Lending an Ear in the Courtroom: Forensic Acoustics

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Forensic acoustics deals with acquisition, analysis, and evaluation of audio recordings to be used as evidence in an official legal inquiry.

Figure 1. *A typical courtroom, as pictured here, may differ in many respects from venues such as the classrooms and professional conference halls more familiar to ASA members, but acoustical forensic science can play a key role in both civil and criminal legal proceedings.*

Introduction

In most circumstances, the memorable sounds of the world around us include the routine and ephemeral sounds of civilization in our urban or rural surroundings; the sociable speech of friends and coworkers; the pleasurable notes of music; and the occasional barks, chirps, croaks, purrs, and thunderous rumbles of the biophony and geophony. However, there are some circumstances in which the sounds around us become the subject of a law enforcement investigation, an accident review, or some other legal proceeding that ends up in a courtroom. Although most acousticians might reasonably prefer to stay out of a courtroom (**Figure 1**), except perhaps to improve the architectural acoustics of the facility, there are surprisingly many circumstances in which the knowledge of acoustical scientists can be helpful to legal and investigative proceedings.

- Does your coworker's voice mail message confess to a crime?
- Was the emergency alarm actually loud enough to be heard when the engine was running?
- Was that subtle background sound due to a telltale malfunction emerging in your passenger plane's airframe?
- Does that music playing in the bar infringe on a valid copyright?
- Was the threatening message on your voice mail the utterance of Mr. Smith or was it Mr. Jones?

Welcome to the Field of Forensic Acoustics!

Forensic science has become a common subject in the media due to dramatic court cases in the news and the emergence of fictional entertainment series on US television like *CSI: Crime Scene Investigation* and *NCIS* on the CBS network and quasi documentaries such as *Forensic Files* on the TLC and Headline News networks. Even the rather arcane specialty of audio forensics sometimes finds its way into the headlines, particularly in sensational cases. Many people listened to online copies of the 911 call center audio evidence related to the tragic shooting of unarmed black teenager Trayvon Martin in 2012, and recent reports have described the recovery and interpretation of cockpit voice recorder "black box" audio from

Germanwings Flight 9525 that crashed in the French Alps in March 2015. Forensic acoustics comes into play also when there is a dispute about the likelihood that an acoustical product presents a hearing hazard or interferes with the audibility of an aural emergency notification alarm. The domain of forensic acoustics even includes forensic musicology for cases of alleged copyright infringement of musical style and intellectual property (Begault et al., 2014). The impact of forensic musicology was evident in the recent successful litigation award of US$7.4 million in damages a court ruled must be paid by entertainers Robin Thicke and Pharrell Williams to the heirs of the late singer Marvin Gaye.

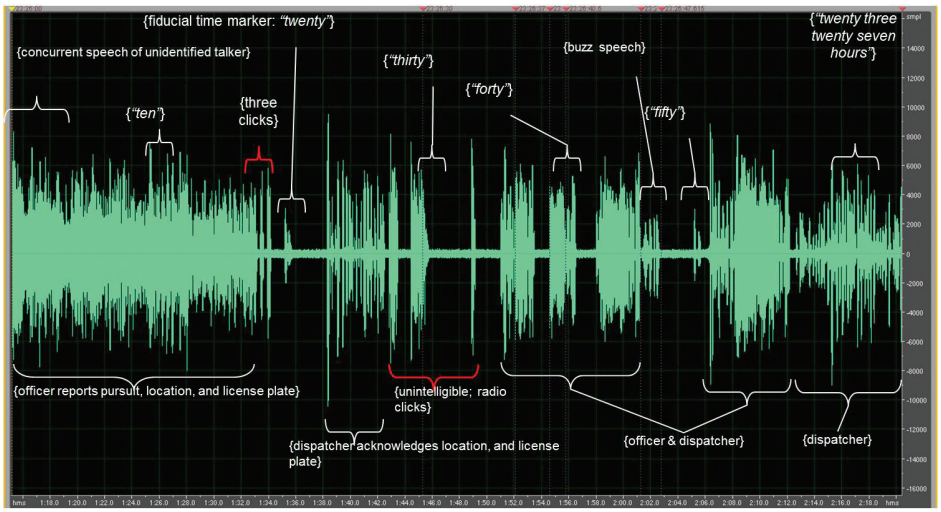

Figure 2. *Example of a forensic audio recording, with manual annotation, displayed with a sound software package. It depicts the amplitude vs. time waveform of approximately one minute of audio recorded at an emergency dispatch center and includes utterances from the land mobile radio system and the local voice of the dispatcher. Figures like this allow experts in forensic acoustics inform and educate attorneys and "triers of fact" (e.g., judge, jury, designated administrator) who are likely inexperienced with forensic audio interpretation.*

Despite its occasional high profile, forensic science has come up against some serious scrutiny and soul searching in recent years, including an influential 2009 report from the US National Research Council that criticized many forensic fields, including audio forensics, for lacking scientific evaluation of reliability and error rates (National Academy of Sciences, 2009). Thus, it is increasingly important that the science in forensic investigations be based on unquestionably objective interpretation and not merely subjective opinions, as has sometimes been the case.

I begin with a description of several key elements, terms, and historical origins of forensic acoustics, primarily in terms of the judicial system in the United States. Next, I consider the challenge of determining authenticity in the age of digital data storage and the corresponding opportunities presented by the increasingly wide deployment of audio recording apparatus in memo recorders, digital cameras, and virtually every contemporary smartphone. Finally, I sum up the field by mentioning areas in which interested members of the Acoustical Society of America (ASA) can get involved to provide new and innovative research that will help advance forensic acoustics.

What Is Forensic Acoustics?

Forensic acoustics, or audio forensics, is the specialty field of acoustics and audio engineering that deals with the acquisition, analysis, and evaluation of audio recordings that are to be presented as evidence in an official inquiry or in a court of law (Maher, 2009). In addition to the analysis and interpretation of tangible audio recordings, forensic acoustics may also treat questions of audibility in the context of litigation or criminal prosecution, such as civil annoyance complaints from an outdoor performance venue, noise levels produced by takeoffs and landings at an airport that violate local statutes, or whether or not a scream or other sound was likely to have been detectable under the circumstances claimed by an ear witness.

Forensic acoustics experts who deal with recorded evidence are most often consulted about three concerns: authenticity, enhancement, and interpretation (Maher, 2010).

Authenticity denotes the acceptance of a recording as being unaltered and true to its source and chain of custody. Criminal and civil cases may hinge on a dispute about the circumstances under which a recording was made and whether audible material in the recording could have been deleted, added, or otherwise edited after the fact (Koenig 1990; Audio Engineering Society, 2000).

Enhancement involves signal-processing techniques that attempt to improve the intelligibility of speech, the clarity of specific background sounds, or the overall signal-to-noise ratio of the recording. Modern enhancement techniques use a high-quality digital copy of the original recording so the original recording medium is used only to obtain the work copy for enhancement (Musialik and Hatje, 2005; Koenig et al., 2007).

Finally, interpretation refers to the description of the acoustical evidence in words, pictures, statistics, and graphs that help address investigative questions, explain the sequence

of acoustical events, and educate the attorneys, defendants, judges, and juries about the meaning, significance, and limitations of the recorded evidence (Audio Engineering Society, 1996; Maher, 2009). **Figure 2** depicts an interpretive annotation that has been added to a time waveform to assist with an investigation.

Forensic Acoustics and the US Courts

Audio forensics traces its origins to the development of portable recording equipment, and examples of the use of audio recordings in US courts date to the mid-1950s. Although the courts generally began to accept the unique importance of audio recordings, especially in cases involving speech obtained via clandestine surveillance or wiretaps, there were significant considerations regarding the Fourth Amendment's protections against unreasonable searches and seizures and concern about the legal admissibility of a recording as being a bona fide representation of the sonic events actually present during the recording process.

The McKeever Case

Among the key cases in the US federal court system regarding the admissibility of audio forensic evidence is United States v. McKeever (1958). In the McKeever case, two defendants were indicted for extortion in an antiracketeering prosecution involving the International Longshoremen's Association. After his indictment, the defendant McKeever had arranged to make a surreptitious tape recording of a conversation he had with an individual who later was a witness in the trial. During the trial, McKeever's defense team sought to challenge under cross-examination the witness' testimony by playing a portion of the clandestine tape recording to refresh the witness' recollection. The court allowed the tape to be played but only via headphones so that the witness could hear it but not the jury. When the defense then sought to have the recording played in court so that the jury also could hear it, the prosecution objected to the use of the tape because its admissibility as evidence had not been established. Specifically, the court had to address the fact that the recording was obtained secretly out of court, the participants were not sworn, the witnesses disputed whether or not they recognized even their own voices, and the legal chain of custody had not been demonstrated to ensure admissibility of the audio evidence.

The court examined these questions and considered a number of prior federal court rulings, then established what the forensic acoustics community now refers to as the Seven Tenets of Audio Authenticity (United States v. McKeever, 1958): "Current advances in the technology of electronics and sound recordings make inevitable their increased use to obtain and preserve evidence possessing genuine probative value. Courts should deal with this class of evidence in a manner that will make available to litigants the benefits of this scientific development. Safeguards against fraud or other abuse are provided by judicial insistence that a proper foundation for such proof be laid."

[…]"A review of the authorities leads to the conclusion that, before a sound recording is admitted into evidence, a foundation must be established by showing the following facts: (1) that the recording device was capable of taking the conversation now offered in evidence; (2) that the operator of the device was competent to operate the device; (3) that the recording is authentic and correct; (4) that changes, additions or deletions have not been made in the recording; (5) that the recording has been preserved in a manner that is shown to the court; (6) that the speakers are identified; and (7) that the conversation elicited was made voluntarily and in good faith, without any kind of inducement."

Since the early 1960s, US Federal Bureau of Investigation (FBI) laboratories have developed techniques and procedures for assessing the authenticity and audible contents of forensic audio recordings obtained from law enforcement investigations, and similar capability has been instituted in other public and private forensic acoustics labs around the world (Koenig, 1990). As described in **Modern Audio Forensics: Digital "Good" and Digital "Bad,"** tenet 3, authenticity determination, has become more difficult in our era of read/write digital recording and computer processing compared with the historic reliance on physical analog magnetic tapes.

Forensic Acoustics and Watergate

A significant turning point in the practice of forensic acoustics in the United States occurred 15 years after McKeever during the Watergate scandal. In 1971, late in his first term in office, President Richard Nixon directed the Secret Service to install audiotaping systems in the Oval Office and the Cabinet Room of the White House, in the president's private office in the Executive Office Building (EOB) next to the White House, and at Camp David, the president's retreat in rural Maryland. The existence of these recording systems was known only to a select group of individuals and to the Secret Service (Nixon Presidential Library and Museum, 2015). President Nixon presumably assumed that the recording system's existence would be of interest to no

one other than presidential biographers and historians after he left office. However, it quickly turned into a political and legal bombshell of historic proportions in 1973 when White House aide Alexander Butterfield revealed during his congressional testimony that there were secret audiotape recordings of conversations between the President and his advisors! After all, this was in the midst of the Watergate investigation and the widespread public concern about the veracity of various White House officials who had testified before Congress and in federal court. President Nixon eventually agreed to release edited transcripts of the various conversations recorded by the secret taping system and later the tapes themselves.

In 1974, interest turned to a particular recording of a conversation between President Nixon and his Chief of Staff H. R. Haldeman recorded in 1972 in the EOB. The investigators were suspicious that the recorded conversation included remarks about the Watergate cover-up, but when the recording was examined, the investigators discovered that 18½ minutes of the recording were obliterated by an unexplained gap consisting of audible buzz sounds but no discernable speech. Investigators suspected that someone had deliberately erased or recorded over that section of the tape to destroy the originally recorded conversation, perhaps with the intention of eliminating incriminating remarks.

John J. Sirica, Chief Judge of the US District Court for the District of Columbia, determined that the potentially altered tape required expert analysis beyond the routine capability of the court (McKnight and Weiss, 1976). He requested that the Watergate Special Prosecutor and the counsel for the president jointly nominate a group of six outside technical experts (including several ASA members) to form a special Advisory Panel on White House Tapes "…to study relevant aspects of the tape and the sounds recorded on it" (Advisory Panel on White House Tapes, 1974).

The Advisory Panel analyzed the physical tape itself and the electrical signals observed on playback and, ultimately of greatest importance, performed magnetic development using ferrofluid to reveal latent magnetic domain patterns on the tape and the magnetization signatures of the recording and erase heads installed in the tape recorders known to be present in the White House. The magnetic development of the tape led the Advisory Panel to the conclusion that the 18½-minute gap consisted of several overlapping start-stop erasures performed with a specific tape recorder available in the White House but not the same device that was used to make the original recording (Advisory Panel on White House Tapes, 1974).

The procedures employed by the Advisory Panel became the standard for audio forensic investigators: (1) examine the physical tape, reels, and structural housing, documenting their characteristics, total length, and mechanical integrity; (2) verify that the recording is complete and continuous and does not exhibit any erasures, splices, or stop/start sequences; (3) listen carefully and critically to the entire tape; and (4) use nondestructive signal processing as needed for intelligibility enhancement.

Modern Audio Forensics: Digital "Good" and Digital "Bad"

For a few decades after Watergate, the discipline of acoustical forensics revolved around two common requests: establish the authenticity of a tape recording and identify the talkers whose utterances are audible in the recording. The work generally focused on analog audio because up until recently, the most frequently encountered recording medium in forensic cases was analog tape.

Analog magnetic tape had a variety of drawbacks including comparatively poor signal quality, stability, and storage capacity. However, as found with the 18½-minute gap in the Watergate tape, the physical medium itself could provide useful forensic information about edits, splices, stop/start/erase sequences, and other alterations affecting authenticity. Our contemporary digital recorders can provide much greater quality, stability, and storage capacity, but the ability to read, alter, and resave the contents of a digital bitstream and even to manipulate the file's date and other file system data without leaving a physical trace in the flash memory or computer disk file has caused serious concern about our ability to authenticate digital audio forensic recordings. If a forensic examiner cannot detect any evidence of tampering, it is still conceivable that the digital data could have been manipulated in some undetectable manner.

One proposed approach to address digital audio authenticity is based on detection of a tell-tale hum in the recording due to interference from alternating current (AC) power leaking into the audio recording (Grigoras, 2005; Cooper, 2008). The electrical network frequency (ENF) of the AC power grid actually varies slightly from its nominal 60-Hz (US) or 50-Hz (Europe) frequency by a time-varying deviation that depends on the instantaneous balance between power generation and consumption on the grid, which fluctuates from

moment to moment. By maintaining a database of the small, instantaneous aleatoric variations of the grid frequency for every date and time, the precise hum frequency present in an evidentiary recording can be matched to the database. The degree to which the recorded hum matches the database pattern can either confirm or refute the claimed date and time that the recording was made. Nonetheless, even in a system involving ENF detection and comparison, an examiner may not be able to rule out the possibility that a clever adversary filtered out the presence of any residual ENF. What's more, a skilled audio forger could conceivably synthesize a fake ENF signal and additively mix it into the evidentiary signal, saving the contrived composite information back onto the digital storage medium as a way to fool a subsequent forensic examiner into believing that the recording is authentic.

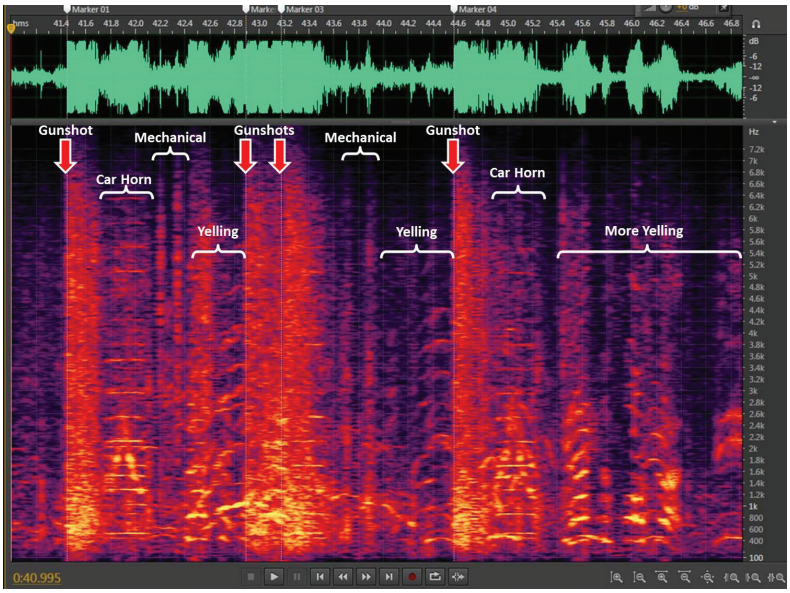

Figure 3. *Example of a time waveform (top) and spectrogram (bottom) depicting an urban surveillance recording containing gunshots, reverberation, mechanical sounds, yelling, car horns, and other background sounds and noise. Several aspects of the recorded soundscape may be of interest in a particular investigation, such as the sequence and timing of audible events and any intelligible speech utterances.*

Many digital audio recording and storage systems incorporate metadata in the digital file format. Metadata may include information about the recording settings, date and time, manufacturer of the device, and its software version. Although metadata can potentially be altered to conceal tampering with the audio data contained in the file, an audio forensic examiner should always review the metadata as part of an authenticity investigation (Koenig and Lacey, 2014).

Other evidence of digital audio tampering can be more subtle, requiring careful consideration of signal continuity and the interpretation of background sounds. An attempt to edit out an embarrassing or possibly incriminating speech utterance, for example, could cause a momentary, but detectable, interruption of the distinctive background sounds present in the original recording (Maher, 2010).

Innovation in Acoustical Forensics

Many key principles of audio forensics have been developed and evolved incrementally over the last 50 years, but certain aspects of the field gain increasing interest from time to time. Here are a few of the current "hot topics" in forensic acoustics that could entice ASA members to join the research effort.

Audio Scene "Fingerprinting"

As noted previously, a forensic recording typically includes prominent foreground sounds that are of interest to the investigation, such as speech utterances, warning alarms, or perhaps gunshots (National Academy of Sciences, 1982; Maher, 2007; Beck et al., 2011). Yet it is the background sounds and environmental acoustics at the recording scene that can sometimes become an even more important part of the forensic evidence. The reverberation and background acoustic emissions can provide valuable information about the authenticity of the recording or help determine the geometric orientation of the sound sources with respect to the microphone. Typical forensic recordings involve a complicated superposition of many different sounds and the effects of microphone and audio encoder peculiarities (**Figure 3**).

In audio forensics, the term acoustical fingerprinting refers to the analysis of background sounds, acoustic reflections, reverberation, and peculiarities of the microphone and recoding system that are detectable in the evidentiary recording (Alexander et al., 2012; Moore et al., 2014). Because many common consumer recording devices include automatic gain control and perceptual audio coding/data compression algorithms intended for speech signals, additional research is needed to understand the degree to which the acoustical surroundings and the characteristics of the recording microphone and digital audio-coding algorithms can be derived from the stored audio recording.

Proliferation of Personal Audio/Video Recording Devices

Technology for portable audio/video recorders has progressed to the point that audio forensic evidence from a crime scene may come from one or more mobile smartphones or cameras carried by journalists or bystanders, security surveillance systems, dashboard-mounted recorders in police cars, and, increasingly, pocket-sized personal video

recorders clipped to the vests of law enforcement officers to document their interaction with the public. As recorder costs continue to decrease, it seems inevitable that more and more investigations will include evidence obtained from these portable devices and dashboard recorders (McGinty, 2015).

The ubiquity of audio recording devices will require an emerging specialty in handling, searching, and analyzing the potentially huge number of recordings available from a public incident that leads to a forensic investigation. The investigative challenge that occurred after the 2013 Boston Marathon bombing involving dozens of surveillance recordings and hundreds of digital photos taken by smartphone and camera-toting bystanders near the finish line provides a glimpse of what is likely to occur in future incidents involving video, audio, and still photo evidence (NOVA, 2013).

Transportation Accident Investigations: The Cockpit Voice Recorder

Because commercial aircraft accidents are so remarkably infrequent, aviation regulatory agencies can afford to spend substantial resources to investigate the cause of accidents when they do occur. Arguably the most important development in accident investigations today is the invention of the flight data recorder (FDR) and cockpit voice recorder (CVR) equipment required on all civilian commercial passenger flights, large private jets, and many military flights, the so-called "black boxes" (National Transportation Safety Board, 2015).

Originally developed using special fireproof magnetic tape, contemporary FDRs and CVRs now record in digital form using nonvolatile solid-state memory. FDR systems on contemporary airliners can record hundreds of flight parameters, actuator positions, and sensor readouts every second, with memory capacity for up to 25 hours. Yet, even with the plethora of flight data, the acoustical information from the CVR is often indispensable for accident investigators to piece together what happened leading up to the accident.

CVRs capture four separate monophonic channels: the pilot's headset microphone, the copilot's headset microphone, a cockpit area microphone (CAM) mounted in the cockpit's ceiling panel, and the fourth channel that often is used to record the intercom communications between the pilots and the flight attendants. Modern CVRs record up to 120 minutes of audio in a memory buffer loop, sequentially overwriting the oldest data with new data. Thus, in the event of an accident, the audio forensic examiner will have a recording containing the sounds from the 2 hours preceding the crash (National Transportation Safety Board, 2007).

Analysis of the four audio channels of CVRs primarily involves transcribing the spoken words of the pilot and copilot, and any other utterances by members of the crew. In addition to the flight crew's speech, the microphones can also pick up nonspeech sounds that can be very important to accident investigators. Engine sounds, airframe vibrations, avionics audible warning alarms, and sounds of cockpit intrusions or other commotion may all have significance to the investigation. For example, the March 2015 demise of Germanwings Flight 9525 in the French Alps has been attributed to deliberate action by the copilot reportedly based in large part on preliminary evaluation of the CVR evidence. What's more, even the sound of the pilots' respirations can give information about the flight crew's health, state of alertness, and level of anxiety or agitation (Stearman et al., 1997; Byrne, 2002; McDermott, personal communication).

CVR systems are typically activated automatically whenever the aircraft is powered up, whereas the FDR systems collect flight data only from the point at which the plane becomes airborne. This means that the CVR may contain important information about flight crew checklist completion, preflight discussion, and similar audio information obtained before takeoff that isn't covered by the FDR information (McDermott, personal communication).

Assessing the Fidelity of Audio Forensic Findings

Audio forensic findings that will end up in court are subject to the same validity considerations used for other types of scientific expertise before the information can be stated in the courtroom. In 1993, the US Supreme Court affirmed in Daubert v. Merrell Dow Pharmaceuticals, Inc., that under Rule 702 of the Federal Rules of Evidence (which covers both civil trials and criminal prosecutions in the federal courts), "The Rules—especially Rule 702—place appropriate limits on the admissibility of purportedly scientific evidence by assigning to the trial judge the task of ensuring that an expert's testimony both rests on a reliable foundation and is relevant to the task at hand" (Daubert v. Merrell Dow, 1993). Assessing the reliability of audio forensic opinions can be a challenge. Unlike DNA comparisons that can be expressed in a formal statistical sense, a forensic acoustics question such as "Is the utterance present in the evidentiary recording the voice of Suspect A?" traditionally has not been amenable to having a strong statistical basis for the opinion. Due to growing judicial skepticism about the scientific basis for almost all forensic testimony in fields ranging from fingerprints and bite marks to handwriting and carpet fiber comparisons, the 2009 report by the National Academy of

Sciences pointed out many areas of concern (National Academy of Sciences, 2009).

For example, voice comparison is a common and important forensic request. An audio recording contains an utterance that the prosecution claims is the voice of the defendant while the defense denies that allegation and claims that the recorded speech was not the voice of the accused but was uttered by someone else. For many years, the common approach was for an expert in speech analysis to employ the aural-spectrographic method, which entails recording the defendant reading a script version of the words spoken in the evidentiary recording. The expert then compares the sound and the visual spectrogram of the evidentiary recording and the defendant's "exemplar" recordings and renders an opinion regarding the degree to which the defendant's exemplar recordings match the evidence. The problem is that the method of "matching" the recordings has traditionally been highly subjective and therefore subject to mistakes and unconscious bias (Bolt et al., 1970; National Academy of Sciences, 1979; Poza and Begault, 2005).

Due in large part to the increasing use of statistically strong DNA evidence in crime investigation, the acoustical forensics field has motivation to move toward the use of likelihood ratio (LR) calculations as a way to deal systematically with the uncertainties present in acoustical comparisons (Morrison, 2011). The LR is a way to consider two competing hypotheses pertaining to a particular event by assessing the probability of an observation of the event given each of the hypotheses (Perlin, 2010; Lindley, 2014). Specifically, the LR is the probability of an observation being made given that the suspect is, in fact, the perpetrator (the prosecution hypothesis) divided by the probability of the same observation being made but that the perpetrator is, in fact, someone other than the suspect (the defense hypothesis).

$$\mathrm{LR} = \frac{\mathrm{Pr}\{\mathrm{Observed\_Event} \mid \mathrm{Prosecution\_Hypothesis}\}}{\mathrm{Pr}\{\mathrm{Observed\_Event} \mid \mathrm{Defense\_Hypothesis}\}} \qquad (1)$$

Consider the hypothetical situation in which a particular bootprint is observed at a crime scene and a suspect is found who is wearing boots that "match" the observed print to a reasonable degree of scientific certainty. The prosecutor's hypothesis is that the suspect is the perpetrator, so the numerator of the LR has probability 1. In other words, if the prosecution hypothesis is correct that the suspect was at the scene while wearing the boots, the probability is 1 that the particular bootprint would be observed. Meanwhile, the denominator addresses the defense hypothesis that the bootprint was left by someone other than the suspect, which would depend on the probability that someone else with the same size and type of boots could have left the print at the crime scene. If only 1 person in 100 owned that particular size and type of boot in the local population, the naive probability of observing the bootprint if someone other than the suspect was at the crime scene would be approximately 1/100, and so the LR in this example is 1/(1/100) or 100. Note that the LR is not in and of itself an objective way to establish guilt. The LR formulation needs to be interpreted as the statistical increase in belief in a match to the suspect based on the particular evidence. Thus, the LR must be multiplied by the "odds of guilt" that are established based on other evidence and testimony in the case (Perlin, 2010).

A common difficulty for forensic examination is that the evidence is distorted, noisy, smeared, or otherwise incomplete. Determining the degree to which a smudged fingerprint matches a particular record in a fingerprint database or the degree to which a recorded utterance matches an exemplar recording ultimately requires discussion of the scientific models and assumptions used.

Conclusions

Forensic acoustics is an interesting specialty field that lies between the scientific world and the legal world. Although the world of science is accustomed to the process of developing new theories and practical techniques that are gradually tested, refined, and modified incrementally through new experiments, publications, and peer review by fellow scientists and engineers, the legal world revolves largely around precedent and the need for judges and juries to make final decisions in a reasonable and quick manner. Members of the ASA are encouraged to become involved in improving the reliability and flexibility of acoustic forensic science, thereby enabling law enforcement, judicial, and accident investigation professionals to work with increased scientific assurance and confidence.

Biosketch

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