HOW RESEARCH INTO THE HUMAN MICROBIOME CAN BE USED TO SOLVE CRIMES

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I. INTRODUCTION

No man is an island. This is a common expression in the English language. People typically use it to illustrate the foolishness of those that spurn the outstretched hand—to mean that no one can survive for long without the help of others, that everybody needs friends, or some other similar sentiment. However, few people know just how true that expression is.

No human is ever truly alone. Humans are literally incapable of doing anything by themselves. Humans carry an enormous amount of microorganisms on and within their bodies that assist the human body in carrying out many essential life processes.[1] This collection of microorganisms, or microbes, living on and within the human body at any given time is referred to by scientists as the human microbiome, and it will be referred to as such throughout this Note.[2] The human microbiome is essential to human life, but has not yet been studied thoroughly, meaning that its potential applications have yet to be thoroughly explored.[3] One potential application of research into the human microbiome involves its use as an evidentiary tool in criminal investigations as a component of forensic science.[4] The fact that all human beings carry these microbes with them wherever they go means that, just like human cells, there is a chance that microbes will be deposited in the environment, meaning that microbe evidence could potentially be gathered at a crime scene.[5] This Note will focus on the potential use of microbe evidence in forensic science. By comparing microbe evidence gathered at crime scenes with knowledge of the human microbiome, it could theoretically be possible to match microbe evidence to suspects. Since this is a relatively recent and developing scientific field, much of this Note will be speculative and hypothetical in

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1 ANN REID & SHANNON GREENE, AM. SOC'Y FOR MICROBIOLOGY, HUMAN MICROBIOME FAQ 2 (2013).

2 *Id.* at 2–3 (defining the terms "microbe" and "microbiome").

3 *See id.* at 2.

4 *Id.* at 10.

5 *See id.*

nature. Nevertheless, it is valuable to begin thinking about this potential evidentiary tool now, so that by the time the research is mature, law enforcement organizations and courts will be able to effectively process such evidence.

This Note is divided into four distinct parts to tackle various issues involved with the human microbiome and its application to the legal setting. Part II explains the concept of the human microbiome. This Part provides a summary of the current research and the implications of said research. Considering that the primary audience of this Note will be the legal community, the summary of the research will not be couched in overly scientific language, but rather will be tailored to an audience with little formal scientific training. Part III explains the potential benefits to forensic science that research into the human microbiome could provide. This Part examines the various ways that microbe evidence could potentially be used to solve crimes and the reasons why it is beneficial to pursue research into the human microbiome in a forensic context. Part IV is devoted to addressing arguments against using microbe evidence. The primary argument against pursuing this line of research is that DNA (deoxyribonucleic acid) evidence already provides the same information to law enforcement investigators. This Part addresses that argument and explains why, even though DNA evidence is commonly used in trials to convict defendants, it would still be beneficial to the public and to law enforcement agencies to pursue research into the human microbiome. Part V focuses on possible ways that microbe evidence could be used in trials. This Part is mainly devoted to the logistical implications of using this evidence and examines potential evidence-law implications. This Part also speculates on issues such as the potential expense of laboratories required to adequately analyze the evidence and the potential ethical issues involved with the collection and testing of microbiome data.

II. WHAT IS THE HUMAN MICROBIOME?

A. GENERAL DISCUSSION

The term "human microbiome" is used to signify simultaneously both the collection of genes contained in the microbes inhabiting the human body, analogous to the human genome (the entirety of the human genetic code); and the collection of different microbe species inhabiting the human body, analogous to the "biome," meaning the various species of flora and fauna living in a given environment, which in this case happens to be the human body.[6] Research into the human microbiome began in large part due to the human genome project, a research project initiated to catalog all of the genes present in humans.[7] Researchers were surprised to discover that the human genome contained only around twenty thousand genes, as

6 *Id.* at 3.
7 Peter J. Turnbaugh et al., *The Human Microbiome Project*, 449 NATURE 804, 804 (2007).

opposed to the one hundred thousand that they had predicted.[8] According to their results, researchers found that humans possess roughly the same number of genes as the fruit fly, a somewhat disheartening and confusing revelation.[9] Researchers began to view the definition of a human being differently. If a human was defined to include the numerous microbes living on and within the human body, meaning that the human genome would then include the genes of the microbial cells as well as the human cells, then the original estimate of one hundred thousand different types of genes would likely be a gross understatement.[10] Therefore, the human microbiome project formed from the ashes of the human genome project when the researchers in the human genome project concluded that their work was far from over.[11] The human microbiome project is defined as the work being performed by researchers across the globe and across many disciplines in discovering the nature of the microbes sharing the human body.[12] Although the primary objective of the human microbiome project thus far has been to catalog the genes of the microbial organisms living on and within the human body and to research the nature of the microbiome and the functions it performs for applications within a medical context, a natural byproduct of this research is that potential forensic applications may also be explored.[13]

The microbiome consists of roughly one hundred trillion bacterial cells, which is about three times more than the number of human cells in the body.[14] The microbiome also contains microbes besides bacteria, such as fungi, viruses, and other single-celled organisms, but bacteria holds more promise for forensic purposes.[15] Indeed, the fungal microbiome is dominated by only one genus, a breed of lipophilic yeast, accounting for a lack of fungal diversity that does nothing to assist the goal of this Note, which is the use of the microbiome in a forensic context.[16] This fact, coupled with the fact that the majority of current research on the human microbiome has been conducted on bacterial cells, means that this Note will focus mainly on the bacterial component of the human microbiome. As discussed in the previous paragraph, the microbiome is much more genetically diverse than are the cells of the human body, so it follows that it is much more diverse concerning the different types of cells that it contains. Only approximately 25 percent of the different types of cells in the human body are human cells, with the rest being composed of microbial cells

8 *Id.*
9 *Id.*
10 *Id.*
11 *See id.*
12 *Id.*
13 *See id.*
14 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 6.
15 *Id.*
16 *See generally* Enshi Zhang et al., *Characterization of* Malassezia *Microbiota in the Human External Auditory Canal and on the Sole of the Foot*, 56 MICROBIOLOGY & IMMUNOLOGY 238 (2012) (study tracking the presence of a particular fungal genus across different areas of the skin microbiome).

constituting the human microbiome.[17] However, despite the much larger diversity of the microbiome in comparison to the human cells in the body, the microbiome is still relatively small in regards to total volume when compared to the rest of the body, although roughly estimated at about two and a half pounds (varying depending on the size of the person), it is still larger than many laypeople may suspect.[18] It is difficult to precisely measure the microbiome in weight, though, because it is spread throughout different areas of the human body, and is not consolidated in one place.[19] For example, blood vessels contain few if any microbes, whereas the intestine contains an immense microbe density, due in part to the extensive surface area of the intestine.[20]

B. Gut Microbiome

The human microbiome is located throughout the human body, but certain areas contain more microbes than others, and different microbes are located in different areas to assist with different bodily functions.[21] The exact functions of the microbiome are still being researched, and much is unknown, but researchers have determined some effects of the microbiome.[22] The intestinal tract, or "gut," is the most frequently studied area of the human microbiome.[23] Some benefits of microbes in the gut that have been identified include an increased ability in our body to absorb vitamins and nutrients that would otherwise be inaccessible, enhanced metabolism of lipids (fat molecules), an increased ability to break down carcinogens and detoxify the body, an increased ability to repair damage to the intestinal lining, and an increased adaptability in the immune system.[24] Disturbances in the effects mentioned above have been noted in subjects with conditions that would cause intestinal disruption, such as inflammatory bowel disease.[25] The microbial community of the gut is thought by researchers to be one of the densest microbial ecosystems observed in the world to date.[26] Because of its immense density and diversity, there is still much that is not known about the microbial ecosystem of the human gut.[27] Researchers have hypothesized that the effects of the microbial ecosystem could potentially be much more far-reaching than studies have indicated so far.[28] Since microbes metabolize matter and release waste products themselves, which are then absorbed into the human bloodstream, the potential far-reaching effects of the microbial

17 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 6–7.
18 *Id.* at 6.
19 *Id.*
20 *Id.*
21 *Id.* at 8.
22 *Id.*
23 *Id.* at 9.
24 Turnbaugh et al., *supra* note 7, at 805.
25 *Id.*
26 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 9.
27 *See id.*
28 *See id.*

ecosystem could include influences on traits such as sleep patterns, mood, and other cognitive processes or behaviors.[29] Some researchers have even suggested recently that differences observed in the gut microbiomes of children with autism could perhaps be responsible for, or at least inherently linked to, their neurodevelopment disorder.[30] Unfortunately there is still a lack of research performed on human subjects, so much remains for the scientific community to learn.[31]

C. ORAL CAVITY MICROBIOME

The mouth also contains many microbes and is a site with great microbial diversity.[32] The oral cavity operates differently from the intestinal tract in that it is constantly in contact with the outside environment.[33] Researchers believe that one of the primary functions of the oral microbiome is the prevention of oral disease.[34] In fact, research has suggested that the human body is so highly adapted to its own specific oral microbiome that the disruption of said microbiome is the primary cause of oral disease.[35] Due to the ease with which samples can be taken of the oral microbiome (as opposed to the gut[36]), researchers have a much clearer picture of a healthy oral microbiome (and by default an unhealthy microbiome), which leads to the increased knowledge of the link between disruption in the oral microbiome and disease.[37] However, there still exists a lack of information as to the exact benefits provided by microbes in the oral cavity.[38]

D. RESPIRATORY CAVITY MICROBIOME

The lungs, or respiratory cavity, are another area of the body that possesses a diverse microbiome, though they have been studied far less than the gut and oral cavity.[39] Due to the medical focus of most microbiome

29 *Id.*

30 *See generally* Bhaskara Lakshmi Reddy & Milton H. Saler, *Autism and Our Intestinal Microbiota*, 25 J. MOLECULAR MICROBIOLOGY & BIOTECHNOLOGY 51, 52–53 (2015) (discussing links between autism and gastrointestinal disorders, along with differences in the gut microbiomes of children with autism that can cause "leaky gut syndrome," allowing more microbes into the bloodstream through the gut than would be found in a person without these anomalies).

31 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 14.

32 *Id.* at 8.

33 LESLIE PRAY ET AL., FOOD FORUM, FOOD AND NUTRITION BD., INST. OF MED. OF THE NAT'L ACAD., THE HUMAN MICROBIOME, DIET, AND HEALTH: WORKSHOP SUMMARY 60 (2013).

34 *See* REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 8.

35 *See id.*

36 *See generally* Alice K. Hawkins & Kieran C. O'Doherty, *"Who Owns Your Poop?": Insights Regarding the Intersection of Human Microbiome Research and the ELSI Aspects of Biobanking and Related Studies*, 4 BMC MED. GENOMICS 72 (2011) (examining ownership and consent requirements for use of fecal matter typically perceived as waste when valued for research purposes, taking into account the potential data relevant to research of the human microbiome contained in fecal matter).

37 *See* PRAY ET AL., FOOD FORUM, FOOD AND NUTRITION BD., INST. OF MED. OF THE NAT'L ACAD., *supra* note 33.

38 *See id.*

39 *See* James M. Beck et al., *The Microbiome of the Lung*, 160 TRANSLATIONAL RES. 258, 258–59 (2012).

research, links have been found between the respiratory microbiome and diseases such as asthma, bronchitis, and emphysema, but little is known as to the exact benefits provided by the respiratory microbiome.[40] However, the research that has been done suggests that, as with the oral cavity, the microbiome is influenced by contact with environmental stimuli from outside the body.[41] A comparison between the respiratory microbiomes of smokers and non-smokers showed major differences in the composition of microbe populations in the lungs.[42] Further emphasizing the interconnected nature of the human microbiome, some studies have suggested a strong relationship between the microbial composition of the intestinal tract and that of the respiratory cavity, with a distinct correlation observed between composition of the microbiome of the intestinal tract and allergic responses in the airway.[43]

E. Ocular Microbiome

The eyes, specifically their ocular surfaces, also possess a microbial community.[44] Although the eyes possess fewer microbes than other regions discussed in this Note, evidence suggests that they nevertheless possess a core microbiome that remains static despite the day-to-day introduction of foreign microorganisms that arises as a result of the exposure of the ocular surface to the elements.[45] Although little is currently known about the ocular microbiome, researchers have suggested that the primary function of microbes native to the surface of the eye is to assist the immune system in protecting the eye against potentially harmful pathogens.[46] Researchers base this conclusion on their surprising finding that microbes native to the ocular surface are similar in nature to identified pathogens that cause ocular disease.[47] Researchers have speculated that these similarities represent an attempt by the body to assimilate pathogens into a normalized immune response, to be used as a "powerful mechanism suppressing microbial pathogenicity."[48] However, the researchers in this study did acknowledge that their sample size was too small to draw decisive conclusions from.[49] Part of the difficulty of obtaining a reliable profile of the ocular microbiome is that the bacteria present on the ocular surface are not easy to cultivate in other environments.[50] Attempts to cultivate microbes on contact

40 *See id.* at 260–61.

41 John R. Erb-Downward et al., *Analysis of the Lung Microbiome in the "Healthy" Smoker and in COPD*, 6 PLOS ONE 1, 4 (2011).

42 *Id.*

43 Beck et al., *supra* note 39, at 262.

44 *See* Qunfeng Dong et al., *Diversity of Bacteria at Healthy Human Conjunctiva*, 52 INVESTIGATIVE OPHTHALMOLOGY & VISUAL SCI. 5408, 5408 (2011).

45 *See id.*

46 *See id.* at 5412.

47 *Id.*

48 *Id.*

49 *Id.* at 5411.

50 Mark D.P. Willcox, *Characterization of the Normal Microbiota of the Ocular Surface*, 117 EXPERIMENTAL EYE RES. 99, 103 (2013).

lenses have yielded some information on the effect of contact lenses on the ocular microbiome.[51] Researchers have found that extended usage of contact lenses does not significantly alter the composition of the ocular microbiome, but does increase the presence of pathogenic microbes, which are more likely to grow on the surface of the contact lens.[52] Although much research still needs to be done on the ocular microbiome, the findings, that humans do possess a core ocular microbiome and that it does enhance the immune response of the eye, are promising and warrant further investigation.[53]

F. VAGINAL MICROBIOME

Another area of the human body known to possess a thriving microbial ecosystem is the vagina in females.[54] Although the vagina is considered by researchers to be one of the main sites of microbial activity in the human body, the diversity of microbe species located in the vagina is relatively low compared to other areas of the body, such as the oral cavity and intestinal tract.[55] A newborn infant receives the majority of its microbiome from its mother during its exit through the birth canal.[56] Researchers studying the ocular microbiome found that the composition of the ocular microbiome in newborns is remarkably similar to the composition of the microbiome of the cervix in an adult female.[57] Researchers have found that the composition of an infant's microbiome when delivered by a caesarean section differs greatly from that of a child that obtains its starting microbiome by receiving a coating of microbes while exiting the mother's birth canal during a natural birth.[58] Newborns also receive their first microbes from touching the skin of the mother and father, suggesting that, like genetic diversity, children inherit microbial diversity from their parents as well.[59] In addition to providing offspring with a starting set of microbes, the vaginal microbiome also helps to prevent urogenital diseases such as yeast infections, urinary tract infections, and sexually transmitted infections.[60] Indeed, the presence of sexually transmitted infections has been found to alter the composition of the vaginal microbiome.[61] As with

51 *Id.* at 101–02.
52 *Id.*
53 Dong et al., *supra* note 44, at 5411–12.
54 *See* Lita M. Proctor, *The Human Microbiome Project in 2011 and Beyond*, 10 CELL HOST & MICROBE 287, 288 (2011).
55 Human Microbiome Project Consortium, *Structure, Function and Diversity of the Healthy Human Microbiome*, 486 NATURE 207, 207–08 (2012).
56 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 5.
57 Willcox, *supra* note 50, at 102.
58 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 4–5.
59 *Id.*
60 Jacques Ravel et al., *Vaginal Microbiome of Reproductive-Age Women*, 108 PROC. NAT'L ACAD. SCI. U.S. 4680, 4680 (2011).
61 *See* Derick Burgad et al., *The Vaginal Microbiota Over an 8- to 10-Year Period in a Cohort of HIV-Infected and HIV-Uninfected Women*, PLOS ONE 15–17 (Feb. 12, 2015), http://www.plosone.org/article/fetchObject.action?uri=info:doi/10.1371/journal.pone.0116894&representation=PDF.

other areas of the human microbiome, the research currently being performed on the vaginal microbiome is still in its infancy.[62]

G. SKIN MICROBIOME

The last area of the human microbiome that will be discussed, and perhaps the most important in terms of legal and forensic application, is that of the skin. All the skin surfaces on the human body contain microbes, including hair shafts, sweat glands, and the insides of pores, with higher concentrations of microbes in moist or oily areas such as armpits and facial creases, as opposed to drier places such as the arms and legs.[63] The diversity of the skin itself as an organ, with many different areas with different consistencies of moisture, oil, hair, and light exposure, serves to foster a wide range of diversity in the ecosystem of microbes using the skin as their home.[64] The skin is also exposed to a wide range of environmental factors that differ from person to person, including the climate, the occupation of the person, the cosmetic products that the person might use, the clothing the person wears, and many others, which can all contribute to the diversity present within the microbial communities living on the skin covering the human body.[65] Researchers have so far determined that one of the major functions of microbes living on the skin is assisting with, and even playing a vital role in, the skin's immune response.[66] The skin is the body's first line of defense against foreign pathogens, and the microbes living on the skin assist the skin in preventing infection.[67] Since several skin disorders, including psoriasis and eczema, are a result of a breakdown in the skin's immune response, researchers have hypothesized that the underlying cause of these disorders could be a problem with the microbiome of the skin.[68] Although researchers do know definitively that microbes on the skin play a vital role in the skin's immune response, like all other aspects of the human microbiome, there is still much that is unknown about the microbes that live on the skin.[69] Although obtaining a sample of microbes from the skin surface is certainly a less invasive procedure than that required to obtain samples from other areas discussed in this paper, other complications hinder the research on the skin microbiome.[70] Since the skin is constantly exposed to the elements, it can be difficult to determine what percentage of microbes found on the skin at any given time are native to the host and which are transient.[71] The skin microbiome is constantly in flux due to changes in conditions and

62 Ravel et al., *supra* note 60.

63 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 8.

64 Elizabeth A. Grice & Julia A. Segre, *The Skin Microbiome*, 9 NATURE REV. MICROBIOLOGY 244, 244 (2011).

65 *Id.* at 245–46.

66 *Id.* at 249.

67 *Id.*

68 *Id.* at 249–50.

69 *See id.* at 251.

70 *See id.* at 247–48.

71 *Id.* at 247.

environmental factors, so it is difficult to obtain a sample that is truly representative of the microbes that play an essential role in the day-to-day processes of the human body.[72] Because of these environmental complications, the skin microbiome, like the other areas of the body, is still not fully understood by researchers seeking to understand the human microbiome.[73]

The human microbiome consists of a large and complex ecosystem flourishing on and within the human body.[74] The human microbiome assists in many of the essential life processes that the human body performs every day.[75] The human microbiome is massive and is constantly in flux.[76] There is much that researchers have yet to learn about it and the potential applications of the research are far-reaching, including advancements in the medical field and potential forensic applications.[77]

III. FORENSIC APPLICATION OF MICROBIOME RESEARCH

Now that the nature of the human microbiome has been explained, it becomes necessary to illustrate how this research could be applied to forensic science. As mentioned in the previous section, microbiomes are extremely diverse and vary wildly from one person to the next.[78] This means that it could hypothetically be possible to identify a person by their microbiome signature in a way somewhat analogous to the use of DNA evidence today.[79] If evidence of a suspect's or a victim's microbiome were to be recovered from a crime scene, then it could be possible for a lab to connect that evidence to the perpetrator of the crime, allowing the crime to be solved and the perpetrator to be convicted. There have already been several studies performed on the microbiome which could be applied in a forensic context. These studies, however, represent only the beginnings of possibilities in which research into the human microbiome could theoretically be used.

A. OFFICE MICROBIOME STUDY

One study focusing on microbes living on human skin was able to identify the people used as test subjects by connecting samples of microbes left on surfaces with samples taken of the microbes living on the skin of the test subjects.[80] The study consisted of microbe samples gathered from keyboards and computer mice.[81] The researchers compared the microbe

72 *See id.* at 246–48.
73 *See id.* at 251.
74 REID & GREENE, *supra* note 1, at 3.
75 *Id.* at 2.
76 *See id.* at 2, 11.
77 Turnbaugh, et al., *supra* note 7, at 804; REID & GREENE, *supra* note 1, at 10.
78 *See* Human Microbiome Project Consortium, *supra* note 55, at 207.
79 *See* REID & GREENE, *supra* note 1, at 10.
80 *See* Noah Fierer et al., *Forensic Identification Using Skin Bacterial Communities*, 107 PROC. NAT'L ACAD. SCI. U.S. 6477, 6477 (2010).
81 *Id.*

samples gathered from the keyboards and computer mice to microbe samples gathered from the respective owners of the keyboards and the computer mice.[82] The researchers also compared the microbe samples to a microbe database containing further microbe samples of an additional 270 human hands.[83] In all of the nine computer mice samples that they compared to the database, the researchers found that the microbe communities from the mice were "significantly more similar to those on the owner's hand than to the other hands in the database."[84] Similar results were obtained from the tests performed on the keyboard samples.[85] The researchers compared microbe samples taken from the fingers of the owners of the keyboards both to the keyboards that they owned and to public computers with which they had never come into contact.[86] The researchers found "that bacterial communities on the fingertips or keyboard of a given individual are far more similar to each other than to fingertips or keyboards from other individuals."[87] The researchers concluded that microbe communities living on the skin are "highly personalized."[88] As suggested by the researchers, the results of this study have obvious and profound forensic applications.[89]

This study also attempted to determine how long microbes from human skin left on surfaces remained viable.[90] The researchers gathered microbe samples from the skin surface of two individuals.[91] Half of the swabs were frozen and stored at -20˚C, while the other half were stored at room temperature.[92] After two weeks, "storage under typical indoor conditions had little to no influence on bacterial community composition, or the ability to resolve differences between the bacterial communities on the skin of the two individuals."[93] The researchers concluded that "skin bacterial communities are relatively stable over time," and noted that "palm surface bacterial communities recover within hours after hand washing."[94] The researchers concluded that since "individuals appear to harbor personally unique, temporally stable, and transferable skin-associated bacterial communities," these bacteria could be used as "'fingerprints' for forensic identification."[95]

In order to compare the microbes found on the surfaces of the keyboards and computer mice to those found on the fingertips and palm surfaces of the subjects, the researchers looked at both the composition of

82 *Id.*
83 *Id.* at 6478.
84 *Id* at 6480.
85 *See id.* at 6477–78.
86 *Id.* at 6477.
87 *Id.*
88 *Id.* at 6479.
89 *See id.*
90 *See id.* at 6477.
91 *Id.* at 6478.
92 *Id.*
93 *Id.*
94 *Id.* at 6477.
95 *Id.* at 6477.

the bacterial communities found on the surfaces and the bacterial DNA recovered from the surfaces.[96] The researchers noted that at any given skin location on the human body, there exists a "high degree of interindividual variability in the composition of bacterial communities."[97] They also noted that only 13 percent of observable bacterial traits on the surface of the palm are shared between any two people on the planet and that "a similar level of interpersonal differentiation is observed at other skin locations."[98] The researchers noted that since the bacteria living on the skin are easily dislodged and are resistant to environmental factors such as moisture, temperature, and UV radiation, humans leave a "persistent 'trail' of skin-associated bacteria on the surfaces and objects that we touch during our daily activities."[99] All of this data leads to the logical conclusion that information on the human microbiome, particularly the microbiome present on the skin, as suggested by this study, would be an invaluable tool to forensic scientists, although the authors of the study do concede that much more research would need to be done before the findings could be confirmed and properly applied.[100] However, some researchers have already begun to test different ways to apply the research in this study.[101] At a conference in 2012, researchers discussed potential methods of forensic identification through the use of microbial evidence, citing this study in support of their suggestions.[102] This suggests that although the research has not yet reached the point of real-world application, the idea of using data on the human microbiome in real-world forensic identifications is being taken seriously.

B. HOME MICROBIOME STUDY

Another interesting microbiome study with potential forensic applications focused on microbe communities in the home.[103] This study followed seven families over the course of six weeks.[104] The researchers in this study were primarily interested in observing how the human microbiome affects and influences the indoor environment as well as other humans sharing that environment.[105] Microbe samples from the skin surfaces of families were compared to surfaces throughout that family's home.[106] Some of the families possessed pets, and in those cases, samples

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96 *Id.* at 6477.
97 *E.g., id.*
98 *E.g., id.*
99 *E.g., id.*
100 *See id.* at 6477.
101 *See* GREGORY DITZLER ET AL., FORENSIC IDENTIFICATION WITH ENVIRONMENTAL SAMPLES 1861 (IEEE International Conference on Acoustics, Speech and Signal Processing, 2012).
102 *See id.*
103 *See* Simon Lax et al., *Longitudinal Analysis of Microbial Interaction Between Humans and the Indoor Environment*, 345 SCI. 1048 (2014).
104 *Id.* at 1048.
105 *See id.*
106 *Id.*

were taken from the pets as well.[107] In total, three dogs and one cat were present across the seven families.[108] Microbe samples were taken from various skin surfaces of the family members and from various surfaces throughout the homes.[109] The researchers compared these samples to different surfaces within the homes in which the respective families lived, as well as to surfaces in the homes of the other families, in order to determine what degree of variance, if any, existed between the microbe communities of the different houses and families sampled.[110]

The researchers found that the "microbial communities of human hands, noses, and bare feet resemble those of home surfaces" in the homes in which the respective humans were living.[111] The researchers also found that "the microbial communities of different houses differed significantly," with the extent of variation depending on the surface sampled, with floor surfaces providing the highest level of variation.[112] Not surprisingly, the researchers found that "humans sharing a home were more microbially similar than those not sharing a home," and that samples with the greatest similarity were those that were taken from the same individual.[113] The researchers found that, although floor surfaces were most diagnostic of microbe diversity, when considering all of the surface samples from a home together, "the family that a sample was taken from was easily predicted."[114]

Samples for this study were taken from the feet, hands, and noses of the humans, and from floors, doorknobs, and light switches in the homes.[115] The researchers pooled samples from each family and used them as "vectors," which were then traced to various surfaces in the home.[116] In this way, the study was more concerned with tracing microbiomes of entire families to homes, rather than microbiomes of individuals to specific surfaces.[117] It is worth noting that the families sampled were ethnically diverse.[118] In one of the "families," the people living together were not genetically related.[119] Two of the people in that family were in a relationship, and they shared more similarities in their microbe communities than did the other two members who lived in different areas of the house.[120] Significantly less divergence was seen in the microbe communities of traditional families consisting of married couples and young children.[121] Further, although far fewer similarities were noted

107 *Id.*
108 *Id.*
109 *See id.*
110 *See id.*
111 *Id.*
112 *Id.*
113 *Id.*
114 *Id.* at 1049.
115 *See id.* at 1048.
116 *Id.* at 1050.
117 *See id.*
118 *Id.* at 1048.
119 *Id.* at 1051.
120 *Id.*
121 *Id.*

between family members and their pets, there were similarities enough to suggest the presence of a microbial relationship between humans and animals sharing the same home.[122]

Three of the families moved homes during the study.[123] This allowed the researchers to sample the surfaces of the homes before the families moved into the homes and after they had been living there for some time.[124] These samples suggested a "rapid colonization of the new home by the microbial signature of the family."[125] The fact that one of the "homes" was actually a hotel room did not affect the results.[126]

This study, while providing less direct relevance to the forensic field than the last study due to the fact that this study was not concerned with matching individuals but rather entire families, nevertheless still pertains to the field of forensic science. The notion that a person can be connected to an object, a place, or even another person by a microbial signature left at the point of contact is further confirmed by this study. The fact that microbe samples were taken from the nose in this study and that similar results were found in the microbial communities of noses suggests that physical contact with the surface may not even be necessary to generate the possibly incriminating connection.[127] As with the previous study, this study concedes that so far little research has been done in this field, and that if the results are to become more widely accepted, more research must be performed.[128] However, the potential applicability of the results of this study suggests that more research should be performed, and that the avenue is perfectly viable and could be very beneficial to forensic science. Yet, it is worth noting that this study itself was more concerned with potential medical applications due to the newly enhanced understanding of the way pathogens interact with the home.[129] This is one of the more recent studies cited in this Note, suggesting that research into the human microbiome is still very much in its infancy and its potential has surely yet to be fully tapped.

C. CORPSE MICROBIOME STUDY

Another study on potential forensic applications of microbe evidence focuses on using microbe data to gather information about corpses rather than using the data to identify potential suspects.[130] This study focuses on observing how the human microbiome changes after the death of the host

122 *Id.* at 1049.
123 *Id.* at 1048.
124 *See id.*
125 *Id.*
126 *Id.*
127 *See id.*
128 *See id.* at 1051.
129 *See id.*
130 *See* Jennifer L. Pechal et al., *The Potential Use of Bacterial Community Succession in Forensics as Described by High Throughput Metagenomic Sequencing*, 128 INT'L LEGAL MED. 193, 193 (2013).

body in order to estimate the time of the body's death.[131] The human microbiome changes throughout its host's life and continues to change after death.[132] Therefore, data on the way changes progress in that microbiome—or necrobiome (a term describing the microbes present on a decaying corpse)—can provide information on the time that the host passed away.[133] For this study, microbe samples were taken from replicate swine corpses (standing in for human corpses) immediately after exposure to the environment and then again at one, three, and five days after the initial exposure.[134] Samples were taken from the mouth and the skin of the corpses.[135] Since bacteria can grow in a wide variety of temperatures, the researchers performing this study assumed a minimum base temperature of 0˚C for their analysis.[136] Using these variables, researchers were able to identify four dominant types of bacteria in each stage of decomposition.[137] Using results from this study, the researchers were able to propose a procedure by which criminal investigators could obtain a microbe sample from a recently discovered corpse, compare the data with recent weather data and known bacterial communities in the area, and obtain a reasonably accurate estimate of the time of death of the individual.[138]

Although the researchers appeared optimistic and confident in their results, they did acknowledge that more research should be performed and more data should be gathered before implementing this procedure in crime labs.[139] They also stated that the methods used to analyze the microbes and the data contained in their DNA requires a high amount of computing power and the expense of implementing these techniques may not yet be economically feasible given that methods already exist to estimate the time of death of a corpse using observations about the state of the corpse and the presence of arthropods.[140] The researchers provide evidence that their method of time-of-death estimation is more accurate than methods currently employed by crime labs, and suggest that even though it may be too expensive at this point, that research should continue to be devoted towards this technique.[141] Although this research does not deal directly with the human microbiome as it has been discussed so far within this Note, it nevertheless deals with an interesting forensic application of microbiology that would follow as a natural byproduct of increased research into the human microbiome.

Research into the microbiome leads naturally to research into the necrobiome. A report recently submitted to the Department of Justice also

131 *See id.*
132 REID & GREENE, *supra* note 1, at 11; *See* Pechal, et al., *supra* note 130.
133 *See* Pechal, et al., *supra* note 130, at 194.
134 *Id.* at 194–95.
135 *Id.* at 195.
136 *Id.* at 196.
137 *Id.* at 197.
138 *Id.* at 202–03.
139 *See id.* at 203.
140 *See id.*
141 *See id.*

investigates the use of microbe evidence as a method of predicting the time of death of a corpse and concludes that this type of evidence provides valuable data that should be used by law enforcement agencies and researched further.[142] The fact that research into the microbiome has potential applications in multiple areas of forensic science only makes the research that much more valuable and worth pursuing.

D. Other Relevant Studies and Potential Applications

Another study suggested that significant variability between individuals exists in the ocular microbiome.[143] Although the potential hypothetical situations in which ocular microbe evidence is relevant in a criminal investigation are few, they are nevertheless possible, meaning that this study is promising. The participants in the study consisted of four white, non-Latino males between the ages of twenty-six and forty-eight years old.[144] The participants were volunteers and none of them wore contact lenses.[145] They were all free from systemic and ocular disease and none had received antibiotic treatments within the past six months.[146] This sample pool is admittedly small and does not accurately represent the population. However, while this would normally be a point of criticism for a scientific study, in the case of potential forensic application, this fact actually boosts the validity of the study's results. The fact that significant variability was found between the ocular microbiomes of these four similar individuals means that even greater variability would potentially exist between the ocular microbiomes of more dissimilar people. These results are encouraging for the potential application of microbiome research in a forensic context, due in part to the small sample size used.

Studies have already demonstrated that research into the human microbiome can be used to identify suspects and estimate the time of death of corpses, but there are even more possible applications of microbiome research that have yet to be explored. Studies have shown that microbiome composition is inherently linked to factors such as age, gender, weight, ethnicity, and other observable traits.[147] Concerning ethnicity and social groups specifically, researchers in Ladakh (a region in India) were able to distinguish between Buddhists and Muslims who had been socially distinct for over five hundred years, but were still genetically indistinguishable, by means of examining the DNA of a microbe in the stomachs of people in that region.[148] Samples taken from fifty patients in the Ladakhi region

142 David O. Carter et al. Characterization of Bacterial and Microbial Eukaryotic Communities (including Fungal) Associated with Corpse Decomposition Using Next Generation Sequencing (U.S. Dep't of Justice, Document No. 248523, 2014).
143 Dong et al., *supra* note 44, at 5408.
144 *Id.*
145 *Id.*
146 *Id.* at 5408–09.
147 Human Microbiome Project Consortium, *supra* note 55, at 211.
148 Wirth et al., *Distinguishing Human Ethnic Groups by Means of Sequences from* Helicobacter pylori*: Lessons from Ladakh*, 101 Proc. Nat'l Acad. Sci. U.S. 4746, 4746 (2004).

enabled researchers to produce these results, indicating that microbe evidence, at least in this specific case, possesses more diagnostic value than DNA evidence.[149] This means that microbe data gathered from crime scenes could theoretically be used to generate a profile in situations in which there is no known suspect. Microbe data could theoretically tell investigators the ethnicity of the perpetrator (or even the social group and association preferences of the perpetrator), the gender of the perpetrator, how old the perpetrator might be, or whether or not the perpetrator is obese.[150] It is true that these facts could be readily obtained by an eyewitness, but microbes may be present when an eyewitness is not; and for that fact alone, microbe evidence is worth researching and developing. This evidence could allow the police to possess a physical description in situations where they would otherwise have very little or no data. This would be invaluable to police forces across the country.

Another physical trait that was found to be inherently linked to microbiome composition was vaginal pH level.[151] Admittedly, this trait would only be useful in a far more narrow set of circumstances than the traits mentioned above, but in a relevant situation such as a sexual assault case, measuring vaginal PH level has the advantage of being more specific than the other traits and could potentially be more diagnostic in applicable situations. For instance, if a suspect is found with microbes that could only have come from a certain female victim's vagina, it is significantly more likely that the suspect is guilty. There has been one study performed concerning the application of vaginal microbe samples in a forensic context.[152] The objective of this study was to use microbe evidence as a means of distinguishing vaginal tissue cells from tissue cells of other areas of the body.[153] The study was performed using vaginal tissue samples from 240 different test subjects with healthy vaginal microbial communities and ages ranging from fifteen to eighty-four years old.[154] However, these samples were obtained through physicians without the informed consent of the patients, so some information was necessarily unavailable.[155] In order to account for this, the study also used samples donated from twelve volunteers, which allowed the researchers to account for other factors, such as menstrual cycle, menopause, recency of sexual activity, and use of condoms.[156] The samples were also compared to other microbiome samples that could potentially be found at a crime scene, including skin from the hands and groin, semen, urine, blood, and feces.[157] Researchers found that

149 *Id.* at 4747.
150 *See* Human Microbiome Project Consortium, *supra* note 55, at 211.
151 *Id.*
152 *See* Corina C.G. Benschop et al., *Vaginal Microbial Flora Analysis by Next Generation Sequencing and Microarrays; Can Microbes Indicate Vaginal Origin in a Forensic Context?*, 126 INT'L LEGAL MED. 303 (2012).
153 *Id.* at 304.
154 *Id.*
155 *Id.*
156 *Id.*
157 *Id.* at 307.

no single microbe marker could be used to determine whether or not the vagina was the point of origin for a specific cell. Instead, by looking at all of the bacterial species contained in the sample and comparing that list to a list of bacterial species known to be commonly found in the vagina or other areas of the body, forensic scientists would likely be able to determine whether or not the vagina was the point of origin of the sample.[158] The researchers admitted that their results do not suggest a definitive test for forensic scientists, but rather suggested that it would be possible to make a determination in most circumstances.[159] They also conceded that more research would need to be performed on the human microbiome before this test could be deemed to be truly diagnostic.[160]

As all of the above-mentioned studies have discussed, the human microbiome's composition is influenced by many factors that could prove diagnostic in a criminal investigation. All of these factors make it worthwhile to pursue research into the human microbiome, particularly into adapting ways to efficiently gather and process microbe evidence to be used in solving crimes and as evidence to be introduced at trial. The human microbiome provides a potential wealth of undiscovered forensic techniques that could be invaluable to law enforcement agencies.

IV. WHY THE AVAILABILITY OF DNA EVIDENCE DOES NOT PRECLUDE THE USE OF MICROBE EVIDENCE

Perhaps the most obvious critique of the choice to invest resources in researching the human microbiome for use in a forensic context is the argument that DNA evidence already provides law enforcement agencies with substantially similar information. Detractors would contend that DNA evidence provides enough information to investigators, making the development of microbiome research both unnecessary and redundant. This Note argues that the human microbiome can potentially provide evidence that is both qualitatively different from DNA evidence and, when it is qualitatively similar to DNA evidence, superior in nature to DNA evidence.

A. SUPERIORITY OF MICROBIOME EVIDENCE

One of the studies discussed above showed that a person could be identified by matching them with samples of microbes from skin left on surfaces touched by that individual.[161] The point could be made that this is the exact purpose for which DNA evidence is already used. However, the researchers in that study make the point that "unless there is blood, tissue, semen, or saliva on an object, it is often difficult to obtain sufficient human DNA for forensic identification."[162] They go on to suggest that since

158 *See id.* at 309.
159 *See id.*
160 *See id.*
161 *See* Fierer et al., *supra* note 80, at 6477.
162 *Id.* at 6479.

microbes are abundant on the surface of the skin, "it may be easier to recover bacterial DNA than human DNA from touched surfaces," while acknowledging that this is only conjecture and that additional studies would need to be performed in order to confirm this theory.[163] However, the mere possibility that there could exist a form of evidence superior to DNA evidence means that research and resources should be devoted to investigating that form of evidence, despite the fact that the research is not currently at the level required for real-world implementation. It is true that collected DNA evidence is highly diagnostic, almost to the point of perceived infallibility, but in reality DNA evidence is not always able to be recovered from crime scenes. The fact that microbe evidence could be present in more scenarios than DNA evidence makes the implementation of microbe evidence a goal worth pursuing.

The researchers in that study even address one of the major, although extremely uncommon, issues with DNA evidence, which is that of identical twins.[164] The researchers note that "even identical twins harbor substantially different microbial communities," meaning that microbe evidence would be probative in the rare situation in which DNA evidence would be completely useless: a case involving identical twins.[165] Although this hypothetical case may sound fantastical, the fact that it could theoretically occur is reason enough to be prepared for it, especially when that preparedness brings with it a host of other benefits to forensic scientists across the nation.

A study focusing primarily on the gut microbiome of identical twins concluded that significant differences existed between the gut microbiomes of each co-twin.[166] This study was performed by comparing the fecal samples of two female, obese, twenty-six-year-old twins who lived approximately five kilometers apart.[167] Neither twin had used antibiotics for six months before the study was performed.[168] Interestingly, researchers found that the twins shared only about 17 percent of microbial DNA in common.[169] In order to verify these results, researchers also took fecal samples from an additional thirty-one pairs of identical twins and twenty-three pairs of fraternal twins.[170] As with the twins who were the main focus of the study, these additional twins were all born in Missouri, were between twenty-five and thirty-two years of age, and had not consumed antibiotics for six months prior to the taking of the samples.[171] The comparison of the samples with these other twins showed that there existed a much greater

163 *Id.*
164 *See id.*
165 *Id.*
166 *See* Peter J. Turnaugh et al., *Organismal, Genetic, and Transcriptional Variation in the Deeply Sequenced Gut Microbiomes of Identical Twins*, 107 PROC. NAT'L ACAD. SCI. U.S. 7503 (2010).
167 *Id.* at 7503.
168 *Id.*
169 *Id.*
170 *Id.* at 7504.
171 *Id.* at 7504–05.

variation rate between people who were not related than between people who were, but there still existed a significant variation rate between the twins themselves.[172] Although the variation between the gut microbiomes of people who were not related was so great that it initially caused the researchers to question the existence of a core gut microbiome, closer consideration determined that there still existed a core microbiome of the gut.[173] Although, as conceded above, the criminal case involving identical twins is exceedingly rare, the fact that the human microbiome appears to offer a reliable way to distinguish between them is promising for criminal investigators. The fact that a scenario is rare does not mean that law enforcement agencies should not be prepared for it. It is true that fecal samples will rarely be obtainable from crime scenes, but the fact that the gut microbiomes of identical twins were found to differ significantly lends additional weight to the claim of the researchers in the study discussed above that identical twins harbor substantially different microbiomes of the skin. While evidence of the gut microbiome is unlikely to present itself at a crime scene, evidence of skin microbes is highly likely to be present. This data shows that microbe evidence can provide valuable evidence that DNA cannot.

As discussed in the previous section, the fact that it could be possible to deduce physical traits of the suspect, such as gender, weight, or ethnicity, from the presence of microbe evidence makes microbe evidence more diagnostic than DNA evidence.[174] The fact that the microbiome is known to change over time is relevant in that it could be possible to deduce an estimate of the age of the suspect from microbe evidence.[175] The strong correlation observed between microbes found on humans and in their living environment suggests that it could eventually be possible to trace a person to places that they had recently visited via a microscopic trail of bacterial evidence left in the person's wake.[176] Indeed, a recent study on the urban microbiome of New York City found bacteria known to be associated with the skin microbiome throughout the surfaces of the subway system, supporting the theory that microbiome data could provide investigators with details about the suspect's environment.[177] None of this information can be supplied by DNA evidence, meaning that microbial evidence will be probative and useful for law enforcement agencies when conducting difficult investigations.

Besides the potential superiority of microbe evidence to DNA evidence in the field of suspect identification, microbe evidence may also be used as a way to discover the time of death of a corpse, as discussed earlier in this

172 *Id.* at 7505.
173 *See id.*
174 *See* Human Microbiome Project Consortium, *supra* note 55, at 211.
175 *See* REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 11.
176 *See* Lax et al., *supra* note 103, at 1049.
177 *See* Ebrahim Afshinnekoo et al., *Geospatial Resolution of Human and Bacterial Diversity with City-Scale Metagenomics*, 1 CELL SYS. 1 (2015).

paper.[178] The same research that can be applied to the human microbiome for the purpose of suspect identification can also be applied to the necrobiome for the purpose of gathering microbe evidence from corpses.[179] Research into the human microbiome has a much wider application to forensic science than mere suspect identification, which is by and large what DNA evidence is currently used for. Microbiome research is still in its infancy. Many applications have yet to be discovered. The known applications alone make microbe evidence worth investing in, but it is important to remember that research into novel concepts often yields unexpected results. For this reason, an investment into microbe evidence should be viewed more as an investment into the general future of forensic science, rather than simply a way to one-up DNA evidence in the realm of suspect identification.

B. Problems with Microbiome Evidence

There are potential issues with microbe evidence that are likely to be illuminated with further research. For example, it is still unknown to what extent sanitizers and antibiotic treatments affect the human microbiome and likewise how they would affect microbe evidence left at a crime scene.[180] It is also still unknown if the increased similarities of microbiomes of people who share living spaces will present undue difficulties in distinguishing microbiomes. As noted in the study comparing the microbiomes of humans to their indoor environments, the microbiomes of two people in a relationship were substantially more similar than the microbiomes of people simply cohabitating.[181] Since that study was not geared towards differentiating individuals, instead observing only how the microbiomes of individuals changed with their environment, it is unknown to what extent the similarity of the microbiomes of people in a relationship would present difficulties when faced with the task of distinguishing those individuals based on microbe evidence alone.[182] Research has also suggested that it is possible to manually alter the human microbiome, although it is still unknown what effect this intentional alteration might have.[183] Research also suggests that it is possible for the function of the microbiome to change based on external stimuli without the composition of the microbiome itself necessarily changing.[184] It is unknown what effect, if any, these types of changes would have on potential forensic applications of microbiome research.[185]

178 *See* Pechal, et al., *supra* note 130.
179 *Id.* at 202.
180 Martin J. Blaser, *Harnessing the Power of the Human Microbiome*, 107 PROC. NAT'L ACAD. SCI. U.S. 6125, 6126 (2010).
181 Lax et al., *supra* note 103, at 1051.
182 *See id.*
183 REID & GREENE, AM. SOC'Y FOR MICROBIOLOGY, *supra* note 1, at 11.
184 *Id.*
185 *See id.*

Many of these unknown variables present serious concerns. If it is possible to completely scrub a crime scene of microbe evidence through the use of a common household disinfectant, then many parties may feel that the usefulness of microbe evidence is significantly decreased, and that it therefore does not warrant investment. However, the fact that it is possible to scrub a crime scene of DNA evidence does not prevent law enforcement agencies from relying on DNA as an evidentiary tool. The truth is that the majority of criminal defendants are not cunning or clever enough to successfully erase their DNA trails, even though it is possible. Additionally, the fact that some are clever enough is just another reason why microbe evidence should be adopted. In today's world, where all research, especially research into the human microbiome (which has fundamentally altered the way scientists view human beings), has global implications, it is important for law enforcement to stay ahead of the curve. Constant integration of new investigation methods will allow law enforcement agencies to stay one step ahead of even the most intelligent criminals. Researchers have suggested that it would be more difficult to erase a microbe trail than a DNA trail, since there is "an abundance of bacterial cells on the skin surface and on shed epithelial cells," and DNA evidence can usually only be culled from a more visible (and thus more easy to erase) source, such as blood, semen, or hair.[186]

Many of the studies performed on the human microbiome carefully noted that participants had not consumed antibiotics within six months of the studies taking place, which tends to indicate that researchers are also concerned about the effects of antibiotics on the microbiome. However, this trend in the studies is also responsible for the general lack of information regarding the effect of antibiotics on the microbiome. Researchers suspect that antibiotics could alter the human microbiome, but they do not yet know in what way the alterations would occur or what effect they would have.[187] One study observed that the vaginal microbiome was highly susceptible to antibiotic treatment, and would shift rapidly over the course of just a few hours when treated with antibiotics.[188] Although studies like this one seem troubling at first glance, they could just as easily prove invaluable in identifying microbe evidence in specific situations. Unfortunately, the scientific community will not know for sure until more research is performed. There is just not enough information to know whether or not the use of antimicrobial agents would significantly affect the use of microbe evidence in a criminal investigation, but even assuming that those agents could be used to destroy microbe evidence, the potential

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186 *See* Fierer et al., *supra* note 80, at 6479.

187 *See* Jose U. Scher, *Intestinal Dysbiosis and Potential Consequences of Microbiome-Altering Antibiotic Use in the Pathogenesis of Human Rheumatic Disease*, 42 J. RHEUMATOLOGY 355, 355 (2015) (speculating that antibiotics could alter the composition of the intestinal microbiome, leading to juvenile idiopathic arthritis).

188 *See* Tina L. Fiedler et al., *Rapid and Profound Shifts in the Vaginal Microbiota Following Antibiotic Treatment for Bacterial Vaginosis*, J. INFECTIOUS DISEASES 13 (Feb. 12, 2015), http://jid.oxfordjournals.org.libproxy.usc.edu/content/early/2015/02/12/infdis.jiv079.full.pdf+html.

benefits of microbe evidence are powerful enough to make microbiome research worth investing in.

Although the studies examined in this paper suggest its unlikelihood, the potential that the microbiome of one suspect could be confused with that of the suspect's loved one, or someone else close to the suspect, is also a legitimate concern. However, if there was any doubt that the microbe evidence was properly linked to the defendant in any given case, then the defense attorney could simply bring up these doubts on cross-examination, which would presumably decrease the weight that the jury would assign to the evidence. Although it should not preclude research into the use of microbe evidence in a forensic context given that the danger of this microbiome confusion appears to be very slim, it is nevertheless a concern that should be addressed if and when it arises.

Even with the unknown variables involved with the use of microbe evidence, it is still worthwhile to invest resources into developing this practice. Even if the only use of microbe evidence was to identify individuals by matching them with microbes deposited at a crime scene—which would be an identical purpose to that of DNA evidence—the fact that microbe evidence could be present when DNA evidence is not would still make research into the human microbiome a worthwhile endeavor.[189] Many criminal investigations rely on evidence of questionable accuracy.[190] With that in mind, any additional evidence that can improve the accuracy of verdicts in criminal trials is a potential boon to the criminal justice system and should be implemented whenever and wherever possible. Even if the presence of DNA evidence might make microbe evidence redundant in some cases, the potential value microbe evidence adds to the cases in which DNA evidence is not present makes research into the human microbiome worth pursuing.

V. THE USE OF MICROBE EVIDENCE AT TRIAL AND THE POTENTIAL LEGAL AND ETHICAL CONCERNS INVOLVED

Since microbe evidence has never been introduced at trial or used in an actual criminal investigation before, it is unknown exactly how the laws of evidence would apply, or what legal and ethical concerns could be brought up in opposition to the introduction of such evidence. Even before the trial phase, it is unknown if the gathering of microbe evidence from individuals, which would be necessary to analyze a sample from a crime scene by comparing it to another individual's sample, would present any legal or ethical barriers. This Section will address these potential concerns that may arise in the future once research into the human microbiome has matured enough for implementation into criminal investigation tactics. No law

189 *See* Fierer et al., *supra* note 80, at 6479.

190 *See* DAN SIMON, IN DOUBT: THE PSYCHOLOGY OF THE CRIMINAL JUSTICE PROCESS 206 (2012).

currently exists addressing the use of microbe evidence in criminal investigations.

A. ADMISSIBILITY OF MICROBE EVIDENCE

The Federal Rules of Evidence in Rule 402 state that relevant evidence is admissible unless the United States Constitution, a federal statute, a rule prescribed by the Supreme Court, or the Federal Rules of Evidence themselves provide otherwise.[191] The Federal Rules of Evidence in Rule 401 state that "evidence is relevant if it has any tendency to make a fact more or less probable than it would be without the evidence; and the fact is of consequence in determining the action."[192] By these rules it seems clear that microbe evidence should be admissible at trial. Rule 403 of the Federal Rules of Evidence states that even relevant evidence can be excluded if its probative value is outweighed by dangers of unfair prejudice, issue confusion, misleading of the jury, cumulativeness, or wasting time.[193] None of these concerns would seem to bar the introduction of microbe evidence. Still, since the Federal Rules of Evidence fail to contain specific guidelines governing this type of evidence, it is more beneficial to consult the ABA Standards for Criminal Justice regarding DNA Evidence, since DNA evidence is similar in nature to microbe evidence.[194] In regards to the admissibility of DNA evidence at trial, the ABA Standards state that the Court can "take judicial notice of facts relating to DNA evidence that are not subject to reasonable dispute," and that expert testimony regarding DNA evidence "should be admissible if based on a valid scientific theory, a valid technique implementing that theory, and testing and interpretation properly applying that theory and technique."[195] These standards could be easily and fairly applied to microbe evidence that is sought to be introduced at trial. Although the science behind the human microbiome may be confusing to the first judges and juries that are forced to sift through microbe evidence, with time it will become a non-issue as microbe evidence becomes more widely recognized. These same concerns are present with the introduction of every new type of evidence. They were likely present the first time fingerprints or DNA evidence were introduced, but those tools have now become widely accepted as part of the criminal investigation process. A case seeking to introduce microbe evidence would require expert testimony, so there is no reason why the *Daubert v. Merrell Dow Pharmaceuticals, Inc.* standard, still widely accepted as the definitive test for admission of scientific expert testimony, could not be applied to expert testimony regarding the use of microbe evidence.[196] In *Daubert*, the Court developed a test for the admission of expert testimony on scientific

191 FED. R. EVID. 402.
192 FED. R. EVID. 401.
193 FED. R. EVID. 403.
194 *See* ABA Standards for Criminal Justice, *DNA Evidence* (3d ed. 2007).
195 *Id.* § 16-5.1 (a–b).
196 *Daubert v. Merrell Dow Pharms., Inc*., 509 U.S. 579, 592–95 (1993).

knowledge or technique that relies on five factors: 1) whether the science can and has been tested; 2) whether it has been subjected to peer review and publication; 3) what the known or potential rate of error involved is; 4) whether there exist any widely accepted standards regarding the technique's operation; and 5) whether or not the technique is generally accepted in the scientific community.[197] This test is flexible and is designed for expert testimony on all kinds of scientific knowledge.[198] The Court intended that the announcement of this admissibility test for expert testimony would allow judges to rule on the admissibility of testimony on new scientific developments as the issues arose in their courtrooms.[199] Since the ruling in *Daubert*, Rule 702 of the Federal Rules of Evidence has somewhat simplified the requirements for admission of expert testimony.[200] The rule has four requirements: 1) the expert's scientific knowledge must help the trier of fact; 2) the testimony must be based on sufficient facts or data; 3) the testimony must be "the product of reliable principles and methods;" and 4) the expert must have reliably applied those methods to the facts of the case.[201] There is no reason why a ruling on the admissibility of microbe evidence at trial should be governed any differently than expert testimony regarding any other scientific development. Although it is true that there does not currently exist enough knowledge regarding the human microbiome to answer some of the questions the *Daubert* factors might raise, that lack of knowledge would simply factor against the admissibility of the expert testimony. A lack of knowledge available on the scientific theory being considered, which would in this case be microbe evidence, would go directly towards the admissibility of the testimony under the factors concerned with whether or not the science has been tested, whether widely accepted standards regarding its use exist, and whether or not it is generally accepted in the scientific community. The flexible test outlined in *Daubert* continues to be applicable.[202]

It is also worth noting that even in a case where a DNA analyst was mistaken in his findings that DNA gathered from physical evidence matched certain people, the First Circuit has ruled that the lower court did not err in allowing the expert to testify.[203] The presiding justice in that case instead stated that the defendant could bring up these challenges, which would then go towards the expert's credibility.[204] To a certain extent, this ruling opens the door for the introduction of microbe evidence at trial. This ruling could mean that even if microbe evidence was not confirmed to be accurate, it could potentially be introduced and would, just like any other evidence, be subject to the defendant's attack on cross-examination.

197 *Id.*
198 *Id.*
199 *See id.*
200 FED. R. EVID. 401–03, 702.
201 *Id.*
202 *Daubert*, 509 U.S. at 592–95.
203 *U.S. v. Shea*, 211 F.3d 658, 668 (1st Cir. 2000).
204 *Id.* at 667.

Although the ruling is not binding in all jurisdictions, the First Circuit's decision is persuasive nevertheless, especially concerning subject matter with little legal precedent, such as microbe evidence.

In a ruling by the Supreme Court, Justice Alito said that an expert statement alleging that a DNA sample, taken from semen contained in a victim's vaginal swab, matched the defendant's DNA profile did not violate the Confrontation Clause, even though the expert did not necessarily know that the sample given to him was from a vaginal swab of the victim.[205] Although this ruling is very narrow, it extends the range of expert testimony on DNA evidence, which theoretically would also extend the range of expert testimony on microbe evidence sought to be introduced at trial.[206] This ruling allows experts to testify that the results of procedures performed by outside laboratories are applicable to the defendant in a particular case without any personal knowledge of the nature of the samples tested by the laboratories.[207] Once again, although this is a narrow holding, it is significant in that it expands the reach of expert testimony on DNA evidence, and therefore would likely expand the reach of expert testimony regarding microbe evidence being used at trial.

B. Issues with the Taking of Microbe Samples

In a study performed on vaginal microbes, it was determined that the same scientific techniques used for DNA extraction could be used to gather and identify microbe evidence.[208] It follows that the ABA standards for collecting DNA evidence from a crime scene could also be applied to microbe evidence.[209] The ABA also provides guidelines for obtaining DNA samples from potential suspects for comparison against samples taken from crime scenes.[210] These guidelines state that a search warrant or judicial order is required before obtaining a DNA sample without the person's consent.[211] Further, there must be probable cause that a serious crime has been committed to obtain a sample from a suspect, along with either: 1) a reasonable suspicion that the person committed the crime, if the test is noninvasive; or 2) probable cause, if the test is invasive.[212] If the person is not suspected of committing the crime, then the order only needs probable cause that a serious crime has been committed and a showing that the sample sought "is necessary to establish or eliminate that person as a contributor to or source of the DNA evidence or otherwise establishes the

205 *Williams v. Illinois*, 132 S.Ct. 2221, 2238 (2012).
206 *Id.*
207 *Id.*
208 Benschop et al., *supra* note 152, at 306.
209 ABA, *supra* note 194, § 16-2.1 (stating that DNA evidence should be collected promptly from the crime scene by a trained forensic investigator and preserved according to written guidelines and with reasonable care).
210 *Id.* at § 16-2.2.
211 *Id.*
212 *Id.*

profile of a person who may have committed the crime."[213] These standards, once again, could easily be applied to the collection of microbe evidence from suspects. In *Maryland v. King*, a Maryland statute requiring the taking of a DNA sample via a swab on the inside of the mouth from every person arrested for a "serious offense" was reasonable and did not constitute a Fourth Amendment violation.[214] This ruling could easily be extended to require a microbe sample from every person arrested. Indeed, a skin swab, which would provide valuable microbe evidence, is much less intrusive than a swab of the mouth. It is true that the human microbiome differs based on the location of the human body that is being sampled, so it is possible that a more extensive procedure may be necessary, but it is unlikely, based on *King*, that any sort of cataloging of microbe evidence would be deemed to be a constitutional violation. For any situation requiring a more invasive test, such as a vaginal swab, it would perhaps be necessary for the police to make a showing of why the evidence was necessary for the specific case. However, it is likely that a woman supplying the police with vaginal microbe evidence would be a victim of sexual assault seeking prosecution of an alleged perpetrator, meaning that Fourth Amendment concerns would be unlikely to be raised. Potential defendants may argue that microbiomes can change over time, meaning that microbe evidence kept on file may not be diagnostic. While this could be true, the fact is that there is still not enough data to say conclusively just how probative or useful a database of microbe evidence from arrestees would be. However, any lack of diagnostic value on the part of this hypothetical database would only serve to help defendants, since less potential evidence would exist with which to convict them.

Some additional requirements of the ABA standards are especially relevant to microbe evidence. A section stating that samples of DNA evidence should be preserved until the prosecutor authorizes their destruction[215] is even more applicable to microbe evidence, since researchers are still trying to obtain information about the human microbiome and the preservation of additional samples could only assist in microbiome research. Researchers have already cataloged and released more than one thousand microbial bacterial reference genomes, but much more research is necessary in order to expand and complete databases on the human microbiome.[216] Samples taken from crime scenes and from individuals suspected of crimes, in furtherance of law enforcement objectives, could serve the dual purposes of assisting law enforcement agencies in solving crimes and assisting researchers by enhancing the total collection of samples available for the purpose of increasing the collective body of knowledge on the human microbiome.

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213 *Id.*

214 *Maryland v. King*, 133 S.Ct. 1958, 1972 (2013).

215 ABA Standards for Criminal Justice, DNA EVIDENCE, *supra* note 194, § 16-2.6.

216 Human Microbiome Jumpstart Reference Strains Consortium, *A Catalog of Reference Genomes from the Human Microbiome*, 328 SCI. 994, 998 (2010).

C. STATISTICAL ANALYSIS ISSUES

One potential issue that could present itself, especially in the first cases in which microbe evidence is sought to be introduced, is the use of statistical analysis. Although statistical analysis can at times be relevant and persuasive, it also has the potential to distract the jury "from its proper and requisite function of weighing the evidence on the issue of guilt."[217] In *People v. Collins*, the California Supreme Court ruled that the prosecutor's use of statistical evidence was inappropriate when it was not based on sound statistical theory and when it had the tendency to confuse the jury and prejudice the defendant.[218] Although this ruling does not preclude the introduction of statistical analysis of evidence, it does provide stricter standards for statistical analysis.[219] This provides a particular challenge for microbe evidence because it is not yet fully confirmed that every human has a unique microbiome, and that those microbiomes are eminently distinguishable from each other. It follows then that the first introduction of microbe evidence will involve some sort of statistical analysis stating the likelihood of the evidence providing a unique match to the defendant. This does not necessarily block the introduction of the evidence, but it is worth noting that the party seeking to introduce the evidence should be careful to make sure that the statistical theory is sound and that it is not stated in a way that would tend to confuse the jury. This should not present a legal issue precluding the use of microbe evidence, but it is nevertheless a pitfall that early adopters of microbe evidence should seek to avoid.

D. RESEARCH ISSUES

Although there appear to be no significant legal boundaries to the introduction of microbe evidence in a law enforcement context, there are some potential issues with the research itself. These issues do not directly pertain to the main focus of this Note, which is the use of microbe evidence as a tool for forensic scientists, but they do bear some relevance and therefore warrant some discussion. In the forum of medical research, the argument has been made that the gathering of microbe samples from objects that someone has touched, rather than the person's body, without the person's permission, is a breach of privacy.[220] Although the overall trend in criminal procedure law in our country makes it unlikely that the gathering of microbe samples from a crime scene would be found to be a violation of privacy, the argument has been made that the wealth of information that could potentially be determined about a person from a microbe sample makes the privacy concerns at stake much more

217 *People v. Collins*, 438 P.2d 33, 38 (Cal. 1968).
218 *Id.*
219 *Id.*
220 Nada Gligorov et al., *Privacy, Confidentiality, and New Ways of Knowing More*, *in* THE HUMAN MICROBIOME: ETHICAL, LEGAL AND SOCIAL CONCERNS 107, 113 (Rosamond Rhodes et al. eds., 2013).

compelling than in other areas of criminal procedure law.[221] Given the potential value that microbe evidence has to law enforcement agencies, it is unlikely that the gathering or analyzing of microbe evidence found at a crime scene will be found to be an unacceptable privacy violation, but it is possible that these privacy concerns could preclude further scientific research that might otherwise be performed on those samples. Some parties have raised concerns that ongoing research into the human microbiome requires researchers as a community to step back and evaluate the role that ethics should play in research on human subjects, and to make ethical research a priority within the community.[222] Some legal scholars have speculated that the wide variety of information that could be potentially exposed about a subject's personal life through microbiome research could lead to insurance and employment discrimination issues, drawing comparisons to the way that research into the human genome sparked similar controversies.[223] Others have raised concerns more specifically about biobanks (repositories of stored biological specimens and associated health data) and their lack of federal regulation, noting that their use is essential to research into the human microbiome due to the fact that many microbe samples are stored in biobanks across the country and used in various research projects regularly.[224] They note that although federal regulations designed to deal with medical research on live human subjects technically apply to biobanks, biobanks were not what the authors of the code had in mind, and therefore the code provides an imperfect fit for biobank regulation.[225] Similarly, other scholars, in anticipation of the potential microbial benefits that may be discovered as research into the microbiome progresses, have speculated on microbe property rights, and to what extent a person possesses legal ownership of their microbiome.[226] These concerns show how the road to increased knowledge of the human microbiome may not be easy. However, as long as studies can be performed on subjects who have given informed consent, there should be no reason why research into the human microbiome cannot progress forward.

E. LAW ENFORCEMENT ISSUES

Some prosecutors may grumble that the introduction of microbe evidence will increase their obligations under *Brady v. Maryland*, a case in which "suppression by the prosecution of evidence favorable to an accused upon request violates due process where the evidence is material either to

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221 *Id.* at 113.

222 *See generally* Rosamond Rhodes et al., *Research Ethics*, *in* THE HUMAN MICROBIOME: ETHICAL, LEGAL AND SOCIAL CONCERNS 128 (Rosamond Rhodes et al. eds., 2013).

223 Diane E. Hoffman et al., *Are Changes to the Common Rule Necessary to Address Evolving Areas of Research? A Case Study Focusing on the Human Microbiome Project*, 41 J.L. MED. & ETHICS 454, 460 (2013).

224 Abraham P. Schwab et al., *Biobanks and the Human Microbiome*, *in* THE HUMAN MICROBIOME: ETHICAL, LEGAL AND SOCIAL CONCERNS 182, 182 (Rosamond Rhodes et al. eds., 2013).

225 *Id.* at 187.

226 Joshua Lederberg, *Beyond the Genome*, 67 BROOK. L. REV. 7, 11–12 (2001).

guilt or to punishment, irrespective of the good faith or bad faith of the prosecution."[227] Prosecutors will argue that defendants will begin to demand microbe evidence in every single case, imposing an unsuitable burden on prosecutors. The response to this argument would be to simply point out the analogous nature of microbe evidence to DNA evidence. In situations where defendants would be entitled to DNA evidence, they would likely also be entitled to microbe evidence. This surely would not present a cause for alarm to any prosecution office concerned with the accuracy of convictions and the interests of justice. It is true that in some cases microbe evidence will have to function differently from DNA evidence, but it is too early to predict just how and when these variances will occur, and it will be necessary to trust in judges and lawyers to resolve these issues as they arise. The introduction of any new form of evidence providing additional data has the effect of simultaneously both convicting and acquitting more defendants than would otherwise have been the case. This is the nature of scientific progress and hopefully enables the American justice system to move closer towards the mythical goal of one hundred percent accuracy. Microbe evidence will help to achieve this goal.

The last concern, but certainly not the least, with the introduction of microbe evidence as a tool for forensic scientists is the additional cost that will be placed upon law enforcement. Law enforcement agencies are government-funded, meaning that any change that could potentially cost large amounts of money to implement may pose a problem, especially a tool that has yet to be fully tested. Researchers have acknowledged that the computing power needed to accurately process microbe data is costly and could be a barrier to both research and potential forensic application.[228] Although politicians, taxpayers, and even law enforcement agencies themselves may initially be reluctant to bear this financial burden, the research shows that the potential benefits outweigh the costs and prove that microbiome research should be pursued so that it can be implemented in a forensic context as soon as possible. With time, microbe evidence will prove to be a formidable evidentiary tool for law enforcement agencies because it will increase the accuracy of convictions and will increase the efficiency with which criminal investigators can obtain a suspect profile and apprehend the perpetrator of the crime. The data that microbe evidence presents is much less subjective than other forms of evidence, such as eyewitness testimony or eyewitness identification, and will therefore improve courtroom efficiency by shortening trials and lessening the burden on the jury. Although it may not initially seem likely, microbe evidence will prove cost-effective over time.

227 *Brady v. Maryland*, 373 U.S. 83, 87 (1963).
228 Pechal et al., *supra* note 130, at 203.

VI. CONCLUSION

Microbes are everywhere. They coat our skin, intestines, breathing passages, and more. All humans carry with them a highly individualized microbiome that is unique to their person. In this way, the human body is more like a coral reef than a single organism, in that it is alive but also serves as a home for countless other organisms.[229] Philosophers have just begun to grapple with the realization that the "self" is actually made up of many organisms.[230] Although it is likely that their conclusion will be that the concept of personal identity should not be changed due to the presence of microbes, the fact that the discussion is even taking place means that the notion of the human microbiome is altering the way we view the world around us.[231]

Although there are studies that suggest that the human microbiome may not provide as much data as other studies suggest,[232] it is nevertheless an unexplored tool that has the potential to provide a new avenue of investigation for law enforcement agencies. Research into the human microbiome is still very young, and although the majority of microbiome research performed thus far has been geared towards the medical field, the forensic applications of this same research are great. Microbe evidence is more readily available at crime scenes and provides more data on potential suspects than DNA evidence, while also fulfilling virtually all the same purposes for which DNA evidence is currently put to use. Microbe evidence has the potential to be very useful for criminal investigators, forensic scientists, and prosecutors. Even potential defendants will benefit from the use of microbe evidence, since it will provide an objective alternative to often unreliable evidence, such as eyewitness accounts. Although some legal scholars have begun to examine the potential applications of microbiome evidence in the forensic context, even going so far as to provide a hypothetical script for qualifying an expert witness on microbial forensics in court,[233] there is still much work to be done before this type of evidence is used practically, both in the field and in the courtroom. Although the research has not yet reached the point of maturity that will enable microbe evidence to be implemented in forensic laboratories, law enforcement agencies should begin thinking about and

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229 REID & GREENE, *supra* note 1, at 3.

230 Nada Gligorov et al., *Personal Identity: Our Microbes, Ourselves*, *in* THE HUMAN MICROBIOME: ETHICAL, LEGAL AND SOCIAL CONCERNS 55, 55 (Rosamond Rhodes et al. eds., 2013).

231 *Id.* at 66.

232 *See generally* Ivan Nasidze et al., *Global Diversity in the Human Salivary Microbiome*, 19 GENOME RES. 636 (2009) (study performed on samples obtained from 120 individuals from eleven countries on five continents on salivary microbes suggests that although differences do exist between salivary microbiomes in different geographic regions, the microbiomes do not vary greatly, although many potential influencing factors were not accounted for in the study); Rajeev Aurora et al., *Contrasting the Microbiomes from Healthy Volunteers and Patients with Chronic Rhinosinusitis*, 139 JAMA OTOLARYNGOLOGY HEAD & NECK SURGERY 1328 (2013) (study showing that microbiomes of patients with chronic rhinosinusitis were not qualitatively dissimilar from patients without the disease).

233 *See generally* Edwin Eugene Stussy et al., *Microbial Forensics: The Biggest Thing Since DNA?*, 51 CRIM. L. BULL., Summer 2015.

investing in microbiome research now, so that when the research has reached the point at which it can be implemented, law enforcement agencies will be ready.