

A History of the Forensic Applications of Mass Spectrometry

1. Introduction

The field of forensic science has been routinely slower than other disciplines to adopt cutting edge techniques, but before the 1990s mass spectrometry has been the exception, rather than the rule, to this trend. As the techniques and capabilities developed, crime labs worked hand-in-hand with the major universities that could afford the newest mass spectrometers and help solve all manner of cases. Mass spectrometry has long held respect in the forensic community and it is widely considered one of the gold standards of instrumental analysis (1,2). In the last few decades, however, one could argue that the forensic community is less aggressively pursuing the latest technological advances in mass spectrometry. Although researchers in academia are quick to develop forensic applications on the latest MS platforms, the adoption of new technologies such as tandem MS into routine casework has proven quite sluggish. The slow acceptance of modern MS technologies is probably caused by a number of factors, not least of which are 1) the lack of time that forensic practitioners have to seek out and test new technologies, 2) the lack of resources for purchasing new technologies, 3) the lack of understanding or appreciation of new technologies because of the historic lack of post-graduate education in the forensic sciences, and 4) the lack of precedent for using new technologies as evidence in court. Only when a technological development is so novel, powerful or has such high-impact will the forensic community rush to adopt it. Such a trend was observed with the advent of GC/MS and LC/MS in the 1970s and 1990s, respectively.

The histogram in Fig. 1 shows the number of publications per year containing the research topic 'Forensic Mass Spectrometry' using SciFinder Scholar 2007 (searched on May 30, 2009) and reflects the growth in the forensic applications of this technology. The years 1969–1990 show a slow but steady increase in the number of publications, which is strongly correlated to the commercial availability of hyphenated gas chromatography-mass spectrometry (GC-MS) systems. From 1990 onwards, the rapid growth can largely be attributed to the commercial availability of hyphenated liquid chromatography-mass spectrometry systems (LC-MS) and to the development of commercial tandem mass spectrometry (MS/MS) instruments.

2. Principles

Forensic chemistry is defined as the study and practice of chemistry applied to criminal and civil laws.

The job of a forensic chemist usually involves classifying evidentiary material into legally relevant groups (e.g., controlled substance or not) followed by subclassification and individualization (e.g., for paint chips from a hit and run). Ideally, outcomes involving individualization should be accompanied by some measure of confidence or uniqueness to assist the court in reaching conclusions about the evidence. However, numerical measures of confidence are actually very rare in most current crime laboratory reports. Instead, today's forensic chemist accomplishes the characterization of physical evidence through the use of presumptive and screening tests – such as color tests, macroscopic and microscopic examinations, microcrystalline test, thin layer chromatography, UV/Vis absorbance etc.–followed by confirmatory tests such as Fourier-transform infrared spectroscopy (FTIR) and gas chromatography/mass spectrometry (GC-MS). Confirmatory analysis implies that the confidence level is close to 100%, but analysts and lawyers usually avoid splitting hairs over the actual meaning. Because of the combination of benefits of mass spectrometry (MS)—selectivity, sensitivity, limits of detection and reliability—MS garners a high level of respect and confidence in the forensic community. The relationship between the mass spectrometry community and forensic science has witnessed a long courtship, but both fields have come a very long way in the last century. This short history attempts to provide the most significant developments in the applications of mass spectrometry to the forensic sciences, with a focus on seminal publications and court precedents.

2.1 Drugs and Toxicology

Mass spectrometry has found widest application in the analysis of drugs, drug metabolites and drug paraphernalia (see Chapter 8 (Volume 4): *Drugs of Abuse in Blood, Urine*). The mass spectrometry community started thinking about the analysis of organics and mixtures around the mid-1950s (3,4). There is very little data regarding the use of MS in court cases or in study of illegal substances until the late 1960s. The reasons for this apparent lack of data are twofold. Although mass spectrometers were commercially available from the mid 1940s, they were big, expensive, usually-customized and difficult to operate (5). There was little guidance for interpreting spectra; these instruments were therefore not strong candidates for routine lab use. Secondly, the United States government did not have legislation in place to classify controlled substances until 1970, making drug trafficking prosecutions extremely rare. The availability of smaller, cheaper, easier-to-use, and computer-controlled instruments and the passage of the controlled substance act paved the way for drug analysis and research using MS. In 1968 and

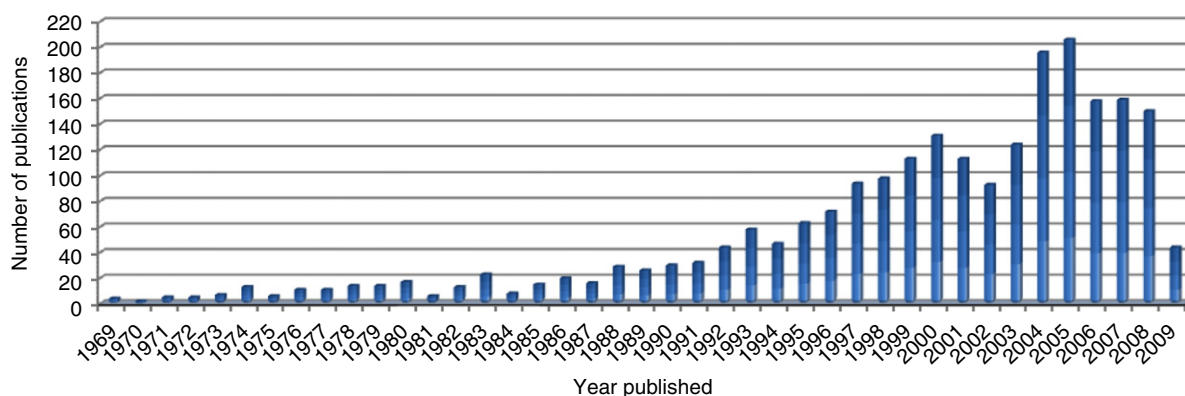


Figure 1 Histogram showing the number of publications per year containing the research topic ‘Forensic mass spectrometry.’ The total number of hits for the search topic as entered was 2290. Search performed using SciFinder Scholar 2007 on May 26, 2009.

1970, Bellman and coworkers at the FDA reported on the analysis of several hallucinogenic drugs using an Associated Electrical Industries (AEI) MS-12 mass spectrometer (6–8). These early applications included LSD, mescaline, psilocin, and psilocybin, among others.

In 1970, Althaus *et al.* reported on the use of GC/MS system at MIT to detect Darvon in stomach contents to solve a drug overdose case (9). The case was apparently solved in about 1 day—a far cry from today’s backlogs—but admittedly took a large team of mass spectrometry experts at MIT to complete. By 1971, Fales’ group at NIH had solved more than 100 overdose cases using GC/MS (10), including the analyses of blood serum and stomach contents. In 1972, Skinner *et al.* reviewed the status of GC/MS for forensic toxicology (11). In 1973, Saferstein and Chao reported on the use of chemical ionization to analyze drugs and drug mixtures (12), which was made possible thanks to the introduction of the technique by Munsen and Field in 1966 (13). In 1974 Catherine Fenselau provided a review of gas chromatography mass spectrometry that included many forensic applications (14 and see this volume, *Henry Marshall Fales, Catherine Clarke Fenselau, Frank Henry Field, and Milam Stephen Burnaby Munson*).

In a 1972 article that was far ahead of its time, Green showed the potential of mass spectrometry to identify drugs from the headspace of drug samples, in *pseudo* real-time, with no sample preparation (besides dissolution in acid or base) (15). He even showed the ability to detect alcohol in circulating blood *in vivo*! The field of ambient sampling MS (16) has recently witnessed an enormous resurgence following the introduction of DESI (17) and DART (18) in 2004 and 2005, respectively.

Table 1

Distribution of case types of the first, somewhat experimental, year of operation in 1973 of a mass spectrometer in the Home Office Central Research Establishment in Birmingham, UK

Distribution of case types

Type	Number
Illegal possession of drugs	59
Suspicious death	47
Explosives	18
Arson	17
Miscellaneous	10
Administration of noxious substance	8
Driving under the influence of drugs	7
Malicious damage	7
Documents	4
Biology	2

Adapted with permission from Zoro and Hadley (19).

In 1976, Zoro and Hadley reported on the workload of the first mass spectrometer operated in a forensic setting during its initial year of operation in Birmingham, UK in 1973–74, as shown in Table 1 (19). The details of the first mass spectrometer are not provided in Zoro and Hadley’s article, but they do mention that at the time of publication (1976) they and the other home offices had a total of nine mass spectrometers in operation, most of which were VG Micromass 12 F instruments. One suspects that a typical forensic lab polled today would report a similar distribution of case types. In most crime labs,

drug cases and toxicology/suspicious death cases still outnumber most other types of analyses by MS, although the absolute numbers are typically at least an order of magnitude larger than the 60 cases per year reported in 1976.

In 1977, mass spectrometry was admitted as evidence in a case involving the detection of a pesticide known as TCDD in animal tissues from the Siuslaw National Forest. The experiments were performed by the EPA (20). The following year, a judge ruled to allow the test results of mass spectrometer as evidence in a capital murder case (21). In the same year (1978), results from GC/MS were admitted in a high priority case involving the American Meat Institute (22). The concern was whether bacon that contained elevated levels of nitrosamines was considered adulterated or not. Mass spectrometry was used in this case because it “is widely regarded as the best available technology, and is deemed to be accurate and reproducible at levels at 10... (parts per billion) or more” (22).

Another important case took place in the 1970s. It was discovered that Tris, a common flame retardant used on children’s pajamas, was also a carcinogen. When first presented with these data on April 1977, a five-member federal commission ruled that this chemical should no longer be used. However, they did rule that with repeated washings Tris-treated clothing could be safely worn and no requirement was made of manufacturers to repurchase the clothing. This ruling was then overturned thanks to the use of negative chemical ionization mass spectrometry, which showed that the Tris metabolite, dibromopropanol, could be found in urine samples from children wearing the treated pajamas (23). A very comprehensive review on urinalysis by probation officer Bigger in 1979 briefly discussed mass spectrometry and provided a couple of examples in the references (24). Bigger admitted that although mass spectrometry had some admirable benefits, such as being ‘the most sensitive and specific technique available,’ that it was too expensive and too slow to be commonplace (24). However, mass spectrometers were in quite high demand at the time. In 1973, a report appeared in the *Wisconsin Law Review* following a survey of drug testing procedures and qualifications of analysts at 100 crime labs (see Table 2) (25). Although mass spectrometers were identified as the most desired piece of equipment, *only two laboratories had one* and only nine labs said they would want one, even if funds were available.

2.1.1 Marijuana. Marijuana, containing the main psychoactive compound Δ^9 -tetrahydrocannabinol (Δ^9 -THC), is currently the most widely used illicit drug in the United States. According to the National Survey on Drug Use and Health, 97 million Americans aged 12 and older have tried marijuana at least once (26). Most laboratories that participate

Table 2

Results of 37 respondents of a survey of 100 crime laboratories in 1972. The laboratories were asked to list their current (or on order) equipment and if money was available, to identify what additional instruments they needed. (19)

Instrument	# Available	# Desired
Gas chromatograph	71	6
Ultraviolet spectrophotometer	55	4
Infrared spectrophotometer	47	2
Melting point apparatus	41	1
Spectrophotofluorimeter	10	4
X-ray diffraction	7	3
Nuclear magnetic resonance spectrometer	1	6
Gas chromatograph–mass spectrometer	2	9
Polarizing microscope	5	0
Chemical microscope	1	0
Emission spectrograph	4	0
Stereo microscope	20	0
Microscope	18	0
Differential thermal analyzer	1	0
Polarimeter	0	1

in workplace drug screenings conduct more GC/MS assays for 11-nor-9-carboxy- Δ^9 -tetrahydrocannabinol (carboxy-THC), the major metabolite of THC, than any other metabolite. A blood or urine test can readily show this metabolite in users for up to 4 weeks after their last contact (1). The long-standing presumptive test for Δ^9 -THC is the classic Duquenois–Levine color test, which may be performed in combination with thin-layer chromatography (27). However, many of those convicted for possession or dealing marijuana filed appeals due to the test’s inability to distinguish between *Cannabis sativa* L. and *Cannabis indica* (28,29). The argument was that under US law in the early 1970s, only *C. sativa* L. was listed as a narcotic. However, the law was later modified because there was essentially no difference between the two in terms of THC abuse (30).

In the 1970s, many labs would only perform the Duquenois–Levine color test and perhaps TLC, and such presumptive tests were often appealed after conviction (31). To this day, SWGDRUG guidelines still permit a combination of TLC, the color test, and microscopic/macrosopic examination to meet the minimum requirements to confirm *Cannabis* when botanical features are present (32). When botanical features are not observable, or when paraphernalia are tested, most labs are required to resort to liquid

extractions or swabs followed by GC/MS to confirm the presence of THC or cannabinoids (32).

In 1965, Budzikiewicz and coworkers (33) were the first to study the cannabinoids using mass spectrometry. They systematically explained the major fragmentation pathways for most of the major cannabinoids, including THC. Whereas many groups around this time were using GC, HPLC and TLC to study cannabinoids ratios for phenotyping, sourcing and activity etc. (34–37), the next mass analysis after the Budzikiewicz work probably didn't take place until a Swedish team developed a GC/MS assay for Δ^9 -THC in human blood in 1973 (38). Through this method, they were able to accurately measure Δ^9 -THC in blood plasma of persons who had smoked cannabis down to levels of one-half billionth of a gram (38). Because mass spectrometers were more commonly used by the end of the 1970s, more groups were studying the cannabinoids using this technique in the last part of the decade (39). GC/MS is now a routine method for identifying THC, cannabinoids and synthetic analogs such as 'spice' in drug seizures (40–43), and LC-MS/MS is common for identifying and quantifying the metabolites of cannabinoids in human urine (44,45).

2.1.2 LSD and other psychoactive drugs. Lysergic acid diethylamide, LSD, was first synthesized by Albert Hofmann at Sandoz Laboratories on November 16, 1938. However, it wasn't until accidentally absorbing a small quantity through his fingertips 5 years later, on April 16, 1943, that its psychedelic properties were accidentally discovered. This drug was thought to be a powerful psychiatric tool by Hofmann who 'couldn't imagine anyone using it recreationally' (46). LSD was probably first examined with a mass spectrometer by Bellman in 1968 (6) and Nigam and Holmes in 1969 followed by several other studies in the early 1970s (47–51). The earliest court cases involving LSD probably occurred in the late 1960s when TLC was the typical method of choice for confirming LSD (52). Similar cases often involved defendants selling to undercover agents (53). Although some early cases questioned the fact that hallucinogenic d form of LSD was not specifically identified in TLC and UV-Vis or FTIR analyses, the language in the federal and individual states' controlled substances acts were largely modified around 1970 to include the various isomers and analogs of LSD as equally punishable (54). However, the earliest application of GC/MS to confirm LSD in a court case was a DEA case in the mid-1980s (55). The drug is very difficult to detect in biological fluids because the effective dose is so small. However, GC/MS of solvent extracts is most commonly used to confirm the presence of LSD and synthetic analogues in seizures (56), and LC-MS/MS can be used to analyze SPE-extracted biological samples.

2.1.3 Cocaine. In the United States alone, more than 34 million Americans admit to trying cocaine or its adulterants at least once in their life (26). Cocaine was first isolated by the German chemist Friedrich Gaedcke in 1855 (57). The study of cocaine continued thereafter with its long history of debatable medicinal uses as a local anesthetic. The popularity of this drug was enhanced by the fact that it was not classified as a controlled substance until the passage of the Comprehensive Drug Abuse Prevention and Control Act of 1970. Until that point, the use of cocaine was quite open and there were very little criminal charges placed on those using or dealing the substance.

Although Djerassi and others had analyzed various tropane alkaloids using MS in the 1960s and early 1970s (58–61), among the first to study cocaine itself were Fales and coworkers in 1971 (10,62), Suzuki *et al.* (63) in 1973, Safferstein and Chao (12) in 1973, Kirchgessner *et al.* (64) in 1974, and Jardine and Fenselau in 1975 (65). By the end of the 1970s, more than a dozen groups had contributed to the analysis of cocaine and its metabolites in bulk samples, plant matter, human tissues, and urine. Kondrat and Cooks were credited with being the first to perform tandem mass analysis on cocaine in 1978 (66, see also this volume, Carl Djerassi and R. Graham Cooks).

After the Controlled Substances Act of 1970 was passed, there continued to be arguments over whether d-cocaine was equivalent to l-cocaine, similar to the arguments seen with chemical variants of marijuana (67) and LSD. Appeals in such cases were typically denied (68). In other instances, when the prosecution did not perform enantiomer discrimination tests, it was common to prosecute the defendant with either the intent to deliver l-cocaine or the intent to possess l-cocaine (69). In effect, this was stating that whether or not the defendant possessed the specific enantiomeric species that is listed as illegal, the courts believed that the defendant possessed and intended to sell controlled substances. Most of this confusion and need to discriminate the d- and l-isomers resulted in the limited use of GC/MS to confirm cocaine during this period.

The two tests most commonly employed by chemists to discriminate between the two forms were a mixed melting point test (70) and a polarimeter test (71). The polarimeter test was much preferred because the defendant witnesses would ridicule the prosecution's witnesses if the sample did not melt at exactly 215 degrees centigrade (70). Another unfortunate way by which a prosecution's expert witness statement has been discredited is when the chemist erroneously reports that there are two isomers of cocaine when there are actually eight (72). Other trivial attempts to dismiss obvious law breakers by attacking expert witnesses were common occurrences. This debate was resolved in the early 1980s when it was pointed out that d-cocaine was not only exceptionally difficult to

make but that it had also never been seen apart from l-cocaine (73). The expert witnesses in the case highlighted the fact that no one has ever reported finding a specimen of d-cocaine (73). Analysts no longer have to identify the isomers of cocaine, which makes FTIR and conventional GC/MS perfectly adequate for confirmatory analyses.

2.1.4 Heroin. The history of mass analysis for heroin is similar to that of other scheduled drugs. The first reported analyses can be traced to articles in the early 1970s, for example, by Fales' group at NIH (10), Saferstein and Chao (12) at the New Jersey State Police, and Jardine and Fenselau (65) at Johns Hopkins School of Medicine. These studies included EI and CI spectra and presented the fragmentation spectra or most abundant fragment ions for many morphine analogs such as codeine and acetylmorphine. In an appeal case in 1975, the defendant's lawyer offered an expert who questioned whether GC-MS, alone, was enough to confirm the identity of heroin in a certain case. Although the analyst indicated that he would have preferred to have a spectroscopic method like FTIR to backup the GC-MS results, the GC-MS results were accepted (74). This case raised an interesting question about one expert witness questioning the data analysis of another expert witness. The court held that whereas a direct question posed from one expert as to the qualifications of another expert would have been improper, it was acceptable for the two experts to disagree on the conclusions drawn from a test.

2.1.5 Urinalysis of athletes – human and equine. At a time when society puts enormous pressure on athletes to perform to inhuman levels, drug testing has had to evolve to detect the newest designer drugs. Back in 1979, when there was much less variety in performance-enhancing drugs, Gideon Ariel, the chairman of biomechanical research for the US Olympic Committee, said, "I know that practically all the American Olympic team qualifiers in many events – weight events, jumping, sprint – use steroids. 'If you don't use them, you don't make the finals.' That's the common belief" (75). Currently banned substances include a huge array of chemicals and substances, even though many of them, like alcohol and marijuana, have questionable beneficial effects on performance in sporting events (76).

The earliest general screening of urine samples was done at the Winter Olympic Games in Grenoble, France, and Summer Olympic Games in Mexico City in 1968 (77). This was instituted in response to an incident at the 1960 Rome Olympics when a Danish cyclist collapsed, suffered a fractured skull, and died due to the amphetamine Ronicol given to him by his coach. This was just the first of many incidents that were evidence of widespread drug abuse in sports.

The origin of what became an epidemic is believed to be the performance of three US weightlifters who broke multiple world records while on the steroid Dianabol (78). Though some viewed 1968 doping controls as a trial project, methodical doping controls that tested all sports at the Olympic games took place at Munich in 1972 (see Fig. 2 (79)). It was at this world gathering that mass spectrometry was introduced in order to identify the doping substances. Since that time, MS has contributed greatly to the quality of testing athletes. In the 1970s and 1980s, there continued to be countless athletes who tested positive for doping despite the possible consequences of being permanently disqualified (78). The potential for world fame and monetary gain pushes many athletes of today to look for the newest designer drugs in hopes that their use will evade detection, being years ahead of the current testing methods.

Overall, worldwide drug testing has grown exponentially since the first application of gas chromatography-mass spectrometry (GC/MS) in the 1980 Olympic Games in Moscow, Russia (78). Interestingly, racehorse drug testing far predates that of human testing. According to Tobin (80), equine drug testing was established around 1903, more than six decades before human testing first occurred. Equestrian urine samples tainted with doping agents have been the subject of court cases since the late 1940s (81–83), presumably because of the far greater profits there were to be made in horse racing. Urinalysis by GC/MS has also been used to screen employees and soldiers employed by the US Government, though perhaps not preceding the wars before the 1980s. It is well known that in Vietnam and before, soldiers were often deliberately given drugs such as amphetamines, barbiturates, heroin, marijuana, and other stimulants (84,85). After Nixon and Congress made changes to the law in 1972 with the Drug Abuse Office and Treatment Act, servicemen were more likely to be charged with or provided help for drug use while on duty (86).

2.2 Arson and Explosives

2.2.1 Arson. The oldest 'instrument' used to detect accelerants in arson cases is the human nose. Whereas the nose can be a sensitive detector, it has many disadvantages, such as the lack of selectivity and objectivity, and the fact that continual exposure to certain odors can effectively 'dull' the olfaction senses. Because of these limitations, another method was deemed necessary (1).

In 1959, Joseph Nicol, a firearms technician at the Chicago police crime lab, promoted the use of mass spectrometry for identifying small quantities of a volatile liquid recovered from fires (87). He also recommended that perhaps large universities or oil company labs could run tests for high priority arson

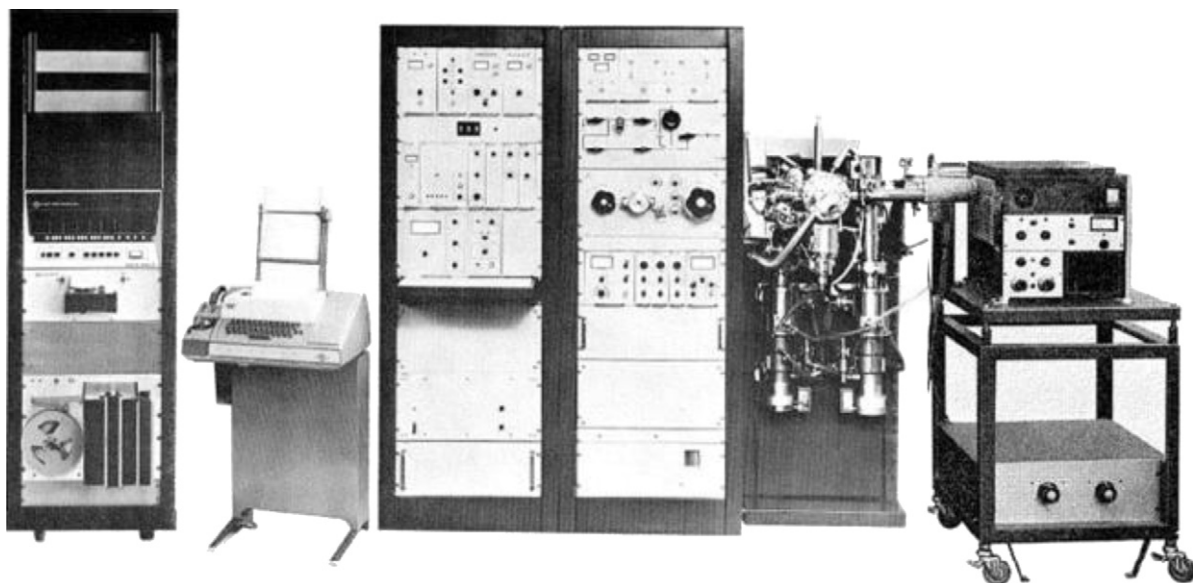


Figure 2
Atlas MAT CH-5 sector MS coupled to a GC with packed column via a glass capillary interface. The instrument was installed in Munich in 1972. (79)

cases, as these were the only organizations that could afford a mass spectrometer at the time. However, because of the financial and accessibility issues cited by Nicol, it took many decades before mass spectrometry was cheap and reliable enough to be routinely employed for arson casework. In 1976, Zoro and Hadley (19) published a review article that outlined the use of GC/MS for accelerants in place of GC-FID or other nonselective detectors, as was frequently done at the time (88–90). Although GC (alone) was very powerful for separating complex mixtures, most GC detectors only provided the relative abundance of each component, not a confirmation of each compound's structure or identity. GC/MS provided this missing link and enabled much more reliable inferences. Figure 3, from Zoro and Hadley's article, shows chromatograms of headspace samples of a fire residue and of a suspected accelerant. Comparison of the two chromatograms showed that the all five major constituents of the sample accelerant were present in the fire debris and that identified peaks number 1 (carbon disulfide), 2 (acetone), and 5 (octane) were not derived from this source (19).

Tandem mass spectrometry is even more selective than conventional mass spectrometry and is therefore capable of detecting lower levels of target compounds, even in the presence of matrix background. This selectivity is typically accomplished through use of a triple quadrupole arrangement: the coupling of two

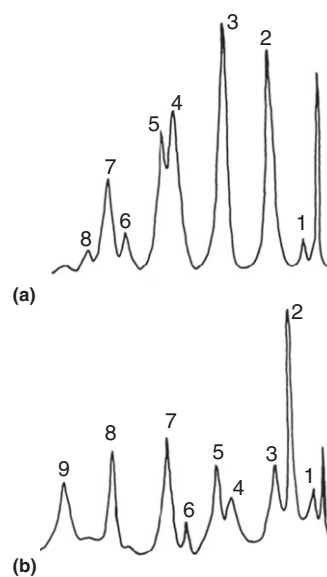


Figure 3
GC–MS analysis of headspace samples: (a) Suspected accelerant and (b) fire debris. The chromatograms shown are freehand copies, which eliminate discontinuities in the integrated ion trace produced by the spectrometer (19).

linear quadrupole mass filters connected via a collision cell – a higher pressure rf-only linear quadrupole (91). Although forensic (drug) applications of tandem mass spectrometry were demonstrated as early as the 1970s, the use of MS/MS on fire debris is considerably more recent (92). There was a significant time lag between the cutting edge applications in the peer-reviewed literature and adoption of the technique into routine analyses. An Interpol review on the advances in fire cause and fire debris in 2001 discusses the development of tandem MS for the analysis of fire debris in court (92). The most recent addition to the arsenal of MS techniques for the analysis of ignitable liquid residues and arson-related evidence is isotope ratio mass spectrometry (IRMS) (93). The technique has even been applied to the matches that are used to start the fires (94,95, see also Chapter 8 (Volume 4): *Organic Materials in Forensic Science*).

2.2.2 Explosives. Chemical identification of post-explosion residues has obvious applications related to terrorist activities. In addition to identifying the explosives used, mass spectrometric analyses can help identify degradation products and taggants in the various samples (see also Chapter 8 (Volume 4): *Explosives*). Taggants are compounds that are deliberately added to certain grades for explosives, like military grade explosives, to help track their fate. Their analysis can be especially important during a trial, as it will be heavily relied on by the prosecution and scrutinized by the defense. The samples taken in such situations are some of the more difficult to analyze due to small volumes and the complex matrices that make up most chemical explosives. Thus the extreme sensitivity and selectivity offered by the mass spectrometer make it the ideal tool for the identification and forensic analysis of chemical explosives (96).

Although mass spectrometers have been used as explosive detectors or ‘sniffers’ since the 1970s (96), they have only recently been identified by the National Research Council as desirable replacements for the considerably cheaper but poorer resolution ion mobility analyzers (97). With the ongoing threat of terrorist activity worldwide, however, the TSA and related agencies have the difficult task of identifying these criminals before they inflict massive damage.

A newer application to the field of forensics is the discrimination of explosives by isotope ratio mass spectrometry (IRMS). A recent article shows the potential of IRMS for identifying bulk nitrogen in ammonium nitrate samples (98). The same group (Bensen *et al.*) has also reviewed the forensic applications of IRMS through 2006 (93).

2.3 Bullets and Gunshot Residue

2.3.1 Bullets. The most commonly employed method of matching bullets fired with the suspect’s weapon is

comparison of physical striations on the bullet itself. However, when this method is not possible or not reliable, mass spectrometry may provide an answer. This solution is to compare the composition of the evidence bullet with the composition of unspent bullets found in possession of the suspect. This approach was first applied (unsuccessfully) to the Kennedy assassination to determine whether certain bullet fragments originated from the same gun. Through the 1970s and 1980s, the most common techniques for the trace level analysis of bullet and casing alloys included neutron activation analysis or atomic absorption (99–101). The first successful attempt to match bullets with MS was in 1975 by Haney and Gallagher using spark source mass spectrometry (SSMS) (102). This approach allowed the investigators to increase the elemental matching beyond an eight-element comparison to nearly complete elemental coverage and with high sensitivity. After the introduction of inductively coupled plasma mass spectrometry (ICP-MS) in 1980 (103), commercial instruments became more common but this type of elemental MS has been very slow to catch on in the forensic community.

In the 1980s, the FBI employed ICP-OES (optical emission spectroscopy) to determine the elemental composition of bullets and often used it to help state and local police link crime scene bullets to those owned by the suspects. In 1994, the method was employed by FBI investigators to confirm that Deputy White House Counsel Vince Foster committed suicide. Though the method was highly praised through the late 1990s, its use was officially ended by the FBI on 1 Sept 2005 due to the questions about its relative probative value, the costs of maintaining the equipment and the resources necessary to do the examinations (104). By 2007, the FBI released another report stating that any testimony suggesting that comparative bullet lead analysis (CBLA) could identify a bullet as coming from any particular box of bullets was insupportable (105). Quite a turnaround! After the publication of the FBI in 2005, a case was appealed; in 2006, the court ruled that CBLA by ICP-AES was inadmissible, and the case was remanded to the trial court for a new trial (106). In certain instances, this reversal has resulted in the release of convicted murderers, as it happened first with Jimmy Ates, who had already served 10 years for the murder of his wife (107). Maybe ICP-MS would have proved more defensible than ICP-OES?

Although ICP-MS (108) and laser ablation (LA)-ICP-MS have the power to analyze down to sub-ppb level impurities and even obtain isotopic analyses of trace elements, almost no crime labs can afford the expense of these techniques, especially given that they are so rarely required.

2.3.2 Gunshot residue. The composition of gunshot residue (GSR), also known as cartridge discharge

residue (109) (CDR) or firearm discharge residue (110) (FDR), consists of the consumed and unconsumed particles from the primer and the propellant. In addition, components from the bullet cartridge case and the firearm may even be present. Once the primer mix burns, it forms a black blast plume that escapes through all available openings on the firearm and solidifies on the surroundings. Because of the difference shapes of firearms, this plume discharge can be characteristic of the type of gun used, such as a revolver, automatic, or shotgun. Trace amounts of these components are typically found on the hands and clothes of those who have been in the vicinity of a discharging firearm. The discharge also collects on objects in the area. This is particularly important because, as Schwoeble and Exline point out (111), the most commonly asked question when a crime involving a firearm has occurred is “Who fired the gun?” (or in the case of suspected suicides, “Are we sure the victim actually fired the gun?”).

The first method for determining whether or not someone had fired a gun by GSR was the paraffin test, also known as the dermal nitrate or diphenylamine test. Teodoro Gonzalez of the Criminal Identification laboratory in Mexico City first applied this test in the United States in 1933. The test was performed by covering a suspect’s hand with a layer of paraffin, which, after cooling, could be broken off and the paraffin treated with an acid solution of diphenylamine, a reagent used to detect the presence of nitrates or nitrites. A positive result would then be read as blue flecks on the wax. Although this did provide positive results for those who fired a gun, it also gave positive results for others who may have come in contact with nitrates or nitrites from other sources, substances common in acid rain, fertilizers, waste water, and sewer lines (112).

Despite its flaws, the paraffin test was quickly adopted by law enforcement agencies and its use became widespread in just a few years. The first reported case admitting evidence based on a paraffin test was decided in 1936 (113). This case then set a precedent that countless other cases followed (114).

Interestingly, the first comprehensive study of the paraffin test was not published until 1967, more than 30 years after the first case reached a verdict (115). An earlier but much smaller study was done in 1955 (116). From the 1967 study, the field learned that ‘rust, colored fingernail polish, and residue from evaporated urine, soap, and tap water’ all tested positive for nitrates or nitrites. Although the conclusion of the study was that the test was obviously nonspecific (115), it is interesting to note that even after this publication courts were still admitting paraffin test results as evidence. This marks a rather unfortunate historical trend of forensic science: forensic techniques are often born out of necessity in crime labs and are adopted by other forensic practitioners before thorough and independent testing of

the operating principles, selectivity, sensitivity, and general scientific validity is available. Only after rigorous scientific validations, sometimes >30 years after its introduction, does the technique show its weaknesses. Another example of this trend can be found with voiceprint analysis (117). Fortunately, mass spectrometry as a forensic technique has not fallen into this category.

Because of the general unreliability of color tests, alternative elemental and mass spectrometric approaches have been developed, such as neutron activation analysis (NAA) (111), graphite furnace atomic absorption spectroscopy (111) (GFAAS), GC-MS (118), ICP-MS (119), LC-MS/MS (120), and DESI MS/MS (121). Although it was acceptable to use GC/MS in the 1980s for gunshot cases (122), the current standard set forth by the American Society for Testing and Materials (ASTM E1588-07) is GSR analysis by scanning electron microscopy/energy dispersion X-ray spectrometry for particles of lead, antimony, barium, and others. However, even SEM-EDXRS analysis has come under question recently because of the lack of uniqueness of GSR particles.

2.4 Trace

Trace evidence is a specific type of physical evidence that often requires some sort of magnification or analytical device for characterization to make it useful for evidence. This type of evidence is typically transferred from perpetrator to the crime scene by contact friction. This theory of evidence, known as ‘Locard’s exchange principle,’ was postulated by Edmund Locard, director of the world’s first crime laboratory in 1910 in Lyon, France. Quite literally, if an object or material has been used in a crime, and at least a few micrograms of it exist, the substance ought to be susceptible to at least one kind of MS analysis.

2.4.1 Hair. Because of the low concentrations of inorganic elements in human hair, only the most abundant metals could be studied initially. As early as the 1930s, scientists have studied the concentration of iron in human hair (123–134). Back then, iron levels were measured through chemical extraction. From the 1950s through the early 1960s, spectrophotometric methods and emission spectrographic techniques were utilized (135–137). With these methods only a few specific trace metals could be measured. In the mid- and late 1960s, atomic absorption and neutron activation analysis were favored, providing analysis on 14–18 different elements in human hair. Early studies included mercury and lead exposure due to poisoning (138,139). Harrison and coworkers performed the first extensive study of trace elements in human hair in 1969 using spark source MS (SSMS) (140,141).

This technique allowed more than 20 different elements to be compared with excellent sensitivity and thereby permitted easy matching of different hair samples to determine possible common origin. However, like many other potential applications, the forensic community never adopted SSMS, presumably because of the lack of stability and problems with interferences inherent in the technique.

Despite the proven methods in the analysis of hair, courts in United States were refuting expert testimonies in hair analysis as late as the 1980s. In particular, in the late 1970s, there was a string of cases involving the credibility of ion microprobe analysis, all of which preceded Daubert (142). Each case followed the same basic progression: the prosecution would have three forensic chemists present their findings as well as research conducted on reliability of the test on human hair, after which the defense would make the case that the scientific community does not yet accept ion microprobe analysis. In all instances, the court would rule in favor of the defense (143).

Hair and nail samples have also been studied using IRMS for the application of human identification. An interesting process involves the use of stable isotope profiling (SIP) in the classification of dietary and recent geographical life history of people. According to one study, the natural variability of ^{13}C and ^{15}N is low enough to provide reasonable classification. Though new, the SIP process holds amazing promise in the future of forensic science (144).

The most recent method for testing hair samples is matrix-assisted laser desorption/ionization (MALDI) mass spectrometry and LA-ICP-MS. Reports indicate that with these techniques chemists are able to identify drugs and their metabolites in complex biological matrices. Impressively, this method requires very short incubation times (15 min) to prepare the hair samples for testing (145). Typical digestion and extraction times for the conventional analysis of drugs and metabolites in hair can take hours to days to complete.

2.4.2 Inks and paints. Ink and paint can provide compelling evidence in many cases (see also Chapter 9 (Volume 5): *Forensic Applications of Inorganic Mass Spectrometry*). Two of the most commonly encountered applications today are in automobile accidents and break-ins. There are several methods currently employed in forensic laboratories to identify paints, as explained by the Scientific Working Group for Materials Analysis (SWGMA) document produced by the Federal Bureau of Investigation (146). Methods described in SWGMA guidelines include FT-IR and pyrolysis GC/MS for classifying the binder polymers and organic pigments in the automotive or architectural paints. Since the publication of these recommendations, methods such as laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) for trace metals within automotive paints

(147) and IRMS for the analysis of white architectural paints have been applied with success (148).

In 1995, IRMS was able to first identify paint and varnish samples by using $^{15}\text{N}/^{14}\text{N}$ and $^{13}\text{C}/^{12}\text{C}$ isotope ratios by EA/IRMS. Differentiation was achieved by a combination of the two elements' isotopic ratios (93). The only real limitation to this practice exists in the differentiation of white paints. Recently, as mentioned before, IRMS has shown potential by differentiating between two samples based on the batches from which the oils were added to alkyd formulations. The study found a false positive rate of 2.6% out of a total 1275 comparisons (148).

2.4.3 Polymers and fibers. The application of MS to fibers, especially man-made fibers, originated through the use of pyrolysis-MS (Pyr-GC-MS) by Saferstein and Manura in the late 1970s (149). Pyr-GC-MS is commonly used in today's trace labs to study fibers and polymers (150) and has discriminatory capability superior to Fourier transform infrared spectrometry (151,152). Pyr-GC-MS analyses are able to be so specific because any one of the hundreds of pyrolysates detected using this method is a possible distinguishing feature of the chemical fingerprint (153).

Pressure-sensitive adhesive tapes represent a major source of forensic evidence because they are cheap, strong, and available at almost every convenience store. Tapes are used to restrain or gag victims, to store illegal narcotics, or even to attach makeshift explosives to a target. Some modern reports have shown that isotope ratio mass spectrometry can resolve questions of common origin when two samples of tapes have otherwise identical chemical compositions (154).

2.4.4 Other trace. Soil is composed of decaying organic material as well as minerals and synthetic materials. The ratio of minerals generally varies quite widely between two disparate sites. Better yet is the ratio of organics and synthetic materials in the soil, which can vary foot by foot at a crime scene. Soil samples will tell a chemist a great deal about where the victim or suspect has been. This study can be applied to vehicle tires, footwear, and clothing (155).

This process of classifying soil samples has changed through the years. It has made the transformation from a mere sandy versus clay visual classification to its modern classification by isotope ratio. Using continuous-flow isotope ratio mass spectrometry (CF-IRMS) scientists can now determine $^{15}\text{N}/^{14}\text{N}$ and $^{13}\text{C}/^{12}\text{C}$ isotope ratios with great specificity. Through this analysis, it has been shown that we can accurately determine soil type and location independent of temporal variation, as is the case with crime scenes. In addition, this tool also offers valuable information regarding soil transfer (156).

3. Conclusion

Through the study of the progression of mass spectrometric application to the field of forensics, one hopes to gain an understanding of what the future holds. Mass spectrometry has a long and essential history in the legal community and continues to provide some of the most reliable evidence in the forensic sciences, second only to DNA, perhaps. Although the techniques and especially the sample introduction and ionization methods have evolved dramatically over the years, there remains the perpetual problem of adequately supplying the education, training, equipment, and infrastructure that forensic laboratories and the legal community depend on to solve legal issues. These issues were identified in the 1970s (157) and are still equally relevant today (158).

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