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Robert Koch (1843–1910): Leadership Development and Journey of a Pioneer in Medicine and Bacteriology

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Abstract. Robert Koch (1843–1910) was a German physician and bacteriologist who was awarded the 'Nobel Prize in Physiology or Medicine' in 1905 for his tuberculosis research and the discovery of the causative agent of tuberculosis (*Mycobacterium tuberculosis*). He significantly improved many laboratory techniques and defined the 'Koch's postulates' – strict criteria established for the proof of etiology of an infectious agent to cause disease in a host. He is also known as the discoverer of the causative microorganism of anthrax (*Bacillus anthracis*) and was the first researcher able to isolate and cultivate in pure culture the 'comma bacillus' (*Vibrio cholerae*) from patients with cholera. Furthermore, Koch worked on the etiology of wound infections and developed methods of water filtration, disinfection, and sterilization. This article about Robert Koch tells not only the story about his life and legacy as a pioneer and founder of modern bacteriology, but also provides an in-depth analysis of his leadership style which he further developed throughout his career, and which helped him rise to the level of an international leader with world fame in both science and medicine.

Key words: Robert Koch, medical microbiology, Koch's postulates, tuberculosis, anthrax, cholera, leadership

Introduction

Scientific advancements rarely run smoothly and are typically not a fast process. As Drews pointed out: "Discoveries, revolutionary ideas, and new concepts were very often neglected, misunderstood, or attacked if they did not follow the mainstream of the time" (1). This was not different in the field now known as bacteriology. Although the first clear evidence for the existence of bacteria came from microscopic observations by Antoni van Leeuwenhoek (1632–1723), it was not unequivocally proven until the 1800s that they were the cause of many diseases (2). This time was the era of Robert Koch. In fact, Koch is widely recognized as the 'Founder of Modern Bacteriology' because of his many fundamental contributions to this field, such as his research on tuberculosis, cholera, and anthrax, as well as the development/advances of numerous basic microbiology laboratory techniques, disease transmission experiments, and microscopic photography/pathology (3–5). The time in which Koch made his many discoveries and scientific improvements is known as the 'Golden Age' of bacteriology (2).

Robert Koch (Fig. 1) was a physician by education and is considered one of the greatest scientists in medicine and microbiology as evidenced by the many honorary doctorates, citizenships, and memberships, as well as medals and prizes, including the 'Nobel Prize in Physiology or Medicine,' awarded to him in 1905 for his investigations and discoveries related to tuberculosis (6, 7). In short, he became a pioneer and leader in his field with an international reputation. Yet, his life was not without controversies.

I describe in this paper Robert Koch not only as a pioneer in science and medicine, but also define the characteristics of his leadership style he exhibited during his career. In other words, this paper provides a description and analysis of the nature and nurture of

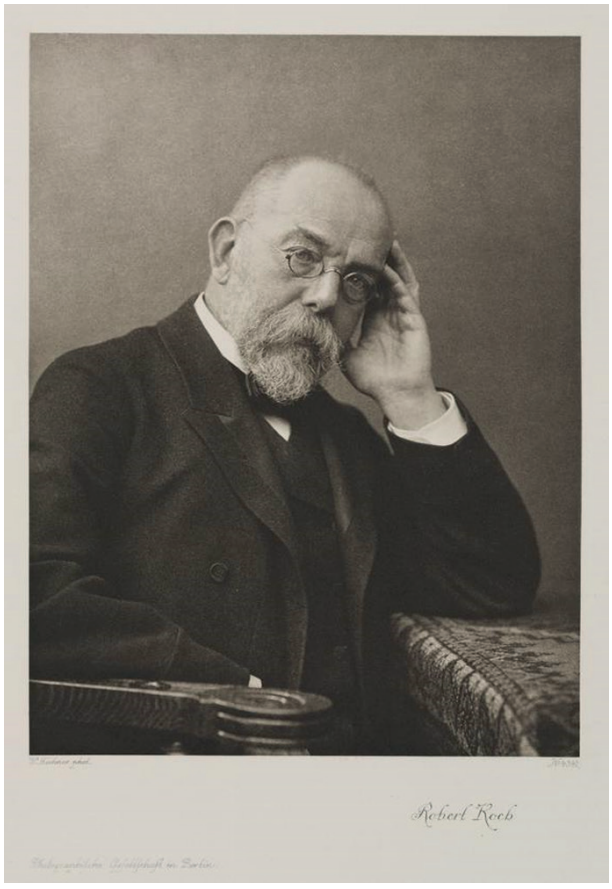

Figure 1. Robert Koch. Portrait, photogravure. Original photograph was taken in Berlin during the later years of Koch's life. Science Museum, London, Public domain: https://collection.sciencemuseumgroup.org.uk; object number: 1982-1459/36

Robert Koch's personality as a physician and biomedical researcher. I will describe his passion for science, the circumstances and patrons, and his scientific accomplishments, as well as the defining moments in Koch's life, which allowed him not only to join the scientific elite in Germany but also become a respected leader in science and medicine on the international stage.

Historical Background and Leadership Development

Early Life and Education

Robert Koch was born on December 11, 1843, in Clausthal, a small mining town located in the upper Harz Mountains in Lower Saxony, Germany. His full name is Heinrich Herrmann Robert Koch, but he was known throughout his life as Robert Koch. He was the third child of a large family which consisted of 13 children of whom, however, only 11 lived to adulthood. His parents were Herrmann Koch and Mathilde Juliette Henriette Biewend. Robert's father was a miner and later became an administrator of the local mining company (8). Herrmann liked to travel to several European countries to broaden his horizon. It is believed that he instilled in Robert the desire to travel. As a matter of fact, it is well documented that Robert Koch took during his career long scientific excursions, including to Italy, Egypt, India, and Africa, as well as to America and Japan (9).

Although Robert Koch had a good relationship with his father, he was closer to his mother and was said to be a special favorite of her. Mathilde was described as a thrifty and self-less woman who managed the large household and who promoted a harmonious family atmosphere in which the children learned proper manners and were encouraged to become self-reliant (6). It is important to mention that Eduard Biewend, Robert's uncle, had apparently an even greater influence on him than his mother. It was Eduard who liked to study nature and take photographs, and who took Robert on numerous excursions into the countryside and interested him in nature and scientific subjects. Thus, Robert developed at an early age a passion for biology and knowledge of wildlife (8). A famous story goes that Robert was able to spell out words from the newspaper at the age of five, an indication that he was curious and interested in learning, and "a feat which foreshadowed the intelligence and methodical persistence which were to be so characteristic of him in later life" (7). Overall, Robert Koch's childhood was happy, and his parents and relatives were participating in the nurturing of his early development. Shoup, who studied twelve world-class leaders, identified seven influences that play a role in three stages of leadership development (10). He pointed out that involved parents (and relatives) and a happy childhood are two of the influences which can facilitate the development of an exemplary leader later in life.

Robert Koch taught himself to read and write before entering the local primary school (*Ger.* Grundschule) in 1848, and he started secondary school (*Ger.* Gymnasium)

in 1851 (6). He was a rapid learner with a special aptitude for the natural sciences and mathematics. However, he showed less interest in the classical languages. In contrast, he studied English enthusiastically which, as it turned out, was of great benefit to him for his later research career and the various trips he undertook to foreign countries. Koch received his high school diploma (*Ger.* Abitur) in 1862 at the age of 19. Although his initial intention was to study philology, the school principal suggested that a career in the natural sciences, mathematics, or medicine might be a better choice. Another option was to follow into the footsteps of two of his older brothers, Adolf and Wilhelm, who emigrated to the United States to pursue careers in business. Robert Koch, however, turned down such an opportunity, perhaps because he was influenced by his fondness for a girl, Emmy Fraatz, who he later married (6).

In 1862, Koch entered the University of Göttingen, where he studied natural sciences and medicine. This institution in Lower Saxony was well-known because it employed many famous professors. For example, Jakob Henle (1809–1885), a pathologist and anatomist, was one of those professors who stimulated Koch's interest in infectious diseases. Henle had published in 1840 a paper about miasmas and contagions, a forerunner of the germ-theory of disease (11). Another example is Georg Meissner (1829–1905), a physiologist, who introduced Koch to animal experimentation which later became extremely valuable to Koch for his research about infectious diseases, or to be more specific, for his proof that specific bacteria are the causative agents of specific diseases.

While in Göttingen, Robert Koch won a research prize for carrying out an anatomical study about nerves, well-illustrated with original drawings (12). He used the prize money to take a trip to Hannover to attend in 1865 a conference for natural scientists and physicians (*Ger.* 49. Versammlung der Gesellschaft Deutscher Naturforscher und Ärzte) (6). It was here that he had the chance to see in person the most famous physician in Germany at that time, Rudolf Virchow (1821–1902), who had developed the cell theory: *Every cell comes from a cell*, and who had ultimately established the field of cellular pathology (13). Virchow is recognized as one of the people who influenced Koch to pursue a career in the medical sciences (6). In 1866, at the age of 23, Robert Koch passed the medical exam and received his doctoral degree in medicine (9). In short, he received a solid education and had contacts with many famous researchers, including Henle, Meissner, and Virchow, and had several opportunities for important apprenticeships, such as in Henle's and Meissner's laboratories.

The formal and informal education Koch received, and the various apprenticeships instilled in him the energy and self-confidence, as well as the in-depth knowledge and skills in science and medicine he needed to be driven and successful in his career. To phrase it differently, while his happy childhood and family were involved in instilling in him a sense of purpose and calling, which Shoup labeled 'Stage I of Leadership Development' (10), the competencies gained through education and learning experiences through apprenticeships, as well as the successes of being noticed as a physician and young researcher were the next important influences which ultimately helped him discover his real interest and niche in which he could prosper and contribute as an emerging leader. Shoup called this the 'Stage II of Leadership Development' (10). It was in this second stage that Robert Koch focused his calling on biomedical research and further developed his scientific meticulousness, persistence, and acumen for which he was admired by his colleagues throughout his career.

Scientific Discoveries and World Fame

After his medical education in Göttingen, Robert Koch went to Berlin for six months of chemical study, then took a position as a medical assistant at the Hamburg General Hospital for a short period, before accepting a position at an institution in Langenhagen (near Hannover). Here, he was allowed to open, on the side, his own private medical practice, and quickly became a popular physician among his patients (6). In addition to his medical duties, he conducted microscopic studies, thus, further nurturing his interest in research. In 1869, Koch moved to several provincial towns, including Braetz, then to Niemegk, and finally to Rakwitz (now in Poland) (8, 14). In the meantime, his wife, who he married in 1867, had given birth to Koch's only child,

Gertrud (6). In Rakwitz, he passed the District Medical Officer's exam and, in 1870, volunteered as a physician in a battlefield hospital in the Franco–Prussian war (1870–1871). After his release from the military, he became the district physician in Wollstein (now in Poland: Wolsztyn) where he began his epochal research about bacterial infectious diseases (7).

In Wollstein, Robert Koch built a small laboratory, equipped with a homemade incubator for his microbial cultures, a microscope, and a microtome for cutting thin slices of biological specimens. It was here where he conducted as a lone scientist his investigations on anthrax (6). Koch was able to culture the anthrax organism in suitable media on microscope slides, and discovered its life cycle, including a description of its cell morphology and spore-forming capability. On invitation of Ferdinand Cohn (1828–1898), a professor at the University of Breslau (now: University of Wrocław, Poland) and an authority on algae, bacteria, and fungi, Koch demonstrated his research findings and was offered by Cohn to publish them in his botanical journal. Robert Koch's paper appeared in 1876 with a detailed description of the methods used and supplemented by several illustrations (15). Koch's work with anthrax was the first convincing proof in history of the definite causal relation of a particular microorganism (*Bacillus anthracis*) to a particular disease (anthrax), thus further supporting the germ theory of disease. Koch's publication was received around the world with great interest and acclamation, and it was certainly an important moment and turning point in his professional life as a physician scientist.

Several researchers studied the role of germs in disease (16). Among them were Jacob Henle, mentioned earlier, who described miasmatic and contagious diseases, Ignaz Semmelweis (1818–1865) who studied the incidence of puerperal fever (childbed fever), and Joseph Lister (1827–1912) who researched conditions and treatment of suppuration. Louis Pasteur (1822–1895), a French scientist, was also studying the causes of infectious diseases but focused more on their prevention. He made major advances in our understanding of the nature of microbial fermentation and the phenomenon of immunity. He is perhaps best known for his work on preventing the spoilage of beverages through pasteurization and using attenuation (i.e., a weakening of virulence) for vaccine development (17, 18). Pasteur became one of Robert Koch's biggest rivals in infectious disease research, as I will describe in detail later.

During his career, Robert Koch also met with Ernst Abbe (1840–1905), who was the driving force behind the Carl Zeiss (microscope) Company. Abbe was initially a lecturer in mathematics, physics, and astronomy at the University of Jena, and an optical consultant for the company. He eventually became the owner of the company after the death of Carl Zeiss (1816–1888). Abbe experimented with optical lens designs, constructed the first oil-immersion lens, and developed an effective condenser to provide optimal illumination of specimens. Koch found these microscopic advancements extremely valuable when examining bacteria and stained preparations (19). It should be noted that Koch and Abbe engaged in a mutually beneficial relationship: while Abbe and the Carl Zeiss Company provided Koch with the important optical equipment he needed to conduct his research, Koch's success and fame helped the Carl Zeiss Company to become the preeminent microscope builder of the world (6).

During the time in Wollstein, Robert Koch also studied wound infections. He further improved methods for staining bacteria in tissue sections and used Abbe's microscope with the oil-immersion lens, which gave him better specimen illumination and resolving power. Koch conducted experiments in animals (mice and rabbits), which he injected with fouling blood and fouling tissue suspensions. Subsequently, the animals developed septicemia and progressive tissue necrosis. Koch observed under the microscope micrococci, some grouped in chain-like arrangements and others appeared as diplococci. He published his work on wound infections in 1878 (20). Alexander Ogston (1844–1929), a Scottish surgeon and bacteriologist, continued Koch's research and employed some of his methods. He observed in pus microorganisms like those described by Koch, which are known today as staphylococci and streptococci. Ogston demonstrated that micrococci are indeed the cause of suppurating wounds (21).

After years living in Wollstein, it became apparent to Koch that conducting research *and* seeing patients left him not only exhausted but also without sufficient

funds. He needed a position in which he was paid better, and which covered his research expenses. Fortunately, circumstances made it possible for him to accept a position as staff member of the Imperial Health Office (*Ger.* Reichsgesundheitsamt) in Berlin in 1880, where he was provided with a laboratory for bacteriological research (6). This move to Berlin was another turning point in Koch's life. Until then, he was the lone researcher, but now had the opportunity to work in a regular research institution with assistants and colleagues, and sufficient funds. In short, Robert Koch underwent a transformation from a lone doctor and physician scientist to a leader of a research group. His first assistants were Georg Gaffky (1850–1918) and Friedrich Loeffler (1852–1915) who both became later well-known bacteriologists. In 1885, Koch was appointed (the first) Professor of Hygiene in Berlin, Friedrich Wilhelms University, and, in 1891 Director of the Royal Prussian Institute for Infectious Diseases (6, 7).

During the time in Berlin, Robert Koch conducted his research on tuberculosis and embarked on the search for the causative agent. Tuberculosis was at that time a significant cause of morbidity and mortality in humans: about one out of every seven people living in Europe and the United States died of this disease (22). Koch developed special culture media and incubation conditions, as well as new staining methods. He eventually managed to isolate the microorganism, to grow it in pure culture, and to induce tuberculosis in animals. This was the moment when Robert Koch had identified the tubercle bacillus and established its etiological role in tuberculosis. He announced this discovery in a lecture before the Physiological Society in Berlin in 1882 and published his findings later that year in the *Berliner Klinische Wochenschrift* (23). The discovery of the causative agent of tuberculosis (*Mycobacterium tuberculosis*) brought him instant international fame, and received widespread awards and acclaims, and, in 1905, the 'Nobel Prize in Physiology or Medicine' (7).

Robert Koch has discussed to some extent in his publications the standards needed for proving the causality of an infectious agent in a particular disease. These included, for example, his publications on anthrax and on wound infections (15, 20). It is believed, however, that it was not until the early 1880s that the postulates appeared more clearly summarized in publications. These publications included, for example, papers about the etiology of tuberculosis and diphtheria, as well as about bacteriological research (23–25). A brief description of Koch's postulates is presented in Table 1.

Robert Koch also conducted experiments about disinfection and sterilization. More specifically, he tested the usefulness of hot air and water steam at various temperatures, and developed devices, such as a high-pressure apparatus, that could effectively kill bacterial pathogens. It turned out that hot water steam was much more effective than hot air because it penetrated faster and deeper into objects. Koch and colleagues described in detail these experiments in 1881 (26, 27).

Robert Koch spent much of his later career traveling to several countries, attending numerous international conferences, and expanding his infectious disease studies. For example, he studied cholera in Egypt and India (1883–1884), Rinderpest in South Africa (1896–1897), the plague in India (1897),

Table 1. Koch's Postulates.

Postulates	**A series of elementary steps that should be followed to determine if a specific organism is the cause of a specific infectious disease**
Postulate 1	The organism must always be present in a diseased host (e.g., human or animal), and not found in a healthy host
Postulate 2	The organism must be isolated from the diseased host and subsequently grown *in vitro* to obtain a pure culture of that organism
Postulate 3	The cultured organism must cause the disease when experimentally introduced into a (susceptible) healthy animal
Postulate 4	The organism must be recovered from the inoculated diseased animal and identified as being identical to the organism originally isolated from the first diseased host

Note: Koch recognized that these postulates need to have some flexibility because there can be cases where diseases that affect people may not affect animals.

malaria in Italy (1898), Batavia (now Jakarta) and New Guinea (1899–1900), and sleeping disease in East Africa (1906–1907) (9). This indicated a shift of his major research interests to tropical diseases.

Regarding cholera, several investigators searched for the cause of this disease. For example, Italian physician Filippo Pacini (1812–1883) carried out investigations of the intestinal mucosa and fluids of cholera patients. He discovered a comma-shaped miroorganism which he described as a *Vibrio* in 1854 (28). He also described that the disease causes profuse watery diarrhea in affected people and recommended injection with saline solution (29). The English physician John Snow (1813–1858), who is considered a pioneer in epidemiology, also conducted investigations on cholera. During an outbreak of this disease in London in 1854, he created a map plotting cases of cholera that occurred in London's West End. Snow found that cholera mortality was clustered around a single source: the water pump on Broad Street. After being allowed by local authorities to remove the pump handle, rendering the pump inoperable, mortality from cholera was much diminished (30, 31). With this research, Snow demonstrated that cholera is a waterborne disease caused by contaminated water, and not airborne as was previously believed. Robert Koch's interest in cholera combined with his extensive experience in microbiological techniques allowed him to be successful in isolating *Vibrio* from patients with cholera and growing the microorganism in pure culture. But, he was unable to reproduce the disease in animals. Today, Robert Koch is credited for his success in isolating the 'comma bacillus' in pure culture, for describing its morphological characteristics and growth requirements, and for its utility in the bacteriological diagnosis of cholera – research he had begun during a cholera outbreak in Egypt in 1883 and continued into the 1890s. He published his main findings about cholera in 1884 (32, 33) and wrote a paper in 1893 about the usefulness of water filtration to prevent the spread of cholera (34).

During the phases of major scientific discoveries, Robert Koch emerged as a true leader with an international reputation. He moved into formal leadership positions in Berlin, recruited and retained the *right* people, such as Georg Gaffky and Friedrich Loeffler, who guaranteed that Koch's work in bacteriology successfully continued and even expanded. According to Shoup, this 'Stage III of Leadership Development' includes the continued steady stream of prodigious patrons and constructive critics, as well as a favorable fate (10). Shoup explained that prodigious patrons are people who "become strategic catalysts for the leader to make it to the next plateau of success or downfall. Throughout the leader's career, there [needs to be] a steady stream or supply of advisors, financial backers, encouragers, kind strangers, and[/or] colleagues so that without such involvement, the leader's story may well have had a different outcome."

Several people played major roles as prodigious patrons in Koch's career. These include Eduard Biewend (Robert's uncle) who interested Koch in nature and scientific subjects as well as the high school principal who suggested to Koch that a career in the natural sciences, mathematics, or medicine might be a better choice than philology. Furthermore, there was Jakob Henle who stimulated Koch's interest in infectious diseases and Georg Meissner who introduced Koch to animal experimentation. Rudolf Virchow influenced Koch to pursue a career in the medical sciences and Ferdinand Cohn offered Koch to publish his research on anthrax in his botanical journal. There was also Ernst Abbe of the Carl Zeiss company who supplied Koch with the newest microscopes as well as Georg Gaffky and Friedrich Loeffler who worked in Koch's laboratory in Berlin and discussed science with him on a regular basis. Both Gaffky and Loeffler were nurtured by Koch to become capable and competent co-workers, whom Koch needed to effectively fill strategic roles in his laboratory to ensure quality performance. Finally, the time Robert Koch spent in the military during the Franco–Prussian war further formed his character and expression of leadership because he was being subjected to work in a strongly hierarchical organization in which discipline was considered a major trait and enforced if absent. Koch's militaristic approach to research was frequently noted by his colleagues inside and outside of Germany (6).

Shoup pointed out that not only a series of supporters is necessary for a leader to develop, but also critics and adversaries: "One's opponents, adversaries and, in some cases, even enemies serve a determinative

force in influencing the emergence of influential leaders" (10). There are two reasons for this. First, "competition raises the standard of performance for leaders to develop and display their best, pushing their limits to excel to be better than the competition." Second, "opponents force the leaders to refine their positions, provide a context for defining moments, and allow for victories" (10). I will address the issue of critics and adversaries in more detail in later sections of this paper.

Finally, Shoup mentioned the importance of a favorable fate in the development of a leader (10). He stated that "leaders emerge to a position of influence both by accident and design." He explains that leaders are not only "active agents" in their own destiny but that also opportunities must exist that provide choices for leaders, while choices provide leaders with opportunities. There is no doubt that Robert Koch was an active agent who supported his career development. But a favorable fate also contributed to Koch's rise to fame, such as the availability of the position in Wollstein where he could set aside sufficient time to conduct his research. The establishment of institutions in Berlin was also a crucial component, where Koch was invited to work as a researcher, director, and professor. Finally, the opportunities to embark on several expeditions to carry out research about various (then also tropical) infectious diseases impacted his fate.

I have shown so far that Robert Koch went through all three stages of leadership development, as was outlined in Shoup's model (10). But, to determine whether Robert Koch was a competent leader or an exemplary leader (the difference lies in ethical behavior), I need to discuss two additional aspects of Koch's life: Koch's controversy with Louis Pasteur and Koch's tuberculin case.

The Koch – Pasteur Rivalry

Robert Koch was primarily concentrating his research on identifying the etiology of infectious diseases using a systematic approach. The introduction of pure culture, solid culture plates, staining, microscopic photography, and animal experimentation using Koch's postulates were important techniques and procedures that allowed him to make significant discoveries in medicine and bacteriology. In contrast, infectious disease research of the French scientists under the guidance of Louis Pasteur was directed towards the prevention of diseases by protecting individuals through immunization. Here, infectious disease problems were studied from a more practical and sometimes economic point of view (35).

Robert Koch and Louis Pasteur had an overlapping interest: the research on anthrax. They met for the first time at the Seventh International Medical Congress held in London in 1881 (6). Pasteur was 59 years of age and at the pinnacle of his career while Koch was 38 years old and had published his research on anthrax and wound infections, as well as on the conservation and photography of bacteria. The first meeting between the two scientists was said to be cordial, but it later turned into an open conflict. Pasteur had carried out some experiments on anthrax, but it was the validity of his method of attenuation of anthrax culture that is believed to be at the basis of the controversy between Koch's group and Pasteur. More specifically, Koch accused Pasteur of using impure cultures, conducting faulty inoculation studies, and using improper microscopic techniques (6). Pasteur responded to the criticism by suggesting having some experiments conducted in Prussia. He sent his young assistant Louis Thuillier (1856–1883) to Berlin in 1882. Inoculation experiments with the attenuated anthrax vaccine were made on an estate in Prussia some 150 kilometers away from Berlin. Although the first experiment failed, the second was successful, and Pasteur's method was accepted in Germany (6).

There were other issues between Koch and Pasteur that contributed to the conflict. For example, both scientists could not speak each other's language and they were thus unable to communicate without translators. There were instances of words being misunderstood and incorrectly translated at scientific meetings infuriating both parties. There were also aggressive words used in scientific publications. Furthermore, the fact that France had lost the Franco-Prussian war of 1870–1871, leading to the annexation of the Alsace-Lorraine region by Prussia, added to the French-German antagonism. In short, a combination of cultural differences, personal idiosyncrasies, different schools of microbiology, and professional rivalries,

as well as national-political competition led to the conflict between Koch and Pasteur (6, 17, 35).

Robert Koch's Tuberculin

In the mid-1880s, Robert Koch attempted to find a specific remedy against tuberculosis. After having conducted experiments in animals with a glycerine extract of tubercle bacteria, which he named 'tuberculin,' he prematurely announced his results at a medical conference in 1890 implying that he had found a cure for this disease (36–38). The response to Koch's announcement of tuberculin was enormous, and many people suffering from tuberculosis traveled to Berlin hoping to get cured. As it turned out, his preparation was found to be ineffective in therapy. In fact, considerable side effects (including delayed-type hypersensitivity reactions) to the agent were in people sometimes severe or even fatal. The result was that Koch's reputation was somewhat tarnished, and disbelief and disgruntlement began to be expressed by his colleagues at both medical conferences and in scientific journal articles (6, 39). Furthermore, it became known that Koch had a financial interest in the manufacture of the product. He would have made a significant amount of money in case tuberculin would have been mass-produced and sold (40). Although Koch's tuberculin preparation was proven to be useless as a treatment for tuberculosis, it was recognized later that a modified version of tuberculin could serve as a diagnostic test to identify people with tuberculosis.

Shoup wrote that "'[g]ood' leadership is a subjective definition . . . [and that] [e]very leader seems to have his or her fans along with opponents making leadership a very value laden or moral enterprise and, therefore, difficult to define with precision" (10). Even though Robert Koch was involved in controversies during his scientific career, he made priceless contributions to human welfare and was described in most parts of his life as being kind and considerate to friends and colleagues (6). The case of the rivalry between Robert Koch and Louis Pasteur points to the immense competition that can be found in many scientific disciplines that involve research activities. Medawar once pointed out that "[s]cientists, like sportsmen and writers, are in the running for a whole variety of prizes and other rewards. . . . The effect upon good scientists of gaining an award is a great moral boost – this expression of the confidence and esteem of others will promote their research and perhaps help them to do better than before" (41). Both, Robert Koch and Louis Pasteur received numerous prizes and honors throughout their careers, as has been well documented (6, 17).

Shoup mentioned that the early development of a sincere belief system with strong moral values set exemplary leaders apart from competent leaders (10). Regarding the tuberculin case, some people may argue that Robert Koch does not deserve to be called an exemplary leader because he prematurely announced his research results implying that tuberculin is the cure for tuberculosis. Other people may argue that without Koch's tuberculin research, we would not have a diagnostic test to identify people with tuberculosis. Gradmann wrote that "[t]here is, however, almost no indication that Koch was deliberately misleading about the supposed effect of tuberculin. He seems to have firmly believed that tuberculin was a curative medium" (40).

Robert Koch can be described as a caring, motivating, and effective leader in his field. He developed during his career into an international leader with principles and values that were instilled in him by many people (i.e., the strong prodigious patrons), and he discovered and used his personal (core) values in meaningful ways, which means, to conduct research about infectious diseases to save the lives of humans and animals. Koch described on several occasions how these values influenced his behavior and the direction of his research activities. For example, he wrote in his publication on anthrax: "We must look for other means to protect the [animal] herds from this angel of strangulation [death] and to protect thousands of people from an agonizing death" (*transl.*: 15). Furthermore, he stated in his publication on tuberculosis: "I have undertaken my investigations in the interest of health care, and this, I hope, will get the greatest benefit from it" (*transl.*: 23). Finally, he wrote in the publication about bacteriological research: ". . . I am convinced that bacteriology will become of the greatest importance for therapy . . . such thinking stimulated me to search, after the discovery of the tubercle bacilli, for substances that can be used therapeutically against tuberculosis" (*transl.*: 25). In summary, Koch's

Table 2. Robert Koch's main contributions to science and medicine

Advancement of laboratory techniques and discovery of pathogens	Year(s) of publication	Reference(s)
Developed slide and plate techniques, and used solid media (gelatin and agar) to prepare pure cultures of bacteria	1876	(15)
Discovered the causative agent of anthrax (*Bacillus anthracis*) and described its life cycle	1876	(15)
Introduced microphotography to the research of bacteria	1877	(19)
Advanced techniques for staining bacteria with various dyes	1877	(19)
Worked on the etiology of wound infections, which later led to the identification of staphylococci and streptococci	1878	(20)
Advanced methods of animal experimentation and microscopic pathology	1878, 1882	(20, 23)
Developed methods of disinfection and sterilization	1881	(26, 27)
Formulated 'Koch's Postulates'	1882, 1890	(23, 25)
Discovered the causative agent of tuberculosis (*Mycobacterium tuberculosis*). He received the 'Nobel Prize in Physiology or Medicine' in 1905 for his research on tuberculosis	1882	(23)
Was the first to describe the isolation and pure culture of *Vibrio cholerae*, and introduced water filtration to prevent the spread of cholera	1884, 1893	(32–34)

own words and actions demonstrate that he has undertaken his microbiological investigations primarily in the interests of public health. Thus, Koch had overall the ethical ends in mind, even with his unsuccessful attempt to cure tuberculosis with tuberculin preparations. This, in my opinion, makes him an exemplary leader. He was the type of leader both colleagues and people of the general public admired and were willing to follow both in Germany and around the world. In other words, he was successful in communicating his vision and his legitimacy of a researcher in science and medicine by pointing to the importance of identifying microbes which cause disease and by challenging existing beliefs that diseases were caused by 'miasma,' a poisonous vapor of bad air (11).

Robert Koch made many remarkable discoveries and advancements during his career in science and medicine (see Table 2), which made him a pioneer in his field. Cook once pointed out that a 'pioneer' is someone who is highly dependent on "the 'climate of the time', *i.e.* the precise moment that is ripe for a particular discovery to be widely revealed, and tends to be one who 'cashes in' on one or more original discoveries in order to claim a breakthrough" (42). This was certainly the case in Robert Koch's life because he not only lived during a period of significant microbiological research activities by scientists around the world but had also a 'sequence of successes' in his biomedical career and was able to publish his research findings in numerous journals.

Aspects of Robert Koch's Later Life and Legacy

In the years following his numerous international travels, the health of Robert Koch declined. There were also changes in his personal life. Robert Koch became acquainted with the 17-year-old art student Hedwig Freiberg, and married her in 1893 after being divorced from his wife Emmy (6). Koch gave his last paper, which was about tuberculosis, at the Prussian Academy of Sciences in April of 1910. Later that same year, he suffered a heart attack and died in Baden-Baden (Germany) on May 27, 1910, at the age of 67. His body was cremated, and the remains were brought to Berlin to the Institute for Infectious Diseases and buried in the mausoleum of the Robert Koch Institute (9).

Conclusion

Robert Koch started out as a happy child who showed an interest in science and mathematics. He was formally educated as a physician and worked initially as a country doctor and lone scientist. He focused on making a living as a doctor, and, as a researcher, had primarily short-term goals, was laboratory data

oriented, and worked as effectively as possible by reinforcing research outcomes. He developed the traits of an emerging leader during this time. When he had his first assistants (Georg Gaffky and Friedrich Loeffler) in Berlin, he turned into a transactional leader, in which he promoted compliance by his followers. His experience as an army officer in the Franco–Prussian war and his sometimes militaristic approach to research influenced his leadership style. He made his co-workers aware that their contributions are necessary if the research team were to reach its goals. Robert Koch then turned into a transformational leader who was preoccupied with a purpose (the 'calling'), had clear higher ranked values, and was oriented towards long-term goals, which means, using his research knowledge about infectious agents to improve the lives of people. To phrase it differently, Koch looked for positive change in the lives of people (i.e., promoting public health) and became more focused on missions and strategies to reach his goals. He was internationally known and became an exemplary leader people looked up to and liked to follow. Robert Koch was highly respected in his time and his greatness is still felt today, both as a leader and pioneer in medicine and bacteriology.

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