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FULL ARTICLE

Establishing Causality in Medicine and Koch's Postulates

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This paper considers Koch's Postulates for establishing causality, particularly in relation to his research on tuberculosis and cholera. In 1882, Koch showed that his claim regarding the tubercle bacillus satisfied all of his postulates, and this claim was then accepted by the medical community. However, he was not equally fortunate in his research on cholera. In 1884, he presented evidence in favor of the comma bacillus being the cause of cholera, but this evidence failed to satisfy one of his postulates; therefore, not all of the medical community were convinced with his research on cholera. Yet, when he presented more evidence for his views on cholera because of the Hamburg cholera epidemic of 1892, this view was finally accepted. This historical material suggests that Koch's Postulates omit some types of evidence, which are important regarding causality. The postulates are, therefore, analyzed in light of some contemporary philosophical views of causality. Because of this analysis, a gap in Koch's Postulates does indeed become apparent. It is shown that if the postulates are modified to fill this gap, they do then explain the acceptance of Koch's views concerning cholera.

Key words: Bacteria, Causality, Cholera, Epidemic, History

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INTRODUCTION

Koch's Postulates provide a set of criteria for establishing that a particular microorganism is the cause of a disease. Here, I will give a detailed historical account of the nature of these postulates and show how they were formulated in the years 1878–1882. Alfred S. Evans, in his important book *Causation and Disease: A Chronological Journey*,[1] shows that Koch's Postulates have played a very important role in the history of medicine. These were originally formulated for bacterial infections, but later, these were also extended to viral infections. Koch's Postulates are standardly given in bacteriology textbooks,[2] and in the 1980s, these were cited in connection with two important research developments, namely, the claim that peptic ulcers had a bacterial cause[3] and the claim that HIV causes AIDS.[1] All this shows that Koch's Postulates have had a central role in the history of medicine and remain important for medicine even today.

The concept of causality has received equal attention in the histories of both philosophy and medicine. Aristotle propounded his famous theory of the four types of causes. Causation was a favorite topic for discussion by philosophers both in the medieval and early modern periods. In the eighteenth century, both Hume and Kant developed philosophical theories of causality, as John Stuart Mill did in the nineteenth century; in addition, causality has not been neglected by contemporary philosophers. Indeed, it is a favorite topic in the philosophy of science currently, and there are a considerable number of causality theories. These include what could be called AIM theories of causality, where AIM stands for Action, Intervention, and Manipulation. These stress the connection between causality and action. Further, there are mechanistic theories of causality, which link causality to mechanism, counterfactual theories of causality, and probabilistic theories of causality. A good recent account of this complex variety of contemporary theories of causality can be found in Illari and Russo's 2014 book, *Causality. Philosophical Theory Meets Scientific Practice*.[4]

We, thus, have vigorous debates about causality in the medical and philosophical communities; but, curiously, there is little interaction between these two debates. Koch's Postulates, which have been central to much medical thinking for more than a hundred years, are hardly, if at all, mentioned by philosophers. One aim of this paper is to bring these two different streams of thought together and to use some contemporary ideas from the philosophy of causality to present a critical assessment of Koch's Postulates.

The structure of the paper is as follows. I have devoted a section to show how Koch's Postulates were formulated and consider the different versions of the postulates that exist. Further, I point out a historical problem that exists concerning these postulates. Koch, showed in 1882, that all his postulates were satisfied for the tubercle bacillus, and this led the medical community to accept his claim that this was the cause of tuberculosis. In his investigations of cholera, published in 1884, however, Koch was unable to show that all his

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postulates were satisfied, and, partly because of this, the medical community did not, at this stage, accept his views regarding the causation of cholera. New evidence regarding cholera did, however, emerge from the Hamburg cholera epidemic of 1892, and this new evidence convinced the medical community of the correctness of Koch's views, *even though not all of Koch's Postulates were satisfied*. In light of this historical puzzle, I then proceed to give a philosophical analysis of Koch's Postulates using a version of what I earlier called the AIM (Action, Intervention, and Manipulation) theories of causality. This analysis is partly supportive of Koch's Postulates, but, at the same time, it identifies an omission in the postulates, which is filled by proposing an additional postulate. After this philosophical analysis, I return to history and show, in the next section, that the extra evidence from the Hamburg epidemic of 1892, although it does not satisfy the original Koch's Postulates, does satisfy the modified postulates that were proposed because of the philosophical analysis. This resolves the historical problem and also suggests that the modified postulates may be of use in contemporary medicine.

This is the general structure of the paper; however, before getting into the details, it may be helpful to provide, as a general background, a few biographical details concerning Robert Koch (1843–1910), who was, undoubtedly, one of the greatest scientists of the late nineteenth and early twentieth centuries. This I will do in the next section.

Robert Koch

Koch was born on 11 December 1843 at Clausthal in the Upper Harz Mountains. His father was a mining engineer. In 1862, he went to the University of Göttingen, where he studied under some of Germany's leading medical scientists and conducted some research himself. He received his M.D. in 1866, and he then undertook further studies in Berlin under the renowned Rudolf Virchow. One might have expected Koch to pursue a research career, but he wished to marry, which he did in 1867. Consequently, to have an income to support his wife and family, he became a country doctor. From 1872 to 1880, he was based in the country town of Wollstein, which had about 3,000 inhabitants. In 1873, he took up research in his spare time, buying the microscope and other equipment he needed. Remarkably, working on his own in this fashion, he reached results that brought him international fame.

Koch (Figure 1) began his research at a time when the germ theory of disease was only just emerging, and was still considerably controversial. According to the germ theory, many diseases were caused by microbes entering the patient's body and multiplying there, producing damage, which is characteristic of the disease. The germ theory had by then been adopted by Lister in Britain to explain wound infections, and by Davaine in France to explain anthrax, a disease of farm animals such as cattle and sheep, which could also affect humans. Davaine had examined the blood of animals infected by anthrax under a microscope and found that it contained rod-shaped microorganisms which

Figure 1: Koch at the age of about 40 years.

he named "bacteridia." He postulated that anthrax was caused by these bacteridia, but there were some difficulties with his theory; therefore, it was not generally accepted. Despite this setback, anthrax proved to be a very suitable disease for the development of the germ theory. Because it was a disease of both humans and animals, it was easy to perform experiments on animals, while still dealing with the human disease. Moreover, the bacterium involved, Davaine's bacteridium, now called *Bacillus anthracis*, is one of the biggest pathogenic bacteria in terms of both length and thickness, and is therefore easy to study under the microscope.

From the beginning of his research career, Koch accepted the germ theory framework, and his first research was on anthrax, which was prevalent in the Wollstein area, and on wound infections, which he had witnessed while serving in the Franco-Prussian war (1870–1871).[5–7] In his early investigations of anthrax, Koch made a remarkable discovery that the anthrax bacillus forms spores, which are very resistant to damage, but which, in a living animal, can turn back into the normal bacillus and lead to disease. This discovery shed light on many hitherto unexplained aspects of anthrax, and, together with Koch's other results, provided much stronger evidence for the anthrax germ theory.

However, Koch's new results would have no effect unless he could get them known to the wider community of medical researchers. Here Koch was lucky. He wrote to Professor Cohn, a leading expert on bacteria, of the University of Breslau, to request his presence when Koch was demonstrating his new results on anthrax. Cohn agreed, and Koch's demonstration greatly impressed both Cohn and Professor Julius Friedrich Cohnheim (another expert from Breslau). Cohn agreed to publish Koch's paper[5] in his journal, and soon Koch would be destined to acquire fame for his discovery.

Subsequently, Koch was appointed to the Imperial Health Office in 1880. Here, he worked with two assistants, namely, Friedrich Loeffler and Georg Theodor August Gaffky, who became well-known bacteriologists in their own right. Perhaps surprisingly, Koch, who had started as a lone researcher, proved to be a very successful team leader, and many of his subsequent research assistants, such as Emil Adolf von Behring, Paul Ehrlich, and Shibasabura Kitasato, made important discoveries.

Koch's first years in Berlin were very fruitful. In 1881, he invented the plate technique for obtaining pure cultures of bacteria. Koch turned his attention to the most dreaded disease of his day, tuberculosis. At the beginning of his 1882 paper, he mentioned:

> "*Statistics show that one-seventh of all human beings die of tuberculosis, and that if one considers only the productive middle-age groups, tuberculosis carries away one-third and often more.*"[8]

However, the bacterium responsible for tuberculosis, now known as *Mycobacterium tuberculosis*, was considerably harder to study than *B. anthracis*. It was very much smaller, being about a quarter the length of *B. anthracis*, and considerably thinner. To make it visible, significant improvements in microscopy were needed. In addition, the bacillus had to be stained, and this was difficult because of its waxy surface. However, Koch found a method of staining using some of the artificial dyes, which the new German dye industry was now producing. The tubercle bacillus is also difficult to culture, as it grows slowly. However, Koch overcame all these difficulties, and in his 1882 paper,[8] he convinced the medical community that *M. tuberculosis* was, in fact, the cause of tuberculosis.

Koch's discovery of the cause of tuberculosis gave him world fame, and the year 1883, when he reached the age of 40 years, marked, in many ways, the height of his career. Throughout his life, he made many further remarkable discoveries and also faced a number of setbacks.

After tuberculosis, Koch went on to investigate cholera. I will deal in more detail with his work on cholera in the main body of the paper. In 1890, it was announced that Koch had found a substance tuberculin, which was a cure for tuberculosis. This turned out not to be the case, although tuberculin was later identified as a useful diagnostic tool. Naturally, this debacle was a blow to Koch's prestige. Moreover, in 1889, Koch fell in love with an art student, Hedwig Freiberg, nearly 30 years his junior. In 1893, he divorced his wife and married Hedwig. The marriage proved to be a happy one, but naturally, there was much disapproval of Koch's behavior in the middle-class society of the nineteenth century. Perhaps for this reason, Koch often left Germany to pursue his research in distant countries. He studied tropical diseases, including rinderpest and sleeping sickness, in both cattle and humans. In 1905, Koch was awarded the Nobel Prize for Medicine. On 27 May 1910, he died in Baden-Baden.

This is only a brief sketch of Koch's life and work, and more details can be found in studies by Brock[9] and Gradmann.[10] Let us now return to the year 1882 when Koch published his famous paper on tuberculosis.[8] Koch's research up to that point had had the objective of providing sufficient observational and experimental evidence to establish that a particular microorganism was the cause of a particular disease. Naturally, conducting this research led Koch to reflect on what evidential criteria needed to be satisfied in order to show that a microorganism was the cause of a disease. His papers up to 1882 contain a number of passages on the necessary criteria, and from these passages, a set of criteria, known as Koch's Postulates, has been drawn.

Koch's Postulates are still cited in contemporary bacteriology textbooks. For example, Ronald Hare's *An Outline of Bacteriology and Immunity* (1963) provides a formulation of Koch's Postulates.[2] So, Koch contributed not just to germ theory but also to the epistemology of causality in medicine. Koch's Postulates are still being cited in debates on the causation of various diseases. A striking example is the discovery by two Australian researchers, Robin Warren and Barry Marshall, that peptic ulcers are caused by a bacterium. A detailed account of this episode, with its analysis, is given by Thagard.[11] In the course of trying to establish this new theory, Marshall appealed to Koch's Postulates. In fact, in 1985, Marshall et al. published a paper with the title, "Attempt to fulfil Koch's Postulates for pyloric *Campylobacter*."[3] This attempt involved the drastic step of Marshall swallowing a sample of the new bacteria to see if this would produce a stomach disease in him. This dramatic example shows that Koch's Postulates were still of great influence more than a hundred years after they were first formulated. In light of this, it is rather surprising that there is no definitive version of Koch's Postulates, but rather a number of different versions. In the next section, I will explain how this has come about.

Koch's Postulates

Koch never gave an explicit formulation of his postulates, and, thus, there are several different versions of his postulates. Brock, in his admirable account of Koch's life, remarks:

> "*Surprisingly, the enunciation of Koch's Postulates in their final 'text-book' form occurred not in a paper by Koch, but in the paper by Loeffler on diphtheria, dated December 1883.*"[9]

In fact, in the period 1880–1884, Koch worked at the Imperial Health Office with Loeffler and Gaffky, his two collaborators. The three of them were engaged in the same research program aimed at identifying the microorganisms causing various diseases. They all used the same techniques and methods. Loeffler succeeded in identifying the bacterium causing diphtheria and Gaffky the bacterium causing typhoid. Very likely, some of the postulates were the result of discussion between these three research colleagues. However, we can, nonetheless, find most of the postulates in Koch's own papers published before 1883, and it is interest-

ing to analyze these passages from Koch, as these give an idea of how Koch's thinking on this subject evolved. Of course, Koch's views were influenced by earlier thinkers as well, and many writers have stressed the possible influence of Jakob Henle, who was one of Koch's mentors at Göttingen. Two works, which deal with this matter, are by Carter[12] and Evans.[1]

Koch first mentions the problem of establishing, or, as he says, proving that a microorganism is the cause of a disease, in his 1878 paper on wound infections. He writes:

> "*. . . there are justified objections to the assumption that bacteria cause infected wound diseases. To prove this assumption, it would be necessary to demonstrate bacteria in every case of such a disease. Moreover, the number and distribution of the bacteria must be appropriate to explain completely the disease symptoms*."[6]

In a similar vein, he says:

> "*. . . a proof would require that we find the parasitic microorganisms in all cases of the disease, that their presence is in such numbers and distribution that all the symptoms of the disease can be explained, . . .*"[6]

We will take Koch's Postulates as being designed to establish that a particular microorganism causes a particular disease. We can then obtain the first two postulates by paraphrasing the above passages as follows:

1. The microorganisms must be shown to be present in all cases of the disease.
2. The presence of microorganisms must be in such numbers and distribution that all the symptoms of the disease can be explained.

At this stage, Koch seems to have relied on just these two postulates, but developments between 1878 and 1882 led him to add another two postulates in his discussion of tuberculosis. In 1881, Koch made one of his greatest contributions to bacteriology by discovering a method of producing a pure culture of a bacterium. Up to that point, bacteria had normally been grown in laboratories in liquid media in test tubes. However, Koch had the idea of growing them on solid media instead. The solid media could be the surfaces of cut potatoes or existing liquid nutrient media with added gelatin, which caused them to solidify when poured onto glass plates. In a liquid medium, the bacteria of interest would mix with other contaminant bacteria, and it was hard to separate them. On a solid medium, it was possible to find a colony of the bacteria of interest, which was distinguishable from the other colonies. By taking a sample from this colony and growing it on another plate, the culture would become purified, and one could repeat this procedure as often as needed until a pure culture of the required bacterium was obtained. Koch demonstrated this new technique at the International Medical Conference at King's College London in August 1881. Lister and Pasteur were present and Pasteur is said to have taken Koch by the hand and exclaimed: "*C'est un grand progrès, Monsieur*."

In his 1882 paper on tuberculosis, Koch added some new postulates, which referred to the pure cultures he was now capable of producing. The relevant passage runs as follows:

> "*To prove that tuberculosis is caused by the invasion of bacilli, and that it is a parasitic disease primarily caused by the growth and multiplication of bacilli, it is necessary to isolate the bacilli from the body, to grow them in pure culture until they are freed from every disease product of the animal organism, and, by introducing isolated bacilli into animals, to reproduce the same morbid condition . . .*"[8(p. 87)]

We get the following additional two versions of Koch's Postulates:

1. The microorganisms must be isolated and grown in pure culture (Postulate 3).
2. It must be possible to reproduce the disease by introducing this pure culture into animals (Postulate 4).

I have formulated the postulates in terms of microorganisms, although Koch himself often speaks of bacteria or bacilli. The reason for this was that Koch's Postulates were later applied to viruses and bacteria. This raised many problems, and good accounts of this development can be found in studies by Evans[1] and Vonka.[13] Quite recently, an appeal to Koch's Postulates was made in the debate on whether HIV causes AIDS (Harden,[14] and Evans[1]). This is another proof of the contemporary relevance of Koch's Postulates.

It is of interest to compare the above version of Koch's Postulates with other versions in the literature. My version is more or less the same as the versions of Hare[2] or of Loeffler in 1883, which is quoted in English translation by Brock.[9] The only difference is that both Hare and Loeffler combine my Postulates 1 and 2 into a single postulate, and so my Postulates 3 and 4 are renumbered as Postulates 2 and 3. Evans[1] gives a version, in which my Postulates 1 and 2 are combined into a single Postulate 1, and my Postulates 3 and 4 are combined into a single Postulate 3. Evans then adds another Postulate 2, which is different from any of my postulates. Carter[15] gives a version of Koch's Postulates similar to that of Evans except that he omits my Postulate 2 altogether rather than combining it with my Postulate 1. Carter[16] gives another five-postulate version. Here, my Postulate 2 is included as his Postulate 3. However, his Postulates 1 and 2 include more material than my Postulate 1.

I am not saying that one version of Koch's Postulates is to be preferred to another. Because Koch never gave an explicit and definitive version of his postulates, these have to be reconstructed from statements he makes in different places, and it is possible to make different reconstructions. In fact, all the versions of Koch's Postulates—those I have mentioned—have a sound textual justification in terms of passages in Koch's papers. Luckily, however, this complexity does not affect the main argument of this paper, as all the

versions include somewhere a version of my Postulate 4, and it is this postulate that is going to be the focus of our attention.

I will conclude this section by mentioning briefly some recent views on Koch's Postulates expressed by Gradmann.[17] He writes: "*The blueprint for Koch's Postulates appears to have originated in a paper written by Friedrich Loeffler . . ..*"[17(p. 886)] Gradmann goes on to say: "*Not only did Koch not write any postulates . . .*"[17(p. 886)], and: "*Koch never conceived any postulates*."[17(p. 888)] Moreover, he refers in his paper to the postulates as Loeffler's Postulates. It is true that Koch never used the term "postulates" and did not produce any explicitly numbered postulates. However, the key question is surely whether Koch formulated the content of the postulates in his published papers. In fact, he clearly did, as the passages from him cited in this section show. Regarding Loeffler's contribution, I do not wish to minimize this. He, and indeed Gaffky, might well have contributed something to the passage, which I cite from Koch's 1882 paper.[8] However, neither Loeffler and Gaffky could have contributed to the passage I cite from Koch's 1878 paper,[6] as this was written when Koch was still working on his own and before Loeffler and Gaffky had become his assistants. As the first two of Koch's Postulates, in the version I give, are based on the 1878 passage, it is clearly a mistake to attribute these postulates to Loeffler rather than to Koch. It also seems to me at best misleading to say that Koch did not write any postulates or that Koch never conceived any postulates.

The Failure of Koch's Postulates for Cholera

Koch was able to satisfy all of his postulates for tuberculosis, and he did convince the medical community that he had found the cause of the disease. Fresh from this triumph, he turned his attention to another dreaded disease of the time—cholera. Here, however, the result was rather different. The postulates, which had worked perfectly for tuberculosis, failed for cholera. I will now explain why this happened.

Koch succeeded in isolating a bacillus, which he called the "comma bacillus," and which he thought was the cause of cholera. However, when he applied his postulates, a problem emerged. Although cholera is a violent and often fatal disease in humans, other animals appear to be immune, so that it was not possible to satisfy Postulate 4 by reproducing the disease through the introduction of a pure culture of the comma bacillus into experimental animals. On his expedition to Egypt to investigate the cholera epidemic there, Koch took 50 mice from Berlin. Yet, it was not possible to infect them by inoculations with cholera material.[10] Koch et al. had no more luck when they tried to infect animals with cholera in India. Koch, in one of his two 1884 papers on cholera, admits the failure with characteristic openness and honesty. He writes:

> "*One should show that cholera can be generated experimentally by comma bacilli. Indeed, we have tried in every imaginable way to meet this condition . . . . To become certain about the possibility of infecting animals with cholera, I inquired all over India whether similar diseases had been observed among animals. In Bengal, however, I was assured that this never happened. This province is especially thickly populated, and many animals live with the people. One would assume that in such a land, where cholera is everywhere and always present, animals would often be infected with cholera materials, and that such infections would be as effective as among humans. But no one ever observes animals with cholera. Therefore, I believe that all the animals available for experimentation and those that often come into contact with people are totally immune. True cholera processes cannot be artificially created in them. Therefore, we must dispense with this part of the proof.*"[18(pp. 160–161)]

Koch argued that the rest of the evidence was sufficient, even without Postulate 4, to establish that the comma bacillus was the cause of cholera. But not everyone accepted this conclusion, and Koch's opponents used his postulates to argue that Koch had not established his case. Coleman, in his 1987 paper, "Koch's Comma Bacillus: The First Year," writes:

> "*In England, France, and elsewhere, serious doubts came to be expressed regarding the identity of the vibrio, its relation (if any) to Asiatic cholera, and much else besides. Howard-Jones shows how little enthusiastic, in fact, was the initial response to the discovery of the comma bacillus*."[19(p. 337)]

Coleman does say, however, that Koch had more support in his native Germany, but that, even here, the important Munich school headed by Max von Pettenkofer rejected Koch's claim that the comma bacillus was the cause of cholera. Pettenkofer had his own theory of what caused cholera, and he and his followers continued to hold this theory and reject Koch's alternative theory for the next decade. Indeed, Pettenkofer may have also influenced the opinion in England, as he published a defense of his own theory and a criticism of Koch's in the English journal *The Lancet* in 1884. He says:

> "*The further one investigates the drinking-water theory the more and more improbable does it appear. Robert Koch, too, the famous bacteriologist, has hitherto failed to substantiate the drinking-water theory, and I feel convinced that the time is not far distant when he will own that he has gone in the wrong direction. Koch has succeeded in finding the comma bacillus in a water tank in a region where cholera was prevalent. I have the greatest respect for this important discovery, not as a solution of the cholera question, but only as a very promising field for pathological, not epidemiological inquiry*."[20(p. 904)]

Later in the paper, I will outline Pettenkofer's alternative theory of the causation of cholera, and show how the dispute between him and Koch was resolved.

One further possibility for satisfying Koch's Postulate 4 remained. This was to produce cholera in humans by infecting them with the comma bacillus. Considering the very dan-

gerous nature of cholera, Koch advises against such an expedient and recommends continuing to try animal experiments. As he says:

> *". . . it would certainly be wiser to continue experiments with guinea pigs and other animals than to follow the recent suggestions that human volunteers consume pure comma bacilli cultures."*[21](p. 176)

Despite Koch's warning, some human volunteers, namely, Koch's rival Pettenkofer and Pettenkofer's follower Emmerich did resort to consuming pure comma bacilli cultures,[22] and, as we mentioned earlier, Marshall also resorted to self-experimentation in the 1980s in order to satisfy Koch's Postulate 4.

Despite these difficulties, Koch did eventually succeed in getting his view of the etiology of cholera generally accepted, but this was not until he had managed to collect some more evidence in favor of his position. This evidence was provided by the Hamburg cholera epidemic of 1892–1893. This was the last major cholera epidemic to strike Europe, largely because of the acceptance of Koch's account of the etiology of cholera, and the consequent adoption of appropriate preventative measures in European cities. But now comes the twist to the story, because, although this new evidence did establish Koch's theory to the satisfaction of the medical community, Koch's own postulates were still not satisfied, even by the augmented evidence. This suggests that Koch's Postulates were inadequate in some way, and in need of modification. I will argue that this was indeed the case.

This argument, which is presented in the next section, proceeds by analyzing Koch's Postulates in light of some contemporary philosophy of causality. In particular, I will focus on what I call the AIM theories of causality. AIM here is an acronym for Action, Intervention, and Manipulation. I will argue, on the basis of a philosophical view of this type, that Koch's Postulates are inadequate, and need to be supplemented. I will accordingly formulate a modified version of Koch's Postulates. Then, in the last section of this paper, I turn back to history and examine how Koch did manage to establish the comma bacillus as the cause of cholera, using his observations on the Hamburg cholera epidemic of 1892–1893. I will show how Koch's practice implicitly conformed to the modified Koch's Postulates that I am going to explore below. Nonetheless, Koch himself never explicitly suggested any change to his original postulates despite the fact that they were never satisfied in the case of cholera.

Some Philosophy of Causality

There are a number of different approaches in contemporary philosophy of causality, but here I will concentrate on what could be called AIM theories of causality that emphasize the links between causality and action, intervention, and manipulation. One of the first to develop a detailed version of such a theory of causality in the twentieth century was Collingwood, in his 1938 paper[23] and a subsequent 1940 book.[24] Collingwood distinguishes three senses of causality, as follows:

> *"Sense I may be called the historical sense of the word 'cause,' because it refers to a type of case in which both C and E are human activities such as form the subject-matter of history . . . . Sense II . . . is the sense which the word 'cause' has in the practical sciences of nature . . . for example, in engineering and medicine . . . . Sense III . . . is the sense which the word has traditionally borne in physics and chemistry and, in general, the theoretical sciences of nature."*[24](pp. 286–287)

Collingwood regards Sense I as the original sense of cause from which the other two developed, but then he was both a historian and a philosopher. We are obviously concerned with Sense II, which is the sense that the word "cause" has in medicine. It is for this sense of causality that Collingwood developed his AIM account. In this sense, what is caused is an event in nature, and Collingwood goes on to say:

> *"In Sense II . . . the word cause expresses an idea relative to human action; but the action . . . is an action intended to control . . . things in 'nature', or 'physical' things. In this sense, the 'cause' of an event in nature is the handle, so to speak, by which we can manipulate it . . . ."*

This sense of the word may be defined as follows:

> *"A cause is an event or state of things which it is in our power to produce or prevent, and by producing or preventing which we can produce or prevent that whose cause it is said to be."*[23](p. 89)

Here, Collingwood relates cause to action and introduces the striking comparison of a cause to a handle by which we can manipulate the effect of the cause.

After Collingwood, the AIM theories of causality were developed by Gasking[25] and Von Wright.[26,27] More recently, the approach has become quite popular among philosophers of science. Menzies and Price have developed an AIM theory of causality.[28,29] They refer to their theory as an agency theory of causality. Woodward[30] has developed a theory that he calls: *"a manipulationist or interventionist account of . . . causation."*[30](p. 5) I refer to my own version as an action-related theory of causality (see Gillies).[31] Pearl's 2000 book should also be mentioned here.[32] Pearl has not committed exclusively to an AIM account of causality, and he introduces other conceptions of causality into his scheme. However, intervention still plays an important role for him. The AIM theories of causality are thus one of the leading trends in contemporary philosophy of causality. In what follows, I will naturally follow my own AIM theory, which differs from some of the others. It is, however, perhaps the closest to Collingwood's original version, and I can explain it by pointing out where it differs from Collingwood.

Let us consider a causal law of the form A causes B. Collingwood stresses that causality is closely related to human action, and he mentions two types of action. One kind of action is designed to produce B, and I will call such an action a *productive action*. The other kind of action is designed to eliminate B or to prevent B from occurring. I will call such an action an *avoidance action*. We can illustrate these two types of action using Pearl's example of turning a sprinkler on or off, and the corresponding causal laws are mentioned in the next two sections.

(i) Turning on the sprinkler causes the grass to become wet.

We can imagine that the sprinkler is operated by a handle, so that Collingwood's analogy between a cause and a handle becomes literally the case in this instance. I will now make a few remarks about (*i*) that will obviously apply to causal laws of the same form. If the sprinkler is turned on, the grass will always, *ceteris paribus*, become wet. For causal laws like (*i*) only "other things being equal" applies. Collingwood has an illuminating analysis of the *ceteris paribus* clause in terms of what he calls[23(p. 91)]: "*conditiones sine quibus non*," that is to say, conditions that must hold if the causal law is to apply. In the case of (*i*), these conditions might be something like the following: the handle is properly attached to the rest of the sprinkler, the sprinkler is connected to the water mains, the water mains are functioning, etc. The point is that these conditions are never explicitly spelled out, but they are tacitly assumed as part of the background to the causal law.

If the *conditiones sine quibus non* do, in fact, hold, then turning on the sprinkler is a sufficient condition for the grass to become wet. This is the standard case of a productive action, where instantiating the cause A produces the effect B. In this case, the causal law is *deterministic*. It should be noted, however, that this does not apply to all causal laws. For example, smoking causes lung cancer, but smoking is not a sufficient condition for developing lung cancer. In fact, many smokers never have this disease. Smoking does, however, under certain conditions, raise the probability of getting lung cancer. This is an *indeterministic* causality, which has become very important in medicine since the 1950s. In the nineteenth and early twentieth centuries, however, medicine used only deterministic causality, so I will ignore indeterministic causality in my analysis of Koch's Postulates.

Let us now turn from productive actions to avoidance actions. Collingwood argues, in the passage quoted above, that, for a causal law of the form A causes B, we can prevent B from taking place by preventing A from occurring. However, this implies that A is a necessary condition for B, and, even confining ourselves to deterministic causality, there are many cases in which this is not the case. Consider our example (*i*). Even if we keep the sprinkler off, the grass may still get wet. There are other causes apart from the sprinkler which can make the grass wet, and is explained in point (*ii*).

(ii) Rain causes the grass to become wet.

Now a causal law such as (*ii*) poses some problems because we cannot manipulate the cause like a handle. We cannot turn the rain on or off at will. What we can do, however, is manipulate some of the *conditiones sine quibus non*, which are implicitly assumed by (*ii*). The causal law (*ii*) only holds if the grass is not covered by a waterproof sheet. Now, in cricket matches, it is desirable to keep the grass of the wicket dry when it rains. So, in the event of rain, covers are put over the wicket. This is a successful avoidance action based on the causal law (*ii*), but it consists in operating not on the cause but on one of the *conditiones sine quibus non*, which are implicitly assumed by the causal law. I will call an action of this sort as a *blocking* action. In this case, the rain continues, but its usual effects are blocked.

Having distinguished between productive and avoidance actions, it is now important to stress that avoidance actions are much more important in medicine. The aim of medicine is to cure and prevent diseases, and not produce diseases. I use the term "avoidance" rather than Collingwood's "prevention," because curing a disease is one way of avoiding the disease, but it is not usually considered to be "prevention." A very important way of preventing a disease is vaccination, and it is clear from the above analysis that vaccination is a blocking action. Infection by a particular bacterium or virus may normally lead to the development of a disease, but, if the immune system is primed through vaccination to deal with that disease, this usual consequence of the infection is blocked.

Vonka emphasizes the importance of avoidance actions in medicine, and he gives St. Thomas Aquinas' maxim, which expresses this idea very well, which is explained in the following section.[13]

Sublata Causa, Tollitur Effectus

I will refer to this as Vonka's Thomist maxim. It can be roughly translated as "If the cause is removed, the effect is taken away." It might be objected that this maxim does not apply to blocking actions, where the cause, for example, rain or infective bacteria, remains, but its usual effects are blocked. However, once a cause has its usual effects blocked, it really ceases to be a cause. So, in this case, we can still say that the cause has been removed, and Vonka's Thomist maxim applies. That concludes my philosophical analysis of causality. Let us now see how it applies to Koch's Postulates.

Any AIM theory of causality stresses the connection between causal laws and interventions. A causal law has to support an intervention. It follows from this, that, in establishing a causal law, it is desirable to have both interventional and observational evidence. By interventional evidence, I mean evidence obtained by making an intervention and noting its results. We could indeed argue for a strong *Principle of Interventional Evidence*, which states that a causal law cannot be taken as established unless it has been confirmed by some interventional evidence. This Principle of Interventional Evidence does not apply universally, as there are some areas of

the social sciences where it is not possible to gather interventional evidence. Russo has suggested, in her 2009 book, that variational evidence can be used in such cases.[33] The idea here is, without intervening in any way, to observe the object of interest under many different conditions, and to note what variations occur under these different conditions. A good example is the famous study by Ancel Keys and his collaborators of diet and the incidence of coronary heart disease in seven different nations.[34] Keys et al. did not intervene in any way, but merely selected groups of men from each of the seven nations, and observed what they ate and how many of them got coronary heart disease. The variation here was quite remarkable. In Japan, for example, the death rate for men aged 50–54 years from coronary heart disease was less than a tenth of that for white American men in the same age group. Keys concluded from such observed variations that the amount of saturated fat in the diet was a cause of coronary heart disease.

Although medicine makes use of such variational evidence, the scientific quest is not limited to such evidence as may be the case in some branches of the social sciences. In medicine, it is always possible to collect interventional evidence because evidence from experiments on animals, tissues, and cells is standardly considered. So, for establishing causality in medicine, I would argue that the principle of interventional evidence should be accepted.

If we turn now to Koch's Postulates, we see that they do indeed satisfy the principle of interventional evidence. Koch's Postulate 4 requires that it must be possible to reproduce the disease by introducing a pure culture of the microorganism into animals. This is clearly an intervention and results in interventional evidence. So Koch's Postulates do gain support from the AIM theory of causality. However, our earlier analysis does also show that there is a lacuna in Koch's Postulates. His Postulate 4 is a productive action. It is using the microorganism to produce the disease. But we argued that causal laws should also be related to avoidance actions, and indeed that avoidance actions are more important than productive actions for medicine. This suggests that Koch's Postulates should be extended by including a clause, which refers to avoidance actions. Here is a way in which this could be done. Postulate 4 could be replaced by a two-clause postulate, 4a and 4b. Postulate 4a would be exactly the same as the original Postulate 4, and so would refer to productive actions. Postulate 4b might be formulated as follows: "It must be shown that if the microorganisms are prevented from multiplying in the patient's body, then the patient will not have the disease."

There are, in fact, three ways in which the microorganism can be prevented from multiplying in the patient. The first (vaccination) is the production of a successful vaccine through killing or attenuating the microorganism. This is a blocking action. The second (prevention) consists in manipulating the environment so that the microorganism is prevented from entering the patient's body. The third (antibiotics) is finding a substance that destroys or severely inhibits the microorganism in the patient's body without harming the patient. The third way only became possible in the twentieth century, but the first two ways were available in the nineteenth century.

I have here justified Postulate 4b using my own version of the AIM approach to causality,[31] but it could also be justified using other versions of the same approach such as that of Woodward,[30] and even using other philosophical views of causality such as the counterfactual theory of causality. Further examination of Koch's Postulates, in light of contemporary philosophy of causality, would certainly be worthwhile. I owe this point to an anonymous referee.

It should be noted that there is a difference between Postulates 4a and 4b. Postulate 4a refers to animals, whereas Postulate 4b refers to humans. From a strictly epistemological point of view, Postulates 4a and 4b should both refer to humans, as we are investigating a disease of humans. However, for ethical reasons, animals must obviously be substituted for humans in an attempt to satisfy Postulate 4a. This shows that considering avoidance actions (as in Postulate 4b) is actually epistemologically better than considering productive actions (as in Postulates 4a). The points in this paragraph were kindly suggested to me in a correspondence by Ladislav Kvasz.

If we replace Postulate 4 by Postulate(s) 4a and/or 4b, then the principle of interventional evidence is still satisfied. The interventional evidence can result from a productive action (Postulate 4a) or from an avoidance action (Postulate 4b) or from both. In fact, the evidence used to establish that *B. anthracis* was the cause of anthrax satisfied Postulates 4a and 4b. Both Koch and Pasteur showed that inoculation of experimental animals with a (at least fairly) pure culture of the bacillus resulted in the animal getting the disease. So Postulate 4a was satisfied. However, the evidence, which completely convinced any remaining doubters, was the production by Pasteur et al. of a successful vaccine against anthrax by the attenuation of cultures of *B. anthracis*. The famous and dramatically successful trial of the new vaccine took place in May and June 1881 at Pouilly-le-Fort. In this trial, 25 sheep were vaccinated, and a further 25 sheep were left unvaccinated as controls. Then all 50 sheep were given a fatal injection of *B. anthracis*. All 25 unvaccinated sheep died of anthrax, while 24 of the 25 sheep that had been vaccinated remained healthy. Only one of the vaccinated sheep was sickly and later died, but it turned out that this sheep was a pregnant ewe, and died of the complications of the pregnancy rather than because of anthrax (for a fuller account of the trial at Pouilly-le-Fort, see Debré[35]).

Obviously Koch knew of the striking evidence in favor of *B. anthracis* being the cause of anthrax provided by Pasteur's successful vaccination. So why did he not include evidence provided by preventative measures in his postulates? There were certainly important differences between Koch and Pasteur, particularly as regards Pasteur's views on the attenua-

tion of pathological bacteria, but these do not explain the bitterness of the controversy that broke out between them. In this controversy, Koch was undoubtedly the aggressor. Pasteur referred in favorable terms to Koch's paper on anthrax of 1876, but in 1881, Koch wrote a paper attacking Pasteur's work on anthrax.[7] Some of Koch's criticisms of Pasteur are undoubtedly correct, but the tone of the paper is exaggeratedly hostile. Koch goes as far as to say: "*Only a few of Pasteur's beliefs about anthrax are new, and they are false*."[7(p. 65)] The timing of this attack was very badly judged, as, shortly after it appeared in print, Pasteur had his great triumph at Pouilly-le-Fort.

Pasteur was 20 years older than Koch, and generally thought of as the grand old man of the subject. Why then did Koch make such a bitter attack on him? Perhaps Koch wished to displace Pasteur as the leading researcher in the field, but, if he did have such a personal ambition, it was likely intensified by the national rivalry, which then existed between France and Germany. The Franco-Prussian war had taken place in 1870–1871, and had resulted in a catastrophic French defeat. This led to bitter feelings on part of the French and a desire for revenge. On the German side, there was a wish to consolidate their superiority to France.

Given this background, it is perhaps not surprising that Koch did not include the evidence provided by a successful vaccine among his postulates. When it came to cholera, however, Koch did appeal to the evidence provided by successful prevention as will be shown in the next section. Thus, although Koch never satisfied his own postulates for cholera, he did satisfy the modified postulates presented in this section.

Koch Establishes that the Comma Bacillus Is the Cause of Cholera

The new evidence, which led to the general acceptance of Koch's claim that the comma bacillus was the cause of cholera, came from the cholera epidemic in Hamburg in 1892. My account of the Hamburg cholera epidemic is mainly based on Richard Evans' classic 1987 book, *Death in Hamburg*.[22] I have also found the relevant section in Brock's life of Koch[9] very helpful.

The first cases of cholera seem to have occurred about the middle of August. The epidemic had definitely started by 25th August. It began to decline in September and had largely disappeared by mid-October. During this short span of time, according to the official statistics, the disease killed 8,472 people. About half of those who contracted the disease recovered, giving a figure of about 16,944 for those who suffered from cholera. However, the official figures may well have underestimated the numbers. Evans calculates that over 21,000 may have contracted the disease and over 10,500 died from it.[22]

Robert Koch was told on 23rd August that he was being sent to Hamburg as the chancellor's official representative, and arrived there on 24th August. Koch inspected conditions in Hamburg with his usual thoroughness, and recommended measures to control the epidemic. In May of the next year, he published his conclusions in his 1893 paper, Water-Filtration and Cholera.[36]

In order to understand this classic paper of scientific medicine, it is important to realize the situation that prevailed in the medical community when Koch wrote it. Koch had published his theory that cholera was caused by the comma bacillus in 1884. It was accepted by some members of the medical community, but not by all. The main rival theory was that of Max von Pettenkofer, a leading figure among German doctors and head of the influential Munich school. On his return from India in April 1884, Koch decided to visit Pettenkofer to see if he could convince him of the new bacteriological approach to cholera. Koch did see Pettenkofer on 29th April,[9] but Pettenkofer was clearly unconvinced, as he published a statement of his own theory and a criticism of Koch in 1884.[20] Pettenkofer continued to have many supporters as is illustrated by what happened when Koch, in 1891, resigned his position as Professor of Hygiene and Director of the Hygiene Institute in Berlin in order to take up a similar position at the new Institute of Infectious Disease in Berlin. Koch naturally hoped that he would be replaced by one of his own followers, but instead a follower of Pettenkofer's was appointed as the new Director of the Hygiene Institute in Berlin. In his 1893 paper, therefore, Koch not only tried to confirm his own theory empirically but also to show that the evidence refuted Pettenkofer's theory. Before examining Koch's paper, therefore, we must have a brief look at Pettenkofer's theory of cholera.

Before the rise of the germ theory of disease, the two principal ways of explaining disease causation were *contagion* and *miasma*, as I have argued in an earlier paper.[37] Contagion was a mechanism by which someone suffering from a disease would transmit it to a person in close contact. Contagions were usually thought of as chemical poisons passed by those suffering from the disease to anyone near them. Miasmas were putrid atmospheres or bad airs, which transmitted the disease to anyone who breathed them. There was much evidence to support the miasma view, as, for example, malaria occurred in marshlands, and diseases of all kinds were more common in overcrowded slums, barracks, ships, and workhouses where the atmosphere often was evil smelling. Moreover, the miasma theory did lead to valuable reforms in preventive medicine. It was held by Chadwick who was perhaps the principal advocate of the construction of sewers in Britain, and who also advocated improved drainage, cleaning, and sanitary regulation of buildings. In hospitals, it led to a belief in cleanliness, fresh air, and avoidance of overcrowding, and so on. Florence Nightingale based her reforms on the miasma theory, which was never converted to the germ theory.

Pettenkofer always accepted the contagion and miasma framework, and he continues to use it in his 1884 article on cholera,[20] but by that time, the germ theory had made considerable advances, and Pettenkofer combines the old frame-

work with some ideas from the germ theory. Thus, he begins his 1884 article as follows:

> "*Cholera is an infectious disease. By infectious diseases are meant those diseases, which are caused by the reception from without of specific infective material into healthy bodies, which material acts like a poison . . . . Infective material differs essentially from lifeless chemical poison in being composed of the smallest possible units of living matter, which when taken into healthy bodies rapidly increase and multiply under certain conditions and by their life-growth disturb the health of the body. These germs of disease belong to the smallest units of life, to the schizomycetes, which lie on the borderland of the invisible, and which, according their form, are known as cocci, bacteria, bacilli, vibriones and spirilla . . .*"[20(p. 769)]

So far, Pettenkofer looks like a supporter of the germ theory of disease, but now he introduces the old contagion/miasma framework as follows:

> "*Infective material is derived partly from sick individuals, in which case the disease is termed 'contagious' and partly from locality (earth), in which it has developed, in which case the resulting disease is termed 'miasmatic'*."[20(p. 769)]

Pettenkofer did not deny that microbes, of which the comma bacillus might be one, were involved in the causation of cholera, but he held that such microbes could not cause cholera directly. The microbes would not cause the disease if they were ingested or if someone came in contact with them in the stools of a patient with cholera. So cholera was not contagious, or at least only very slightly contagious. Cholera could not be spread through soiled linen, contaminated drinking water, etc.

If we call the relevant microbes "x", then x alone will not cause cholera. Microbe x has to come in contact with another factor "y" in the soil which causes x to germinate and produce the actual infective material of cholera "z" in the form of a miasma. This theory explained why cholera could move from place to place. The factor x, which was harmless in itself, could be transported by humans from one cholera area to another. If x were deposited in the new site through human excrement, then, if the soil conditions were appropriate, it would, in conjunction with y, produce a cholera epidemic. Pettenkofer studied local soil conditions, the movement of the water-table, conditions of temperature and rainfall, etc., in the hopes of learning the conditions that would cause x to germinate and produce an epidemic. Through such studies, he hoped that means would be found to prevent cholera epidemics. His theory was called the "soil theory (*Bodentheorie*) of cholera."

Although Pettenkofer made some concessions to the new germ theory of disease, he unfortunately retained what was to prove the principal weakness of the contagion/miasma framework. Within that framework, there was no plausible mechanism by which a disease could be transmitted through drinking water. Drinking water neither involves any close contact with a person suffering from a disease, and so could not be considered as a form of contagion, nor generates a harmful miasma. As we have seen, the miasmatists advocated the construction of sewage systems and greater cleanliness, and both these factors did reduce the incidence of many diseases, but these measures were powerless against the diseases transmitted through drinking water, which included both cholera and typhoid. Cholera and typhoid epidemics continued to affect towns, like Hamburg, which had installed excellent sewage systems. Pettenkofer was responsible for the installation of a new water supply for Munich. He arranged for spring water to be transported from the mountains to the city, and to replace the previous supply of water from wells in the city. He did not think it necessary to filter the water in the new supply, and shortly after it came into operation, a massive typhoid epidemic hit the city.[22]

Despite this setback, Pettenkofer did not alter his views, and, in fact, most of his 1884 paper on cholera is taken up with arguing that cholera cannot be transmitted by drinking water. He argues against advocates of the drinking water view, both the earlier John Snow and the contemporary Robert Koch.

I will now turn to an analysis of Koch's 1893 paper, which, in the opinion of the overwhelming majority of the medical community, decided the argument in favor of Koch's theory of cholera. There is no English translation of this paper of Koch's. So the quotations given are my own translations, which were kindly revised and corrected by Christian Wallmann. In the first paragraph of his paper, Koch states his views about the transmission of cholera:

> "*I have always maintained that in the light of our experiences to date direct infection from person to person is possible but from every appearance it occurs not very frequently, that on the contrary in real epidemics and mass outbreaks of cholera the principal role devolves on indirect infections from the many carriers of the cholera germ, and that among these carriers water is one of the most important*."[36(p. 183)]

Koch here wants to stress that cholera is not transmitted exclusively by water, but that water transmission is one of the most important ways in which the disease spreads. This opinion completely contradicts that of Pettenkofer.

Koch now turns to the evidence from the Hamburg epidemic, which he thinks strongly confirms his views and refutes those of Pettenkofer. This evidence concerns the different rates of cholera in Hamburg and Altona. Altona was a small town downstream along the Elbe from Hamburg. Originally, it must have been an independent town, but by 1892, there was no open space between Altona and Hamburg, so that Altona had become a suburb of the big city. Altona had, however, a different water supply from Hamburg. Hamburg took its water from the Elbe before the river entered the city, and its water was unfiltered. Altona took its

water from the Elbe after it had flowed through Hamburg, but Altona's water was filtered by slow sand filters. Presumably, filtration had been thought necessary in Altona because, at the point where it took its water, the river water was polluted with the wastes of Hamburg, whereas the Elbe water above Hamburg was thought to be purer, and so not in need of filtration. Koch begins by pointing out that the difference in the incidence of cholera in Altona and Hamburg was very striking:

> "*Cholera behaved most surprisingly at the boundary between Hamburg and Altona. On both sides of the boundary the character of the soil, buildings, sewers, population, in effect everything that is relevant here is completely the same, and yet cholera in Hamburg went only right up to the boundary of Altona and halted here. In one street, which marks the boundary for a long stretch, cholera occurred on the Hamburg side, while the Altona side remained free of the disease*."[36(p. 184)]

Evans[22] gives some detailed statistics, which completely bear out what Koch is saying here. For example, in the area near the Elbe, the incidence of cholera on the Altona side of the boundary was 0–5 per thousand inhabitants, while on the Hamburg side, it was 25–30 per thousand inhabitants. It is worth noting that Koch stresses that all the conditions apart from the water supply were the same on both sides of the boundary. Koch must have been aware, from Pettenkofer's earlier criticisms, how Pettenkofer was likely to argue against Koch's claim that cholera was transmitted by the water supply. Pettenkofer's line would probably be that, although there was a correlation here between water supply and cholera incidence, this was not causal in character, and that the real cause of the difference lay in other factors. Indeed, Pettenkofer would have had to argue that the cholera microbes had germinated on the Hamburg side of the boundary to produce a miasma, but had failed to do so on the Altona side. To counter such a claim, Koch stresses that the character of the soil, sewers, etc. were the same on both sides of the boundary. He elaborates this argument in the next passage where he claims that the Altona/Hamburg case is like a laboratory experiment:

> "*Here we have therefore to do with a kind of experiment, which has been carried out with more than a hundred thousand people, but despite its enormous dimensions satisfies all the conditions, which are imposed on an exact and completely decisive laboratory experiment. In two large population groups, all the factors are the same, except a single one which is different, namely the water supply. The group, which was supplied with unfiltered water from the Elbe, was heavily affected by cholera, the group supplied with filtered water to a very small extent. This difference must be considered of yet greater weight, since the Hamburg water is taken from a place, where the Elbe is comparatively little polluted, but Altona must use water from the Elbe after it has received the complete liquid waste, including the faeces, from nearly 800,000 people. Under such conditions there is for the scientific thinker first of all no other explanation, except that the difference, which the two population groups show regarding cholera, is caused by the difference in water supply, and that Altona was protected against cholera by the filtration of the water of the Elbe*."[36(p. 184)]

Koch's next point is that the difference between Hamburg and Altona is very easily explained by the assumption that cholera is a disease caused by bacteria. As he says:

> "*For the bacteriologist nothing is easier than to give an explanation for the confinement of cholera to the area of Hamburg's water supply. He needs only to point out, that cholera bacteria reached Hamburg's water supply from the output of Hamburg's sewers, or, which is much more probable, from the dejecta of those with cholera, who were to be found on the numerous small boats anchored in the Elbe above the place from which Hamburg's water is taken and that, after this had happened, among the people who used the water, according to the degree of its pollution, more or less numerous cholera cases must have occurred . . . . Altona takes water which initially is much worse than that of Hamburg, but through careful filtration is freed wholly or almost completely from cholera bacteria*."[36(p. 185)]

So it is easy to explain the contrast between Hamburg and Altona, as regards cholera, if we assume a bacterial cause for the disease. Conversely, however, as Koch goes on to say, it is very hard, if not impossible, to explain this difference on other hypotheses, such as the claim that cholera is caused by a miasma. As Koch writes:

> "*Why anyone would want to derive the behaviour of the Hamburg-Altona cholera from cosmic-telluric, or from purely meteorological factors is a puzzle to me; since sky, sun, wind, rain and so on were distributed absolutely equally on both sides of the boundary*."[36(p. 185)]

Having thus disposed of Pettenkofer's (and other) miasma theories of cholera, Koch now proceeds to give some more evidence in favor of his own theory. So far, he has shown that cholera is transmitted by drinking water, and that this is easily explained on the bacteriological theory of the disease. However, to confirm this explanation, it was necessary to show that the slow sand filtration carried out on the Altona water really did remove bacteria. This is what Koch now does.

Koch begins by making some technical remarks about sand filtration. If it is to remove bacteria, it must be *slow*, and the water must trickle through a sufficiently *thick* layer of sand. Koch mentions a speed of 100 mm/hour, and a thickness of 30 cm.[36] He remarks that not all sand filtration systems satisfy these criteria, but that the water filtration at Altona, although one of the oldest in Germany, fortunately does satisfy them, and it is to this fact that the citizens of Altona owe their preservation from the worst ravages of cholera. In the water of the Elbe, there were between a thousand and a hundred thousand germs per cubic centimeter. Since the summer

of 1890, the filtered water at Altona had been tested for bacteriological content weekly. Koch gives the following results:

> "*During a period of two years up to the summer of 1892, the number of germs in a cubic centimetre of the filtered water remained, with the exception of a short period in January 1891, always under a hundred. Numbers under 20 were the norm.*"[36](pp. 192–193)

This showed that the filtration system did indeed remove most of the bacteria from the water of the Elbe. Koch does mention a short period in January 1891 when the filtration system did not work so well. He goes on to explain this as caused by ice forming in the cold weather and interfering with the filtration process. The problem of ice did not affect cholera, which only flourishes in warm weather. The Hamburg epidemic of 1892 took place during a very hot summer. However, epidemics of the other water-borne disease (typhoid) could occur in winter. So Koch discusses how the problem of ice forming in the filtration system could be overcome.

So far, Koch has not mentioned the comma bacillus, which he regarded as the cause of cholera. In a way, it was not necessary for him to do so. If cholera is a bacterial disease, then the fulfilment of his first two postulates would show that the comma bacillus was the relevant bacterium. If Altona's slow sand filtration system removed nearly all bacteria, it would remove the comma bacillus along with the others. However, he did also test for the presence of the comma bacillus, which he here refers to simply as the cholera bacterium, in the water systems of Hamburg. He states the results as follows:

> "*We succeeded in detecting the cholera bacteria in the water of the Elbe . . . They were also detected in the water immediately before filtration. They were not found in the filtered water.*"[36](p. 199)

This completes the evidence, drawn from the Hamburg cholera epidemic of 1892, which Koch presents in his 1893 paper. This new evidence led to the overwhelming majority of the medical community abandoning Pettenkofer's soil theory of cholera and accepting Koch's view that cholera was caused by the comma bacillus. Koch's recommendation that all water-supply systems should use properly filtered water was accepted and implemented in Germany and the rest of Europe, and, as a result, there were no more European cholera epidemics.

Yet, although Koch, thus, succeeded in establishing the cause of cholera, he never succeeded in satisfying his Postulate 4. Instead he succeeded in satisfying what we have suggested as a Postulate 4b; that is to say, he showed that if the comma bacillus was prevented from entering someone's body by removing it from the supply of drinking water, then that person would not get cholera. It is a perfect instance of Vonka's Thomist maxim: *sublata causa, tollitur effectus* (if the cause is removed the effect is taken away).

CONCLUSION

In this paper, I have shown that Koch managed to satisfy all his postulates in the case of tuberculosis, and that, therefore, his views as to the cause of tuberculosis were accepted by the medical community. In the case of cholera, however, Koch did not succeed in satisfying all his postulates, and, therefore, he did not succeed in convincing the whole of the medical community in 1884 that the comma bacillus, which he had discovered, was the cause of the disease. However, the additional evidence provided by the Hamburg cholera epidemic of 1892 did result in Koch's views becoming generally accepted, although his postulates were still not satisfied. This suggests that Koch's Postulates omit some types of evidence, which are important regarding causality. An analysis of the postulates in light of some contemporary ideas in the philosophy of causality suggests a modification of the postulates to fill this gap. It is then shown that the final acceptance of Koch's views is explained by these modified postulates.

Although my aim in this paper is largely historical, that is, to consider Koch's Postulates in relation to Koch's own research, Koch's Postulates are still considered to be of contemporary relevance. Might therefore the modification of the postulates suggested in this paper be of some contemporary use? This could be the case. For example, if Marshall had considered the modified postulates instead of Koch's original postulates, he might never have indulged in the dangerous self-experiment of swallowing *Helicobacter pylori* inoculum, but instead relied on the evidence that peptic ulcers are eliminated by taking antibiotics and eradicating the bacteria at the site of peptic ulcer. In general, the dangerous self-experimentation of figures like Pettenkofer, Emmerich, and Marshall becomes no longer necessary if Postulate 4b is included with Postulate 4a.

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