing advancement. Additionally, the benefits to using the model cannot be ignored.

While the statistical model may have a complex approach, it still provides an excellent avenue for quantifying an observational paleopathological approach. An observational approach may be sufficient, but it is also not always reliable and consistent (Mays, 2018). This is where the statistical model allowed the creation of a more standardized analysis of traditional methods. The concerns regarding the p-value, focus on an aspect of the model that questions the very validity of hypothesis testing in observational and inference-based studies (Wellek, 2017). This very point could be deemed nonsensical given that hypothesis testing is a key component to scientific methodology (Mizrahi, 2020). Additionally, the concerns regarding the p-value more frequently stem from misinterpretation, reproducibility, and overreliance, rather than practice. This would suggest that a proper approach and caution during interpretation can alleviate concerns regarding both the model and the p-value.

Wellek (2017) recommends four criteria for hypothesis testing to maintain good practice when using a statistical approach. The first of which is to ensure proper interpretation of the p-value. This requires a knowledgeable understanding of its use in the statistical model for proper reporting. This concern is addressed in section 3.3 where a clear understanding of the statistical

procedure and meaning of the p-value is highlighted and rooted in relevant literature. The second is to clarify which specific p-value (if many are reported) is the basis for significance. Given that this project only derived a single p-value, this concern is void. The third involves clear reporting if multiple testing procedures are used to eliminate concerns regarding developed procedures. The final practice is to apply the most powerful of different procedures if multiple tests of variable weight are applied. The Fisher's exact test applied to the sample would be considered the most powerful in determining the frequency of tuberculosis within the selected population given the lack of testing options.

6.2 Differential Diagnosis of Tuberculosis and Brucellosis

Some of the typical challenges that bioarcheologists face include poor preservation, small sample sizes, time or budget constraints, and those highlighted by the osteological paradox (Dewitte & Stowjanowski, 2015). While Bruckneudorf had good preservation, Hirschstetten individuals tended to be quite fragmented. This did complicate the differential diagnosis aspect as there may have been more to learn than what was observed. For example, the case study on Hirschstetten individual 134 revealed some vertebral fusion. This was only observed because a fragmented piece of two vertebrae was still intact. However, it is possible for further vertebral fusion to have occurred prior to burial but not have been recovered due to a lack of preservation caused by the conditions of the environment. This would then go undocumented in differential diagnosis. Additionally, the small sample size does affect the population representation and further complicates project insights.

Of the individuals studied, 32 were from Bruckneudorf and 22 were from Hirschstetten, creating a total sample of 54 individuals. However, the Bruckneudorf collection is some 413

burials and Hirschstetten is comprised of 205 burials. This project looks at a very small percentage of the individuals available. This is also attributed to time and budget constraints. On a grander scale and with a larger research project, differential diagnosis has the potential to reflect a greater representation of the Avar population's experience with both brucellosis and tuberculosis (see section 7.1 for more on this). Furthermore, reflection on the concerns raised by the osteological paradox must be made.

The acknowledgment of the osteological paradox addressed the main concerns with typical practices in paleopathology. These concerns included: a) hidden heterogeneity in frailty or a concern in the difference of susceptibility to disease between individuals, b) selective mortality or the idea that data taken only from the deceased are a biased representation of past populations, c) demographic nonstationary which highlights the need to account for migration, mortality, and fertility changes in studied populations, and d) the interpretation of skeletal lesions and related inferences about individual and population health. Concerns regarding selective mortality were addressed in the application of the multidisciplinary, One Health, and Biocultural approaches. These approaches allowed for the study to include burial goods and cultural background information on the population to be paired with data taken from the deceased.

This perspective also acknowledged the problem of a limited viewpoint regarding the use of observational-based analysis. The timeline of the selected cemeteries was during the middle-to-late Avar period, when the population would have been sedentary. This removes the concern of unrepresented individuals who may have been lost during migration as addressed by the demographic nonstationary aspect. Additionally, the statistical model was used to eliminate a biased diagnosis of disease and frequency of disease within the population, whereas the differential diagnosis portion was specific to looking at observational differences between

tuberculosis and brucellosis. With the individuals selected for study, those under the age of 16 were excluded to account for concerns with hidden heterogeneity as they would have had a difference in susceptibility to disease than those over the age of 16 (Pedersen et al., 2019). Finally, the use of multiple skeletal indicators as opposed to a single indicator eliminates the concerns originally highlighted by Goodman (1993) that it was insufficient for determining the health of a population. Research analysis also did not include statements regarding the health of a population, given the established illusions of the term ‘health’ and that lesions do not indicate healthy versus diseased.

Vertebral lesions in the case of tuberculosis versus brucellosis appeared to be very distinct. Vertebral lesions suspected to be tuberculosis created a porous, perforated, and purely destructive appearance as described previously and pictured in Figure 6 (Arriaza et al., 1995; Aufderheide & Rodriguez-Martin, 2014; Baker et al., 2015; Kelley & El-Najjar, 1980; Mays et al., 2001; Pálfi et al., 2015). Brucellosis, however, had a unique reparative appearance, simultaneously showing degradation and new bone formation as seen in Figure 10. This aligned with the descriptions also previously identified (Chelli Bouaziz et al., 2021; Jones, 2019; Ortner, 2008; Tuli, 2019). Radiographic imaging provided a closer view at the internal structure of pathological vertebrae and revealed that the lesion pattern was consistent throughout the whole body in each affected vertebra. Additionally, photographic imaging provided a closer look at the outer appearance of lesions and inner appearance of vertebrae that were found fragmented such as that shown in Figure 6.

Furthermore, most cases of suspected tuberculosis had pathologies seen in multiple locations around the body including the pelvis and ribs. While non-vertebral features do not create as strong of an argument as vertebral indicators, they were prominent and always

accompanied with further signs. On the other hand, brucellosis was only observed with vertebral centralized pathology. Finally, the cases of tuberculosis were more centralized in the thoracic area, while cases of brucellosis were more centralized in the lumbar area. These observations aligned clearly with the expected outcome given the clinical presentation of each disease. Tuberculosis is primarily respiratory, so it would affect the lungs and their surrounding bones like the thoracic vertebrae and ribs (Matos & Santos, 2006; Pradeepkiran, 2021). This aligned with hypothesis two, that given the lower transmission rates of brucellosis than tuberculosis and its rare observation in archaeological contexts, a lower frequency of brucellosis in comparison to tuberculosis would be expected in the medieval Avar population (Bendrey et al., 2020; D’Anastasio et al., 2010).

6.3 Multidisciplinary, Biocultural, & One Health Approaches

Multidisciplinary, biocultural, and One Health approaches are all designed to allow a larger perspective on complex issues and allow for greater understanding. A multidisciplinary approach ensures the inclusion of different strategies from multiple fields. The biocultural approach combines biological and cultural factors to consider how one might affect the other when looking at human health and adaptation. The One Health approach considers the interconnected ties between people, animals, and the environment. Ultimately, the application of each strengthens our understanding of this populations’ experience with tuberculosis and brucellosis.

Due to archival complications, complete burial records were not available for the individuals studied from Bruckneudorf. Fortunately, records for individuals studied from Hirschstetten were made available for analysis (Penz & Lehofer, 2023). As previously discussed

in section 2.3, all goods expected to be associated with Avar burials were found, including pottery, stone tools, weapons, textiles, jewelry, and animal bones. Findings showed that women were often buried with clay spindles, bone knives, and needle boxes. Additionally, they tended to be buried with jewelry like earrings, bracelets, necklaces, and rings. Jewelry made from clay was typical, however, elites tended to have jewelry made from bronze, glass, and iron. Men were often buried with leather goods, belts, horseback riding equipment, and weapons. Weapons typically included arrow heads, lighters, and iron combat knives.

In general, graves often included pottery and clay goods such as bowls, pots, and cups. Stone tools such as grinding plates and tapping stones were uncovered. Nearly every grave also included bones from animal offerings. Chicken was the most popular but bones from sheep, pigs, goats, cattle, deer, and horses were also usual. Some burials were also accompanied by dogs, suspected to have been companions. It was noted that there were some cases of bone discoloration in burials with bronze, iron, or colored textiles. Additional notes stated that grave robbery was suspected due to the dislocation and scatter of both bones and grave goods. Hut fragments of wood, stone, and clay were suspected to be signs of regular settlement. This aligns with the suspected timeline of the Hirschstetten cemetery being late Avar period, as they would have been transitioned from nomadism to be sedentary.

It must be considered that in this population, there would be extensive contact with other active groups in Europe and with animals than would be seen today. This is in addition to daily human-to-human contact. As seen in the report of burial goods such as jewelry, pottery, and textiles from Hirschstetten, influence from outside population and trade goods would suggest contact with potential carriers. This increased risk of transmission could be a contributing factor to the rate at which different diseases spread within a population. Tuberculosis would be caused

by methods that are difficult to identify including inhalation of unseen droplets, direct contact with the infected, and contact with animals, similar to brucellosis.

Brucellosis would be transmitted through meat consumption, unpasteurized milk consumption, and contact with animals like cattle, horses, pigs, sheep, and goats, all of which would have occurred daily (Fournie et al., 2017). Signs of contact with each of these animals were also discovered in the burial sites from Hirschstetten including bones from commonly farmed livestock and horse burials symbolizing their significance to the population. Findings of these animals confirm that the population had frequent contact with livestock known to carry both brucellosis and bovine tuberculosis. This was in alignment with hypothesis three that brucellosis is more common in populations with ties to husbandry and farming given its zoonotic origin, so it was expected to be identified in this population (Fournie et al., 2017; McKeown, 2009; Moreno, 2014; Zuckerman et al., 2014).

Aspects of community lifestyle are where the One Health approach can be beneficial when looking at the interconnected factors like animals, people, environment, and their effects on the spread of disease. The drawback to this is that the biocultural and One Health approaches would involve not only defining these social and environmental factors but also finding a way to reasonably measure them when looking at data. Results suggest that there may be a connection between animals, people, and the environment. The frequency of tuberculosis being nearly 35.58% and the frequency of brucellosis being nearly 7.40% could be attributed to different Avar lifestyle factors such as increased husbandry, unique connection to horses, and increasing contacts with migration. The inclusion of prior literature and data on the Avar population (diet, occupational practices, origins, and conquests) provided the unique insight that is sought after in the multidisciplinary, biocultural, and One Health approaches. The more significant components

in the application of One Health, multidisciplinary, and biocultural approaches to this project are in conjunction with the burial goods discovered in the archaeological context.

7.0 Conclusion

Results showed a higher frequency of tuberculosis than brucellosis, though brucellosis still appeared as expected in alignment with the hypotheses. The frequency of tuberculosis using the Fisher's exact statistical model came out to 35.58%. The suspected frequency of brucellosis came to approximately 7.40%. The null hypothesis could not be rejected due to the p-value totaling to 0.748 which is greater than the 0.05 marker set to suggest statistical significance. The questions guiding this research were: What is the frequency of tuberculosis versus brucellosis in this population? Will the use of different diagnostic techniques make it possible to positively identify brucellosis versus tuberculosis? What effect could community lifestyle have on the spread of infectious disease in this population?

The use of the Fisher's exact statistical model provided the frequency of tuberculosis. Concerns regarding the use of p-values and sample size were considered and addressed, though further development was suggested. Differential diagnosis also distinguished tuberculosis from brucellosis and the use of radiographic and photographic imaging strengthened lesion analysis. Future directions on both techniques are needed, and a stronger argument could be made with a paired methodology. It was also determined that the Avar lifestyle likely played a role in the spread of both diseases given increased contact with animals that commonly carry zoonotic disease and new contacts with European populations. There was also acknowledgement of a need to standardize the use of a One Health, multidisciplinary, and biocultural approach in the context of paleopathology.

Ultimately, this research project successfully made a stride towards understanding the approaches to differential diagnosis in paleopathology. Additionally, it provided insight on the Avar experience with tuberculosis and brucellosis, a topic that had not yet been explored in this population. Finally, the benefits of including biocultural, multidisciplinary, and One Health approaches in paleopathological projects were weighed. The importance of converting these theoretical frameworks into measurable factors so that they may be tied into data-based research projects was also suggested. In conclusion, further research and analysis is recommended in three separate categories: a) the differential diagnosis of tuberculosis and brucellosis, b) the use and adjustment of the Fisher's exact statistical model and those like it in paleopathological projects to obtain frequency of disease in a population, and c) to determine exact methodology for using social theoretical approaches in tandem with data-based approaches.

7.1 Future Directions

This project provided an avenue for understanding what areas in the field of bioarcheology and paleopathology need further study. The most obvious of which is that brucellosis is understudied from a paleopathological perspective. As it stands, there is no other method for diagnosis other than an observational-based approach and occasionally, a microbiology-based approach. This is unreliable, inconsistent, or underutilized and alternative techniques should be considered. A similar approach to the statistical model taken with tuberculosis would be an excellent next step, but the model would demand further development.

The statistical model built by Boldsen (2005) and Pedersen (2016), should be implemented in future projects and perhaps tested with different diseases. This would require looking at populations that are most susceptible to specific diseases to create a sensitivity and

specificity scale. Additionally, the statistical method would work best when paired with a proteomic or aDNA component to further strengthen both the claim for diagnosis and the validity of the model. Finally, the use of the biocultural, multidisciplinary, and one health approaches should be implemented in further paleopathological research projects. However, there needs to be a development in these approaches that clearly articulates how to consider multiple social aspects at once and how to measure these factors when pairing with a data-based approach as these methods are not similarly quantifiable. Additionally, these guidelines need to be developed in a way that allows paleopathologists and bioarcheologists to address the osteological paradox in their framework.

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