



## U.S. initiatives to strengthen forensic science & international standards in forensic DNA



John M. Butler\*

National Institute of Standards and Technology, Gaithersburg, MD, USA

### ARTICLE INFO

#### Article history:

Received 19 May 2015

Received in revised form 15 June 2015

Accepted 24 June 2015

#### Key words:

Forensic science

National Commission on Forensic Science

Organization of Scientific Area Committees Standards

Core DNA markers

Standard reference materials

### ABSTRACT

A number of initiatives are underway in the United States in response to the 2009 critique of forensic science by a National Academy of Sciences committee. This article provides a broad review of activities including efforts of the White House National Science and Technology Council Subcommittee on Forensic Science and a partnership between the Department of Justice (DOJ) and the National Institute of Standards and Technology (NIST) to create the National Commission on Forensic Science and the Organization of Scientific Area Committees. These initiatives are seeking to improve policies and practices of forensic science. Efforts to fund research activities and aid technology transition and training in forensic science are also covered.

The second portion of the article reviews standards in place or in development around the world for forensic DNA. Documentary standards are used to help define written procedures to perform testing. Physical standards serve as reference materials for calibration and traceability purposes when testing is performed. Both documentary and physical standards enable reliable data comparison, and standard data formats and common markers or testing regions are crucial for effective data sharing. Core DNA markers provide a common framework and currency for constructing DNA databases with compatible data. Recent developments in expanding core DNA markers in Europe and the United States are discussed.

Published by Elsevier Ireland Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

This review article has two primary sections. The first section covers recent initiatives and activities in the United States to improve forensic science. The second section discusses international standards to aid forensic DNA testing.

### 1. U.S. initiatives to strengthen forensic science

Many disciplines of forensic science, including DNA analysis, are undergoing change in the United States and around the world. New methods are being developed, validated, and put into use to help in criminal investigations. The validity and accuracy of older and even current methods are being challenged. New approaches for interpreting evidence via probabilistic modeling are being introduced. A better appreciation of difficulties that can exist for the field of forensic science is gained when the diverse cultures of scientific laboratories, law enforcement, and the legal community interact.

The publication of the National Academy of Sciences' (NAS) National Research Council (NRC) report in February 2009 [1]

calling for improvements in forensic science in the United States has been felt around the world. This article reviews the 13 recommendations made in the NAS/NRC report (see Table 1) and provides a brief overview of activities since 2009 attempting to strengthen forensic science (see Table 2). These activities include the White House's National Science and Technology Council's Subcommittee on Forensic Science (NSTC SoFS), the National Commission on Forensic Science (NCFS), and the Organization of Scientific Area Committees (OSAC).

#### 1.1. Raising concerns regarding forensic science and the NAS 2009 report

While there have been concerns raised in recent years in books (e.g., [2,3]) and law review articles (e.g., [4]) regarding the quality of some forensic examinations, the erroneous identification of Brandon Mayfield by FBI fingerprint examiners following the 2004 Madrid train bombing [5,6] has probably had the largest impact on recent scrutiny of latent print identifications as well as other disciplines in the field. In November 2005, the United States Congress authorized the National Academy of Sciences to conduct a study on forensic science [1].

From January 2007 to November 2008 a 17-member committee met eight times, heard from 70 presenters, and discussed the

\* Corresponding author at: NIST Special Programs Office, 100 Bureau Drive, M/S 4701, Gaithersburg, MD 20899, USA. Fax: +1 301 975 8620.

E-mail address: [john.butler@nist.gov](mailto:john.butler@nist.gov) (J.M. Butler).

**Table 1**

Summary of 13 recommendations made in the 2009 National Research Council report entitled “Strengthening Forensic Science in the United States: A Path Forward”.

1	Create an independent federal entity called the National Institute of Forensic Science (NIFS)
2	Establish standard terminology to be used in reporting on and testifying about the results of forensic science investigations and establish model laboratory reports with minimum information specified
3	Research (and publish in respected scientific journals) the validity of forensic methods, quantify limits of reliability when forensic evidence conditions vary, develop measures of uncertainty in the conclusions of forensic analyses, and automate techniques
4	Remove public forensic laboratories from law enforcement or prosecutor’s administrative control
5	Research human observer bias and error in forensic examinations and develop standard operating procedures to minimize potential bias and error
6	Work with the National Institute of Standards and Technology (NIST) and partners to develop tools for advancing measurement, validation, reliability, information sharing, and proficiency testing in forensic science and to establish protocols for forensic examinations, methods, and practices
7	Mandate accreditation for all laboratories and facilities (public or private) and mandate individual certification of forensic science professionals
8	Establish routine quality assurance and quality control procedures to ensure the accuracy of forensic analyses and the work of forensic practitioners
9	Establish a national code of ethics for all forensic science disciplines that can be enforced through certification
10	Improve graduate education programs with attractive scholarship and fellowship offerings and establish continuing legal education programs for law students, practitioners, and judges
11	Improve death investigations through establishing a nationwide medical examiner system with all medicolegal autopsies being performed or supervised by a board certified forensic pathologist
12	Work to achieve nationwide fingerprint data interoperability from Automated Fingerprint Identification Systems (AFIS) and work to improve accuracy of computer algorithms used
13	Coordinate local forensic science efforts related to homeland security with the Centers for Disease Control and Prevention and the FBI through planning and conducting preparedness exercises

information received [1]. In February 2009 the National Research Council issued a 352-page report entitled “Strengthening Forensic Science in the United States: A Path Forward.” In a presentation given about a year after the report was released, the leader of the committee, Judge Harry T. Edwards, noted that “seven of the 17 Committee members are prominent professionals in the forensic science community, with extensive experience in forensic analysis and practice; 11 members of the Committee are trained scientists (with expertise in physics, chemistry, biology, engineering, biostatistics, statistics, and medicine); 10 members of the Committee have Ph.Ds., 2 have M.Ds., 5 have J.Ds., and one has an M.S. in chemistry” [7].

This 2009 NRC report, which is often referred to in forensic circles as “the NAS report”, proposes 13 recommendations to improve forensic science in the United States [1]. Table 1 provides a simplified summary of each of the 13 recommendations made in this report.

Key to most of the recommendations made is the establishment of a National Institute of Forensic Science (NIFS), which the NAS committee envisioned would carry on the work of solving problems identified in their report. Recommendation 1 emphasizes that NIFS should focus on (a) establishing and enforcing best practices for forensic science professionals and laboratories, (b) establishing standards for mandatory accreditation and certification, (c) promoting scholarly, competitive peer-reviewed research, (d) developing a strategy to improve forensic science research and education programs, including forensic pathology, (e) establishing a strategy, based on accurate data, for the efficient allocation of available funds to give strong support to forensic methodologies and practices in addition to DNA analysis, (f) providing funds with conditions that aim to advance the credibility and reliability of forensic science disciplines, (g) overseeing education standards and accreditation of forensic science programs in colleges and universities, (h) developing programs to improve understanding of forensic science disciplines and their limitations within legal systems, and (i) assessing the development and introduction of new technologies in forensic investigations [1].

Recommendation 3 calls upon NIFS to competitively fund peer-reviewed research to (a) demonstrate the validity of forensic methods, (b) establish quantifiable measures and limits of reliability and accuracy that can be expected as forensic evidence conditions vary, (c) develop quantifiable measures of uncertainty in the conclusions of forensic analyses, and (d) produce automated techniques capable of enhancing forensic technologies. This

recommendation also emphasizes that research results should be published in respected scientific journals with a formalized and rigorous peer-review [1].

In May 2010, Judge Harry Edwards, who co-chaired the NAS committee, spoke on the importance of this work to the court system [7]. He noted: “What our Committee found is that, although there are many dedicated and skilled forensic professionals, the quality of practice in the forensic disciplines varies widely and the conclusions reached by forensic practitioners are not always reliable” [7]. Judge Edwards further commented: “From my vantage point, the response to the Report has been very positive and I have seen a ground swell of support in favor of major reforms to correct the ills of the forensic science community” [7]. He goes on: “If courts blindly follow precedent that rests on unfounded scientific premises, this will lead to unjust results” [7]. Judge Edward emphasizes that: “When scientific methodologies once considered sacrosanct are modified or discredited, the judicial system must accommodate the changed scientific landscape” [7]. These comments highlight an important challenge for forensic science that deals with a judicial system that is based on precedence (i.e., looking to the past) while attempting to embrace new discoveries and improvements (i.e., looking to the future).

The 2009 NRC report begins with strong words: “The forensic science system, encompassing both research and practice, has serious problems that can only be addressed by a national commitment to overhaul the current structure that supports the forensic science community in this country. This can only be done with effective leadership at the highest levels of both federal and state governments, pursuant to national standards, and with a significant infusion of federal funds” ([1], p. xx). Since NIFS does not exist and probably will never exist as originally envisioned by the NAS committee due to a challenging fiscal environment for federal funding in recent years, other ongoing efforts are trying to address most of the recommendations summarized in Table 1.

### 1.2. Responding to concerns raised

Table 2 includes a brief timeline of events occurring in the past few years regarding efforts to improve forensic science. For real change to happen in forensic science in the coming years, improved policies need to be established and enforced, best practices defined and implemented, research sufficiently funded

with new and improved methods adopted by forensic laboratories, and changes embraced by participants and stakeholders.

The U.S. Congress has considered several measures to fund further forensic science improvements. A handful of formal briefings and hearings on what is needed to improve the field have been held over the past few years, but as of early 2015 the proposed bills have not made it out of their individual committees.

It is unclear how soon or even if there will be additional federal funding to aid forensic science improvements.

Below some recent efforts are described: (1) to examine and establish improved policies, (2) to standardize and improve forensic practices, and (3) to fund research in forensic science.

**Table 2**  
Brief timeline of recent U.S. efforts to strengthen forensic science.

Date	Event
November 2005	U.S. Congress authorizes the National Academy of Sciences (NAS) to conduct a study on forensic science, which is subsequently funded by a grant from the National Institute of Justice (NIJ)
January 2007–November 2008	A 17-member “Committee on Identifying the Needs of the Forensic Science Community” is established by NAS, meets eight times, hears from 70 presenters, and discusses information received
February 2009	Based on the NAS committee efforts, the National Research Council issues a 352-page report entitled “Strengthening Forensic Science in the United States: A Path Forward” which proposes 13 recommendations (see Table 1); in forensic circles, this report is referred to as “the NAS Report”
July 2009–December 2012	The White House National Science and Technology Council (NSTC) Committee on Science establishes a Subcommittee on Forensic Science (SoFS) that operates with five Interagency Working Groups (IWGs); deliberations involve dozens of meetings over a three-and-a-half year period with nearly 200 subject matter experts spanning 23 Federal departments and agencies and 49 state and local participants; SoFS IWG activities conclude with hopes to share information learned
June 2010	NIJ-sponsored Forensic Death Investigation Symposium held in Scottsdale, Arizona [140]
September 2010	NSF-sponsored workshop “Cognitive Bias and Forensic Science” held in Chicago, Illinois
February 2012	NIJ-sponsored working group publishes “Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach”
November 2012	Forensics@NIST 2012 conference and webcast held to showcase NIST activities in forensic science
December 2012	NSF-sponsored workshop “Strengthening Forensic Sciences through Connections with the Analytical Sciences” held in Arlington, Virginia
February 2013	The Department of Justice (DOJ) and the National Institute of Standards and Technology (NIST) announce plans to form the National Commission on Forensic Science (NCFS), as a federal advisory group to DOJ, and to establish scientific guidance groups that will be administered by NIST; one of the duties in the NCFS charter is “to consider the recommendations of the National Science and Technology Council’s Subcommittee on Forensic Science”
April 2013	NIST-organized working group publishes “The Biological Evidence Preservation Handbook: Best Practices for Evidence Handlers”
April 2013	NIST-organized forensic governance meeting held in Washington, DC, which includes a discussion of an article written by Tjark Tjin-A-Tsoi from the Netherlands Forensic Institute on trends and challenges
June 2013	NIST meets with the chairs of current Scientific Working Groups (SWGs) (see Table 3) to discuss potential structures for an organization to house the guidance groups
August 2013	The National Science Foundation (NSF) issues a “Dear Colleague Letter” encouraging submission of grant proposals on topics involving forensic science
September–November 2013	NIST gathers information from a public Notice of Inquiry regarding aspects of guidance groups; 82 responses are received including input from the United Kingdom, Canada, Germany, and Australia
September 2013–April 2014	The White House Office of Science and Technology Policy (OSTP) establishes a research strategy working group consisting of representatives of DOJ, NIST, and NSF to discuss potential methods to improve forensic science research efforts
January 2014	The National Commission on Forensic Science membership is announced and involves a range of stakeholders including judges, lawyers, academic researchers, and practitioners
February 2014	At the first NCFS meeting, which is held in Washington, DC, NIST announces a proposed structure for the scientific guidance groups called the Organization of Scientific Area Committees (OSAC)
February 2014	In conjunction with the first NCFS meeting, a 10-page document entitled “Strengthening Forensic Science: A Progress Report” is issued by OSTP with input from the research strategy working group
February 2014	At the American Academy of Forensic Sciences (AAFS) meeting in Seattle (and via webcast), NIST presenters provide a detailed description of the planned OSAC structure
May 2014	Just prior to the second NCFS meeting, a 79-page report entitled “Strengthening the Forensic Sciences” is issued by the White House that describes information learned by the SoFS regarding accreditation, certification, proficiency testing, and a proposed national code of ethics for forensic service providers
May 2014	Based on input from the OSTP research strategy working group, NSF announces a “Dear Colleague Letter” encouraging submission of applications for Industry/University Cooperative Research Centers (I/UCRC) in forensic science
July 2014	The National Research Council issues a 252-page report entitled “Science Needs for Microbial Forensics: Developing Initial International Research Priorities”
August 2014	Just prior to the third NCFS meeting, NIST announces plans to fund a Forensic Center of Excellence focused on development and deployment of probabilistic methods for pattern evidence and digital evidence
October 2014	Just prior to the fourth NCFS meeting, OSTP issues a draft report entitled “Achieving Interoperability for Latent Fingerprint Identification in the United States” (see update on report below)
December 2014	Forensics@NIST 2014 conference and webcast held to showcase NIST research activities four program areas: digital forensics, DNA, ballistics/ toolmarks, and statistics
January 2015	First in-person OSAC subcommittee meetings held in Norman, OK
January 2015	At the fifth NCFS meeting, recommendations were approved by the Commission regarding the scientific literature in support of forensic science and accreditation of medicolegal death investigation (MDI) offices and certification of MDI personnel by 2020 (see <a href="http://www.justice.gov/ncfs">www.justice.gov/ncfs</a> )
February 2015	OSAC holds its first public Scientific Area Committee meetings in conjunction with the AAFS meeting
April 2015	NCFS charter is renewed for an additional two years, and the prohibition on developing or recommending guidance regarding digital evidence is removed
April 2015	During the sixth NCFS meeting, OSTP issues final report entitled “Achieving Interoperability for Latent Fingerprint Identification in the United States” [141]
Ongoing	NIJ funds numerous research grants in forensic science and fellowships for graduate students (see <a href="http://www.nij.gov">www.nij.gov</a> )

## 2. Examining and establishing improved policies for forensic science

### 2.1. National Science and Technology Council Subcommittee on Forensic Science (NSTC SoFS)

In response to the problems identified in the 2009 NRC report, the White House Office of Science and Technology Policy (OSTP) coordinated the establishment of the Subcommittee on Forensic Science (SoFS) under the National Science and Technology Council (NSTC) to identify challenges and opportunities for addressing the NRC report recommendations. The NSTC is the principal means by which the executive branch coordinates science and technology policy across the Federal research and development enterprise. The SoFS was chartered in July 2009 [8] and operated until late 2012 [9]. The SoFS leadership team included co-chairs Ken Melson (from the Department of Justice) and Mark Stolorow (from the National Institute of Standards and Technology), executive secretary Robin Jones, and OSTP liaison Rick Weiss, who continued Duane Blackburn's work.

Activities of the SoFS were coordinated through five interagency working groups (IWGs) that were each chartered with distinct objectives. The five IWGs were (1) Accreditation and Certification (AC IWG) [10], (2) Standards, Practices, and Protocols (SPP IWG) [11], (3) Education, Ethics, and Terminology (EET IWG) [12], (4) Research, Development, Testing, and Evaluation (RDT&E IWG) [13], and (5) Outreach and Communication (OC IWG) [14]. The IWG activities involved nearly 200 subject matter experts from 23 Federal departments and agencies. Importantly, this effort also engaged, as advisory members, 49 individuals representing state and local forensic laboratories [15] out of the recognition of the importance of drawing on the unique perspectives and input from the broader practitioner and criminal justice communities.

The SoFS also chartered a task force to coordinate the development of a strategic plan for achieving interoperability for latent fingerprint identification in direct response to the NRC report's recommendation that the Federal Government launch a "broad-based effort to achieve nationwide fingerprint data interoperability" ([1], p. 277). In addition, as will be described in more detail later in this article, the SoFS RDT&E IWG worked with several scientific working groups to produce annotated bibliographies for a number of the forensic disciplines.

In May 2014, OSTP released an initial 79-page report describing some of the activities and findings of the five SoFS IWGs [15]. This SoFS report addresses topics of (1) accreditation of forensic service providers, (2) certification of forensic examiners, (3) certification of medicolegal personnel, (4) proficiency testing of forensic examiners, and (5) a national code of ethics for forensic service providers. Several appendices are also provided in the 2014 SoFS report. These appendices, which are primarily focused on accreditation issues, cover the following topics: estimating costs of accreditation, a listing of federal forensic providers and their accreditation status, a listing of publicly funded forensic crime laboratories operating in the United States as of 2005, a SoFS tally of publicly funded forensic service providers that were not accredited as of 2009, additional forensic service providers not included in the Bureau of Justice Statistics 2005 survey that were accredited as of 2009 [16], additional resources relevant to accreditation, discipline-specific certification testing categories with accrediting details and fees, additional resources on certification, information on the American Board of Medical Specialties, information on the American Board of Medicolegal Death Investigators certification, information on the American Board of Pathology requirements for certification in anatomic pathology and forensic pathology, a listing of accredited toxicology laboratories and medical examiner and coroner offices, some

additional resources regarding medicolegal death investigation, cost estimates for implementing a proficiency testing program, a listing of proficiency test accreditation bodies and proficiency test providers, and the three components of proficiency testing.

In May 2015, OSTP released a report, *Achieving Interoperability for Latent Fingerprint Identification in the United States* (see Table 2) that is based on the task force's work in this area. The report describes the current state of latent interoperability among Automated Fingerprint Identification Systems (AFIS) and identifies a series of actions that can be taken by Federal agencies to implement that standards needed to achieve interoperability, develop an overarching national connectivity strategy and infrastructure, and support State and local agencies in building connections across jurisdictions. The report recommends that the Federal Government encourage adoption of established standards for latent print encoding and searching by state and local agencies, work to improve state-to-state and local-to-state AFIS system connectivity, foster the development of inter-state and state-local AFIS governance agreements, and support performance testing and training activities.

Ideas and collective work generated out of the SoFS efforts have served as an important foundation for the work that is currently being carried out by the NCFS and OSAC, and many of the people involved in the SoFS are serving in these organizations.

### 2.2. National Commission on Forensic Science (NCFS)

Following the completion of the SoFS activities in December 2012 (see Table 2), the baton for efforts to improve forensic science in the United States passed to a partnership established between the U.S. Department of Justice (DOJ) and the National Institute of Standards and Technology (NIST).

On February 15, 2013, a joint DOJ-NIST press release announced plans to create the NCFS [17]. While the NCFS focuses on policy matters, a second part of the DOJ-NIST partnership involves improving the practice of forensic science through the establishment of what were initially termed "guidance groups". As will be described later, these guidance groups were intended to supersede the scientific working groups (SWGs) that DOJ previously supported. First year activities of the NCFS and formation of the OSAC have been described previously [18] but some key information is revisited here. The NCFS is scheduled to meet approximately four times each year—and did so in 2014 with meetings being held on February 3–4, May 12–13, August 26–27, and October 28–29. In 2015, additional meetings (prior to this article being completed) occurred on January 29–30 and April 30–May 1.

The NCFS is a federal advisory committee for the U.S. Department of Justice and as such follows prescribed rules that include public meetings and a balance of perspectives and interests from relevant stakeholders. The Federal Advisory Committee Act (FACA) of 1972 and its amendments [19] provide strict rules including: (1) prior to each meeting, notices shall be posted in the Federal Register, (2) meetings shall be open to the public, and (3) opportunities for public comments on committee activities and recommendations shall exist. Meeting summaries and other relevant documents for the NCFS are available online at <http://www.facadatabase.gov/> (see Committee 83353) as well as at the official NCFS website: <http://www.justice.gov/ncfs>. By FACA rules, the NCFS charter must be renewed every two years. The first NCFS term went from April 23, 2013 to April 23, 2015, and the NCFS charter was renewed on April 23, 2015 for an additional two years.

The objectives and scope of activities for the NCFS per its 2013 charter include providing "recommendations and advice to DOJ concerning national methods and strategies for: strengthening the validity and reliability of the forensic sciences (including medico-

legal death investigation); enhancing quality assurance and quality control in forensic science laboratories and units; identifying and recommending scientific guidance and protocols for evidence seizure, testing, analysis, and reporting by forensic science laboratories and units; and identifying and assessing other needs of the forensic science communities to strengthen their disciplines and meet increasing demands generated by the criminal and civil justice systems at all levels of government” [20]. Although there was an initial ban on “develop[ing] or recommend[ing] guidance regarding digital evidence” [20], this prohibition was verbally lifted at the third NCFS meeting by Deputy Attorney General James Cole. The renewed NCFS charter permits developing and recommending guidance on digital evidence, and additionally states that the Attorney General will refer recommendations regarding measurement standards and priorities for standards development to the Director of NIST, as the Attorney General deems appropriate.

The Commission is composed of an impressive group of individuals who have a wealth of knowledge and a wide range of expertise and experience. From over 325 applicants, 31 voting and 8 ex-officio members were selected to achieve a diversity of experiences and perspectives including federal, state, and local forensic science service providers; research scientists and academicians; federal, state, local prosecutors, defense attorneys and judges; law enforcement; and other relevant stakeholders.

NCFS subcommittees have been formed to perform work between the full Commission meetings. This subcommittee work is then vetted and discussed in the public NCFS meetings. The seven initial subcommittees are (1) Accreditation and Proficiency Testing, (2) Human Factors and Cognitive Bias, (3) Interim Solutions, (4) Medicolegal Death Investigation, (5) Reporting and Testimony, (6) Scientific Inquiry and Research, and (7) Training on Science and Law. Information on the activities and membership of the NCFS can be found at <http://www.justice.gov/NCFS>.

Commission members, many of whom come from outside the forensic science community, have had to be educated on the issues faced by practitioners in the forensic science industry. The initial Commission meetings have focused on several topics including laboratory accreditation, automated fingerprint identification system (AFIS) interoperability, cognitive bias concerns in forensic examinations, and becoming acquainted with what

was accomplished through the previous efforts of the NSTC SoFS.

Recommendations made by the Commission to the U.S. Attorney General and adopted by DOJ become binding to the DOJ forensic laboratories, namely the Federal Bureau of Investigation (FBI), Drug Enforcement Administration (DEA), and Alcohol, Tobacco, Firearms and Explosives (ATF) Laboratories. However, the influence of the deliberations and the impact of the NCFS work can have a much wider effect. Indeed, the global forensic science community may be watching what this Commission does.

### 2.3. Forensic governance

On April 22, 2013, NIST convened a group to discuss issues surrounding governance of forensic laboratories (see Table 2). This invitational meeting, which was hosted by the Washington DC Consolidated Forensic Laboratory, included forensic laboratory directors from private and public (Federal, state, and local representatives) laboratories in United States and Canada discussing relevant and important topics.

The Netherlands Forensic Institute (NFI) model for improving delivery of forensic services was reviewed and lessons learned were shared by the NFI chief executive officer at the time Tjark Tjin-A-Tsoi. His observations and experiences regarding governing a modern forensic science organization have been described in a 28-page article entitled “Trends, Challenges and Strategy in the Forensic Science Sector” [21]—an article that was written for purposes of discussion during this April 2013 gathering on forensic governance. The NFI article reviews factors driving growth in forensic services including new technological capabilities (e.g., DNA and digital forensics), an increased awareness among customers regarding the value, efficiency, and potential of forensic science, and new customers from outside the scope of traditional forensic science users [21].

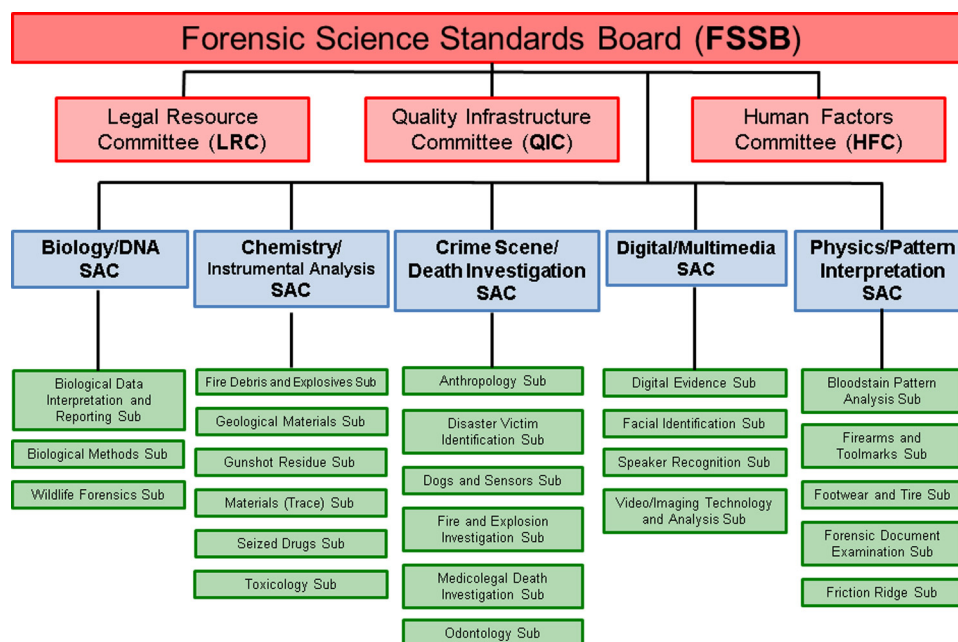
Growth in the number of forensic services desired from laboratories operating under limited, fixed budgets has resulted in backlogs and often lengthy delivery times for the services requested. While the solutions adopted by NFI may not work for every forensic laboratory, their approaches may be worth considering. In order to provide timely service, NFI has worked

**Table 3**

Summary of 21 scientific working groups that existed in 2014. Most will be replaced by the newly formed Organization of Scientific Area Committees (OSAC).

Scientific working group (SWG)	Topic (forensic discipline)	Start	Sponsor	Website
SWGDMAM	DNA	1988	FBI	<a href="http://swgdam.org">swgdam.org</a>
SWGDMAT	Materials (trace)	1992	FBI	<a href="http://swgmat.org">swgmat.org</a>
SWGDFAST	Friction ridge (fingerprints)	1995	FBI	<a href="http://swgfast.org">swgfast.org</a>
SWGDRUG	Controlled substances	1997	DEA	<a href="http://swgdrug.org">swgdrug.org</a>
SWGDMIT	Imaging technologies	1997	FBI OTD	<a href="http://swgit.org">swgit.org</a>
SWGDMDOC	Document examination	1997	FBI	<a href="http://swgdoc.org">swgdoc.org</a>
SWGDMDE	Digital evidence	1998	FBI OTD	<a href="http://swgde.org">swgde.org</a>
SWGDMGUN	Firearms & toolmarks	1998	FBI	<a href="http://swggun.org">swggun.org</a>
SWGDMFEX	Fire debris & explosives	1998	NIJ	<a href="http://swgfex.org">swgfex.org</a>
SWGDMSTAIN	Bloodstain pattern	2002	NIJ	<a href="http://swgstain.org">swgstain.org</a>
SWGDMTREAD	Shoeprint & tire tread	2004	FBI	<a href="http://swgtread.org">swgtread.org</a>
SWGDMDOG	Dog & orthogonal detector	2004	FBI	<a href="http://swgdog.fiu.edu">swgdog.fiu.edu</a>
SWGDMGSR	Gun shot residue	2007	NIJ	<a href="http://swggsr.org">swggsr.org</a>
SWGDMANTH	Anthropology	2008	FBI	<a href="http://swganth.org">swganth.org</a>
SWGDMTOX	Toxicology	2009	NIJ	<a href="http://swgttox.org">swgttox.org</a>
SWGDMISWG	Facial identification	2009	FBI OTD	<a href="http://fiswg.org">fiswg.org</a>
SWGDMVI	Disaster victim identification	2010	FBI	<a href="http://swgdvi.org">swgdvi.org</a>
SWGDMMDI	Medicolegal death investigation	2010	NIJ/FBI	<a href="http://swgmdi.org">swgmdi.org</a>
SWGDMGEO	Geological materials	2011	USACIL	<a href="http://swggeo.org">swggeo.org</a>
SWGDMWILD	Wildlife forensics	2011	USFWS	<a href="http://wildlifeforensicscience.org/swgwild">wildlifeforensicscience.org/swgwild</a>
SWGDMSPEAKER	Voice analysis	2012	FBI	<a href="http://swg-speaker.org">swg-speaker.org</a>

Abbreviations: FBI: Federal Bureau of Investigation; DEA: Drug Enforcement Administration; FBI OTD: Federal Bureau of Investigation Operational Technology Division; NIJ: National Institute of Justice; USACIL: United States Army Criminal Investigation Laboratory; USFWS: United States Fish and Wildlife Service.



**Fig. 1.** Organizational chart reflecting the 33 operating units of the Organization of Scientific Area Committees (OSAC) as of April 2015. SAC: Scientific Area Committee, Sub: subcommittee.

to improve processes and has instituted service level agreements with customers where the working relationship is formalized between NFI and the customer in terms of a specific number of investigations to be completed for that specific customer over the period of a year [21]. Any work beyond the agreed upon number of investigations covered by their annual government budget must be paid for by the customer, which helps customers appreciate that resources are limited and prioritization of effort is beneficial. In addition, the NFI article describes efforts to conduct process redesign in order to reduce and optimize time spent performing casework [21]. Research and development efforts have also been made to find new ways to increase the speed of forensic processes. For example, their “DNA 6 h” service now provides processing of crime scene DNA and a DNA database comparison within six hours [21]. By implementing service level agreements and improved processes, NFI eliminated their 18,000 case backlog and reduced average delivery time from 140 days (in 2007) to less than 14 days (in 2012) [21].

Presentations were also made at the April 2013 forensic laboratory governance meeting on the FORESIGHT Project, which is an NIJ-funded, West Virginia University-led effort to benchmark forensic laboratory productivity (<http://www.be.wvu.edu/forensic/foresight.htm>) [22,23]. Finally, a history of efforts in U.S. laboratory governance changes and challenges was provided by the National Forensic Science Technology Center (<https://www.nfstc.org/>). An important point to make here is that having quality research or quality casework is not always enough to delivering the best forensic services. How forensic laboratories are governed makes a difference in the quality and speed of service delivery [23].

### 3. Standardizing and strengthening forensic practices

The NRC 2009 report recognized a need to standardize forensic practices in the United States [1,24]. Over the past several decades the U.S. has had various technical working groups (TWGs) and scientific working groups (SWGs) that have discussed forensic practices and in many cases provided guidance in an effort to strengthen practices and protocols. In 2013, NIST and DOJ announced an initiative to develop guidance groups that have

now become the OSAC. An important goal of OSAC is help identify and develop technically sound, consensus-based documentary standards and guidelines to improve the practice of forensic science in a coordinated manner.

#### 3.1. Technical/scientific working groups

In order to help promote quality assurance efforts in forensic DNA, the FBI Laboratory established the Technical Working Group on DNA Analysis Methods (TWGDAM) in November 1988 [25]. TWGDAM issued quality assurance guidelines in 1989 [26], 1991 [27], and 1995 [28] which served as predecessors for the Quality Assurance Standards issued by the FBI’s DNA Advisory Board in October 1998 [29] and April 1999 [30]. The success of TWGDAM lead to the formation of other TWGs: TWGFIBE for fibers (in 1992), TWGFAST for friction ridge analysis (fingerprints) (in 1995), TWGDRUG for drug analysis (in 1997), TWGIT for imaging technologies (in 1997), and TWGDOC for documents (in 1997).

Beginning in 1998, TWGs were changed to Scientific Working Groups (SWGs) such that TWGDAM became SWGDAM, TWGFAST became SWGFAST, etc. TWGFIBE became SWGMAT expanding beyond fibers to other aspects of trace materials. Three additional SWGs were also added in 1998: SWGDE covering digital evidence, SWGGUN covering firearms and toolmarks, and SWGFEX working with fire debris and explosives. Additional SWGs have been added since the turn of the century (Table 3).

Collectively the 21 SWGs listed in Table 3 have had over 750 participants and over the years of their existence have produced more than 250 documents. Seven of these 21 SWGs were created after the 2009 NRC report [1]. In addition, at least three other SWGs existed previously with FBI funding: SWGIBRA covering illicit business records, SWGMGF dealing with microbial genetics and forensics, and SWGCBRN working on chemical, biological, radiological, and nuclear terrorism [31].

These SWGs operated independently and without consistent procedures for membership, document development, etc. In a presentation he gave in May 2010, Judge Harry Edwards expressed specific concerns about the SWGs [7]. At that time, he listed the following concerns: “(1) SWG committees meet irregularly and

have no clear or regular sources of funding; (2) there are no clear standards in place to determine who gains membership on SWG committees; (3) neither SWGs nor their recommendations are mandated by any federal or state law or regulation; (4) SWG recommendations are not enforceable; (5) a number of SWG guidelines are too general and vague to be of any great practical use; (6) SWG committees have no way of knowing whether state or local agencies even endorse the standards; (7) complaints are not filed when a practitioner violates a SWG standard; and (8) SWG committees do not attempt to measure the impact of their standards by formal study or survey” [7]. Judge Edwards summarized his SWG concerns: “In other words, there is nothing to indicate that the standards are routinely followed and enforced in a way to ensure best practices in the forensic science community” [7].

As of late 2014, NIJ and the FBI stopped funding the vast majority of SWGs except SWGDAM and SWGDE. While the Drug Enforcement Administration (DEA) continues to fund some aspects of SWGDRUG, it is expected that the activities and efforts of the SWGs will be transitioned into the OSAC efforts that were first described to the forensic science community in February 2014 and are in the process of being established [18].

### 3.2. Organization of Scientific Area Committees (OSAC)

OSAC is a NIST-administered effort to provide subject matter expertise to the development of forensic science documentary standards within the United States. The goal of OSAC is to populate a registry of standards and a registry of guidelines with documents that can be used to improve the practice of forensic science and adopted by accrediting bodies to evaluate the quality of work in forensic laboratories. The enforcement of OSAC standards will come through the voluntary accreditation process and the performance of laboratory audits.

OSAC consists of 33 operating units (Fig. 1): a forensic science standards board (FSSB), three resource committees, five scientific area committees (SACs), and 24 subcommittees that focus on specific discipline needs [32]. Most topic areas covered across the 21 SWGs listed in Table 3 are part of the 24 subcommittees. OSAC is more expansive though than the SWGs with the addition of an odontology subcommittee and two DNA subcommittees where one focuses on methods and the other on data interpretation. The availability of resource committee expertise in human factors, legal issues, and quality infrastructure further strengthen the overall capabilities of OSAC.

The initial OSAC membership, which was finalized in December 2014, consists of 542 individuals. Some individuals serve at more than one level of the organization. For example, the five SAC chairs are part of the FSSB and subcommittee chairs participate on their SAC as well as their subcommittee. There are up to 20 voting members on each subcommittee and up to 15 voting members on each SAC. Membership terms across the organization are for three years with initial members serving for two-, three-, or four-year staggered terms. Those who applied but were not selected as part of the initial group of voting members are eligible to serve as OSAC affiliates by receiving an invitation from an OSAC unit chair to participate on task groups to address specific topics.

To reduce costs, most of the OSAC activities are performed via virtual meetings. After development of documents at the subcommittee level (often through focused efforts of an assigned task group), these documents are evaluated at the SAC level where public comments are sought and considered as documents are being reviewed. Documents and webcast archives from public SAC meetings as well as the OSAC charter and terms of reference are available on the public OSAC workspace [33]. The first public SAC meetings were held in February 2015 in Orlando, Florida, in conjunction with the American Academy of Forensic Sciences (AAFS) conference.

An initial gathering of a catalog of 718 standards and guidelines (best practices) covering all aspects of forensic science [34] is serving as a starting point for OSAC efforts. As documents on this catalog are reviewed, prioritized, and revised, they will be considered for inclusion on the OSAC Registry of Standards if technical merit and an appropriate consensus-based documentary standards development process have been met. New standards may also be developed by OSAC or in collaboration with a standard developing organization. Standards must be approved at the SAC level and FSSB level to become part of the OSAC Registry of Standards whereas guidelines are approved by the SAC to be listed on the OSAC Registry of Guidelines. OSAC provides a level of coordination that has never existed before and will hopefully lead to important improvements in the practice of forensic science in the near future.

### 4. Federally funded research in forensic science

Most forensic science research in the United States is funded through the National Institute of Justice (NIJ), which is part of the U.S. Department of Justice's Office of Justice Programs. However, other public research programs and funding opportunities do exist through the National Science Foundation (NSF), Department of

**Table 4**

A summary of the application reviews on forensic science published in the journal *Analytical Chemistry* from 1983 to 2011 (see [46–60]).

Year published	Years covered	# Articles reviewed	# DNA articles reviewed	DNA (%)
1983 [46]	1981 & 1982	490	0	0.0
1985 [47]	1983 & 1984	536	0	0.0
1987 [48]	1985 & 1986	496	6	1.2
1989 [49]	1987 & 1988	602	18	3.0
1991 [50]	1989 & 1990	691	48	6.9
1993 [51]	1991 & 1992	824	102	12.4
1995 [52]	1993 & 1994	843	146	17.3
1997 [53]	1995 & 1996	811	152	18.7
1999 [54]	1997 & 1998	782	138	17.6
2001 [55]	1999 & 2000	243	91	37.4
2003 [56]	2001 & 2002	469	148	31.6
2005 [57]	2003 & 2004	789	250	31.7
2007 [58]	2005 & 2006	560	181	32.3
2009 [59]	2007 & 2008	552	163	29.5
2011 [60]	2009 & 2010	575	122	21.2
	Total	9263	1565	16.9

Defense, the Department of Homeland Security, the Combating Terrorism Technical Support Office, and the National Institutes of Health (NIH). Some of these organizations fund basic research that is eventually shown to have forensic science applications. There is currently no overarching structure or organization monitoring what is being funded or trying to determine what gaps and needs may exist.

In February 2014, the White House Office of Science and Technology Policy issued *Strengthening Forensic Science: A Progress Report* [35], which highlighted a number of accomplishments with research funding in recent years. This progress report primarily focuses on research efforts conducted or federal funding provided through NIJ, NSF, or NIST, which will be briefly discussed below.

#### 4.1. National Institute of Justice (NIJ)

The National Institute of Justice's Office of Investigative and Forensic Sciences has over a six year period (2009–2014) awarded more than 250 research grants and \$125 million for the forensic sciences [35–37]. Each year multiple solicitations are made for proposals addressing forensic science improvement. Between 2009 and 2014, NIJ issued 23 solicitations that resulted in 269 funded research projects [36]. According to an April 2015 summary, these NIJ grantees have produced 77 final technical reports, 255 publications, and 640 presentations on their research findings [36].

A listing of open and closed projects by discipline topic can be accessed on the NIJ website [38]. For example, under the “Crime Scene Investigation” area as of November 2014, there are 28 awards listed (10 of which are still open) totaling \$11,826,253 [38]. In the area of forensic DNA, more than \$48 million has gone into over 100 projects covering nine topic areas: (1) alternative genetic markers, (2) compromised DNA evidence, (3) human DNA quantitation, (4) general tools and information, (5) miniaturization and automation, (6) mitochondrial DNA, (7) non-human DNA, (8) sperm detection and separation, and (9) Y-chromosome [38].

NIJ has also partnered with NIST to produce guidance documents on latent print examination [39] and biological evidence

preservation [40]. The February 2012 document on human factors in latent print examination represents a multi-year effort from a 35-member expert working group that produced 34 recommendations and detailed process maps to improve the practice [39]. The April 2013 document on biological evidence preservation came from a technical working group of 22 members and provides 28 recommendations covering issues surrounding retaining biological evidence as well as packaging and storing it [40].

NIJ signed a Memorandum of Understanding with NSF in October 2012 to provide opportunities for joint review and co-funding work in social, behavioral, and forensic sciences [41].

#### 4.2. National Science Foundation (NSF)

NSF has a mission to fund basic research and thus has not traditionally been viewed as a source of funding for forensic science efforts, which by their nature are more applied. However, in August 2013, NSF issued a “Dear Colleague Letter” inviting proposals to any directorate across NSF that cover fundamental research questions with the potential to advance aspects of forensic science [42]. In May 2014, NSF and NIJ announced the availability of grants for Industry/University Cooperative Research Centers (I/UCRCs) [43]. The I/UCRC program seeks to develop long-term partnerships among industry, universities, and government agencies. While NSF (with seed funding from NIJ) provides some financial support to establish the center, research funds come from center membership fees. According to a search of the NSF awards database as of April 2015, NSF planning grants to establish forensic I/UCRCs have been given to Iowa State University, Florida International University, West Virginia University, George Washington University, Northeastern University, and Michigan State University.

According to the OSTP February 2014 progress report [35], NSF found in a recent scan of their public awards database almost 200 projects relevant to forensic science. They note, however, that most of these projects have more of an education rather than a research component.

**Table 5**

A summary of information reviewed as part of the most recent Interpol tri-annual International Forensic Science Managers Symposium covering literature and activities from 2010 to 2013 [61].

Topic	Author(s)	Numbers of references cited
Firearms	Erwin J.A.T. Mattijseen (Netherlands Forensic Institute)	159
Gun shot residue	Sébastien Charles and Bart Nys (INCC-NICC Brussels, Belgium)	49
Toolmarks	Nadav Levin (Israel National Police)	189
Paint	Laetitia Heudt, Marc Lannoy, Gilbert De Roy, Laurent Kohler (INCC-NICC Brussels, Belgium)	201
Fibers and textiles	Ray Palmer (Northumbria University, UK)	68
Forensic geology	Ritsuko Sugita, Hiromi Itamiya, Hirofumi Fukushima (National Research Institute of Police Science, Japan)	221 cited but only 102 references listed
Arson & fire debris analysis	Niina Viitala and Mika Hyypä (National Bureau of Investigation, Finland)	157 cited but only 140 references listed
Explosives & explosive residues	Douglas J. Klapec and Greg Czarnopys (Bureau of Alcohol, Tobacco, Firearms and Explosives, USA)	1341
Drug evidence	Jeffrey H. Comparin and Robert F.X. Klein (Drug Enforcement Administration, USA)	668
Toxicology	Wai-ming Tam, Lai-chu Chim, Wing-sum Chan, Tai-wai Wong, Kit-mai Fung, Wing-cheong Wong, Wai-kit Lee, Wing-sze Lee, Kit-man Fan (Hong Kong Government Laboratory)	324
Forensic audio analysis	Catalin Grigoras, Jeff M. Smith, Geoffrey Stewart Morrison, Ewald Enzinger (University of Colorado-Denver, USA and University of New South Wales, Australia)	133
Forensic video analysis	Matthew E. Graves (United States Army Criminal Investigation Laboratory)	31
Imaging	Arnout Ruifrok, Zeno Geradts, Jerrien Bijhold (Netherlands Forensic Institute)	256
Digital evidence	Paul Reedy and Jaime Buzzeo (Department of Forensic Science, District of Columbia and A.I. Solutions at NASA Headquarters, USA)	190
Fingermarks and other impressions	Nicole Egli, Sébastien Moret, Andy Bécue, Christophe Champod (University of Lausanne, Switzerland)	472
Body fluid identification and DNA typing in forensic biology	Christine Jolicoeur (Ministry of Public Security, Québec, Canada)	114
Questioned documents	Franck Partouche (IRCGN, Rosny Sous Bois, France)	275
Forensic science management	Max M. Houck, Melissa Porter, Bronwen Davies (Department of Forensic Sciences and George Washington University, Washington, DC, USA)	120



**Table 6**

Annotated bibliographies supplied to the Research, Development, Technology, and Evaluation Interagency Working Group (RDT&E IWG) by various groups in response to specific questions regarding the foundational literature in support of specific forensic disciplines. These bibliographies are available at <http://www.nist.gov/forensics/workgroups.cfm#B> [62].

Forensic discipline	Number of articles or amount of information provided to RDT&E IWG	Submitter	Received by RDT&E IWG
Firearms & toolmarks	24 primary references (94 pages of material responding to 25 questions)	Association of Firearm and Tool Mark Examiners (AFTE) and SWGGUN	June 14, 2011
Bloodstain pattern analysis	39 pages responding to 19 questions	SWGSTAIN	September 29, 2011
Bitemark analysis	62 pages responding to 18 questions	American Board of Forensic Odontology (ABFO)	October 2, 2011
Fiber analysis	32 pages responding to 18 questions	SWGSTAT	October 18, 2011
Shoeprint & tire tread	38 pages responding to 14 questions	SWGTREAD	November 16, 2011
Latent print analysis	63 pages responding 74 questions	SWGFAST	November 17, 2011
Arson investigation & burn pattern analysis	32 pages responding to 16 questions	T/SWGFEX	December 12, 2011
Digital evidence	11 pages responding to 18 questions	SWGDE	January 17, 2012
Hair analysis	21 pages responding to 20 questions	SWGSTAT	September 21, 2012
Paint & other coatings	29 pages responding to 19 questions	SWGSTAT	September 21, 2012

Since 2009, NSF has funded two workshops on forensic science issues (see Table 2). A “Cognitive Bias and Forensic Science” workshop was organized by law professor Jonathan Koehler and held September 23 and 24, 2010 at Northwestern Law School in Chicago, Illinois. Purdue University chemistry professor Graham Cooks organized “Strengthening Forensic Science through Connections with the Analytical Sciences”, which was held December 3 and 4, 2012 in Arlington, Virginia. The first workshop involved 19 participants and produced a 57-page report [44]. The second workshop involved 59 participants and presenters and resulted in a 96-page report [45].

#### 4.3. NIST research program

NIST has performed forensic science research in a number of areas over the past century. For several decades, NIJ supported NIST research efforts through interagency agreements with the NIST Office of Law Enforcement Standards (OLEs). Since 2011, most funds to conduct forensic science research have come to NIST directly from Congress although some support from other agencies continues. As of early 2015, there were six primary focus areas for NIST intramural research in forensic science: (1) ballistics and associated tool marks, (2) digital and identification forensics, (3) forensic genetics, (4) toxins and drug analysis, (5) trace evidence,

**Table 7**

Listing of recent NIST-sponsored webcasts and events.

Date	Topic	Website
July 10–11, 2012	Measurement science and standards in forensic firearms analysis	<a href="http://www.nist.gov/oles/forensics_firearms_2012.cfm">http://www.nist.gov/oles/forensics_firearms_2012.cfm</a>
November 28–30, 2012	Forensics@NIST 2012	<a href="http://www.nist.gov/oles/forensics-2012.cfm">http://www.nist.gov/oles/forensics-2012.cfm</a>
January 28–30, 2013	ANSI/NIST-ITL Standard Workshop 2013	<a href="http://www.nist.gov/itl/iad/ig/ansi_workshop_jan_2013.cfm">http://www.nist.gov/itl/iad/ig/ansi_workshop_jan_2013.cfm</a>
April 12, 2013	DNA analyst training on mixture interpretation	<a href="http://www.nist.gov/oles/forensics/dna-analyst-training-on-mixture-interpretation.cfm">http://www.nist.gov/oles/forensics/dna-analyst-training-on-mixture-interpretation.cfm</a>
April 30–May 1, 2013	Emerging trends in synthetic drugs workshop	<a href="http://www.nist.gov/oles/synthetic_drugs.cfm">http://www.nist.gov/oles/synthetic_drugs.cfm</a>
June 4–5, 2013	Measurement science and standards in forensic handwriting analysis	<a href="http://www.nist.gov/oles/handwriting.cfm">http://www.nist.gov/oles/handwriting.cfm</a>
November 19–20, 2013	DNA technical leader summit	Held in Norman, Oklahoma in conjunction with the FBI CODIS Conference (event was not webcast)
February 18, 2014	Organization of Scientific Area Committees (OSAC) webcast from AAFS	<a href="http://www.nist.gov/forensics/aafswebcast.cfm">http://www.nist.gov/forensics/aafswebcast.cfm</a>
March 24, 2014	Cloud computing forensic science workshop	<a href="http://www.nist.gov/itl/forensic-science-workshop.cfm">http://www.nist.gov/itl/forensic-science-workshop.cfm</a>
May 28, 2014	NIST DNA analyst webinar series: probabilistic genotyping and software programs (Part 1)	<a href="http://www.nist.gov/forensics/nist-dna-analyst-webinar-series-pt1.cfm">http://www.nist.gov/forensics/nist-dna-analyst-webinar-series-pt1.cfm</a>
June 18, 2014	NIST mobile forensics workshop and webcast	<a href="http://www.nist.gov/forensics/mobile_forensics2.cfm">http://www.nist.gov/forensics/mobile_forensics2.cfm</a>
August 6, 2014	NIST DNA analyst webinar series: validation concepts and resources (Part 1)	<a href="http://www.nist.gov/forensics/nist-dna-analyst-webinar-series-validation-concepts-and-resources-part-1.cfm">http://www.nist.gov/forensics/nist-dna-analyst-webinar-series-validation-concepts-and-resources-part-1.cfm</a>
September 18, 2014	NIST DNA analyst webinar series: probabilistic genotyping and software programs (Part 2)	<a href="http://www.nist.gov/forensics/dna-analyst-webinar-probabilistic-genotyping-software-programs.cfm">http://www.nist.gov/forensics/dna-analyst-webinar-probabilistic-genotyping-software-programs.cfm</a>
December 3–4, 2014	Forensics@NIST 2014	<a href="http://www.nist.gov/forensics/forensics-at-nist-2014.cfm">http://www.nist.gov/forensics/forensics-at-nist-2014.cfm</a>
January 26–27, 2015	Improving biometric and forensic technology: the future of research datasets	<a href="http://www.nist.gov/forensics/biometric-forensic-technology-webcast.cfm">http://www.nist.gov/forensics/biometric-forensic-technology-webcast.cfm</a>
February 16–17, 2015	Public meetings of the five OSAC Scientific Area Committees	<a href="https://workspace.forensicosac.org/kws/public">https://workspace.forensicosac.org/kws/public</a>
July 20–24, 2015	International symposium on forensic science error management: detection, measurement and mitigation	<a href="http://www.nist.gov/director/international_forensics_home.cfm">http://www.nist.gov/director/international_forensics_home.cfm</a>

and (6) statistics. In addition, other agencies fund additional research at NIST in explosives detection, fingerprint analysis, and fire research. More information on NIST research is available at <http://www.nist.gov/forensics/research/index.cfm>.

In August 2014, NIST announced a competition to establish a Forensic Science Center of Excellence. This work, which will begin at the awarded universities in mid-2015, will focus on developing probabilistic methods for dealing with pattern evidence and digital evidence and providing training materials with these new methods. More information is available at <http://www.nist.gov/coe/forensics/>.

## 5. Progress report and thoughts on the future

This next section provides a brief look on the progress made in recent years, forensic literature reviews, efforts underway to evaluate foundational literature, and recent online training events.

### 5.1. Office of Science and Technology Policy progress report

In connection with the first NCFS meeting, the White House's Office of Science and Technology Policy released a 10-page report entitled "Strengthening Forensic Science: A Progress Report, February 2014" [35]. This report is organized into eight parts: (1) federally sponsored forensic science research activities, (2) development of standards, guidelines, and best practices, (3) efforts to strengthen the federal research agenda, (4) progress with strengthening scientific capacity, (5) new technology and tools, (6) selected workshops and symposia, (7) education and training, and (8) international collaborations. To be able to move the entire forensic enterprise forward, continued progress will be needed in each of these areas. Hopefully future progress reports can be prepared and shared at regular intervals.

### 5.2. Forensic science literature reviews

Over the years a number of literature summaries have been gathered to reflect publications on various topics in forensic science. Table 4 provides a summary listing of *Analytical Chemistry* application reviews that covered three decades of forensic science publications and activities spanning from 1980 to 2010. A total of 15 review articles were published every other year during this time period [46–60]. These articles initially focused on three aspects of forensic science: (1) drugs and poison, (2) forensic biochemistry, and (3) trace evidence. However, over the years coverage of the literature reviewed expanded to additional forensic activities. Across the 15 articles, the number of articles reviewed ranged from 243 in 2001 [55] to 843 in 1995 [52] with 9263 citations in total (Table 4). Almost 17% of these articles (1565) relate to DNA.

Tom Brettell and Rich Saferstein began these reviews while working at the New Jersey State Police Forensic Science Bureau (Hamilton, NJ) and the first eight reviews (1983–1997) were written solely by them [46–53]. Additional co-authors were included in more recent reviews to gain further expertise on specific forensic disciplines. In their 1999, 2001, and 2003 reviews, Norah Rudin and Keith Inman participated as co-authors to survey forensic DNA topics [54–56]. John Butler covered forensic DNA information for the 2005, 2007, 2009, and 2011 reviews [57–60]. Jose Almirall replaced Rich Saferstein on the 2007, 2009, and 2011 reviews to examine trace evidence [58–60].

These *Analytical Chemistry* application reviews [46–60] surveyed articles primarily from the *Journal of Forensic Sciences*, *Science & Justice* (and its predecessor *Journal of the Forensic Science Society* prior to 1995), *Forensic Science International* (and its daughter journal *Forensic Science International: Genetics* after 2007), *Journal of the Canadian Society of Forensic Science* *Journal*

*of Forensic Identification*, *Forensic Science Review*, *Analytical Toxicology*, *The Microscope*, and *Chemical Abstracts*. While the review article information is helpful to define the range of literature published during the time periods covered, the brief descriptions given for each article in no way attempt to prioritize publications listed or provide an assessment of the quality of the work. The reviews were methods-focused to enable readers to find information that might aid forensic laboratory work.

Another set of literature reviews to aid international forensic science efforts is compiled regularly by Interpol. Interpol holds a forensic science symposium every three years that involves a review of literature in multiple forensic disciplines. In the most recent proceedings, a total of 4968 references were cited in the 18 different reviews covering the time frame of 2010 to 2013. This last cycle of reviews following the Interpol International Forensic Science Managers Symposium in October 2013 is currently the only set that is available on the Interpol website [61]. Table 5 summarizes the 18 topics reviewed in 2013. The depth of coverage for each topic varied from 1341 articles cited in the review covering explosives and explosives residue to only 31 publications cited in the forensic video analysis summary. Authors of these forensic discipline summaries were from Australia, Belgium, Canada, Finland, France, Hong Kong, Israel, Japan, the Netherlands, Switzerland, the United Kingdom, and the United States (see Table 5).

### 5.3. Foundational literature evaluation

As mentioned previously, annotated bibliographies were provided to the Subcommittee on Forensic Science's RDT&E IWG in 2010 and 2011 for 10 forensic disciplines (Table 6) [62]. These bibliographies furnished the SWG membership perspective for that discipline at the time and were given in response to specific questions raised by the RDT&E IWG. For example, the latent print bibliography was prepared by a dedicated task force from the University of Lausanne under the direction of Professor Christophe Champod. The 63 pages of material provided by this group give commentary on 87 references organized by questions such as "what scientific literature establishes the key sources of bias and characterizes the effectiveness of measures to mitigate bias?" and "what scientific literature describes how distinct or similar fingerprints are across: The overall population? Related individuals? Identical twins?" [63].

At the third NCFS meeting in August 2014, the Arnold Foundation and the American Association for the Advancement of Science (AAAS) announced a plan to provide an analysis of foundational literature in forensic science building upon the efforts of the RDT&E IWG bibliographies and more recent sources [64]. AAAS has assembled a nine-member advisory committee and plans to conduct a quality and gap analysis of ten forensic disciplines: (1) bloodstain pattern analysis, (2) digital evidence, (3) fire investigations, (4) firearms and toolmarks/ballistics, (5) footwear and tire tracks, (6) forensic odontology-bitemark analysis, (7) latent fingerprints, (8) trace evidence-fibers, (9) trace evidence-hair, and (10) trace evidence-paint and other coatings [64]. Evaluations of the first three of the ten disciplines under examination are expected to be released before the end of 2015.

In January 2015, the NCFS approved a views document relating to scientific literature in support of forensic science and practice [65]. This document states: "The NCFS believes that a comprehensive evaluation of the scientific literature is critical for the advancement of forensic science policy and practice in the United States. While other forms of dissemination of research and practice (e.g., oral and poster presentations at meetings, workshops, personal communications, editorials, dissertations, theses, and letters to editors) play an important role in science, the open, peer-

reviewed literature is what endures and forms a foundation for further advancements” [65]. This document further specifies that foundational, scientific literature supportive of forensic practice should meet criteria such as being published in journals that utilize rigorous peer review and are indexed in searchable databases to enable relevant articles to be easily located.

#### 5.4. Training and technology transition

For new methods and technology to have an impact they must be transitioned from research into effective practice in a forensic casework environment. An important part of technology transition is training. The National Forensic Science Technology Center (NFSTC) in Largo, Florida has provided in-person and on-line training courses for many years. For example, twenty technology transition workshops conducted between 2007 and 2011 are available on the NFSTC website [66]. The NIJ Forensic Technology Center of Excellence administered by RTI International in Raleigh, North Carolina provides regular in-person workshops and on-line training events [67].

Since 2012, NIST has also provided a number of free webinars and webcasts of meetings to aid training forensic scientists in a number of areas including DNA mixture interpretation, validation, and use of probabilistic genotyping software programs (Table 7). Forensics@NIST conferences held in 2012 [68] and 2014 [69] that showcased NIST research efforts in forensic science were webcast and archived videos of presentations are available for future viewing.

Over the years, technical assistance funding, such as the Paul Coverdell Forensic Science Improvement Grants Program and DNA capacity building programs administered by NIJ, has provided forensic laboratories with opportunity and resources to transition to new technologies. Without the funding to increase capacity of operations, a laboratory might not have the incentive or ability to

evaluate, purchase, validate, and implement new methods, instrumentation, and analytical software.

#### 5.5. Summary and a look to the future

As described in this review article, a great deal of activity has occurred in an effort to strengthen forensic science disciplines since the NRC report was published more than six years ago. However, there is still much to be done, and more progress has been made on some of the NRC recommendations than on others. The National Commission on Forensic Science and the Organization of Scientific Area Committees are beginning to take action on policy and practice issues, respectively. Progress is being made on many fronts by various stakeholders in the forensic science community. To meet the many needs for strengthening all of the forensic disciplines in the future, increased research funding and focused efforts will continue to be crucial. A commitment to make appropriate changes will need to come from laboratory management and staff. Embracing change will be possible as communication improves among the many stakeholders who create and use forensic services.

### 6. International standards in forensic DNA

The second part of this review article covers standards available around the world related to forensic DNA analysis. Two types of standards will be described: (1) documentary or paper standards, which are sometimes referred to as technical standards that provide specific requirements for the operation of a laboratory process, and (2) physical or measurement standards, which in the form of certified reference materials aid in the calibration of laboratory measurements. Proper use of these two types of standards helps make processes more consistent within and among laboratories. Reliable data comparison among laboratories

**Table 8**

Summary of available documentary standards and guidelines on forensic DNA. If an earlier version of a document has been superseded, then only the latest version (as of April 2015) is noted.

Source (date)	Document title	Reference
DNA Advisory Board (1998/1999)	FBI Quality Assurance Standards (QAS) for forensic and databasing laboratories	[29,30]
SWGAM (2011)	Revised FBI QAS for forensic and databasing laboratories and accompanying audit documents	[82]
SWGAM (2010)	Interpretation guidelines for autosomal STR typing by forensic DNA testing laboratories	[83]
SWGAM (2012)	Validation guidelines for DNA analysis methods	[84]
SWGAM (2013)	Interpretation guidelines for mitochondrial DNA analysis by forensic DNA testing laboratories and mitochondrial DNA nomenclature examples document	[85,86]
SWGAM (2013)	Training guidelines	[87]
SWGAM (2014)	Guidelines for missing persons casework	[88]
SWGAM (2014)	Interpretation guidelines for Y-chromosome STR typing	[89]
SWGAM (2014)	Guidelines for STR enhanced detection methods	[90]
SWGAM (2015)	Guidelines for the collection and serological examination of biological evidence	[91]
ENFSI DNA WG (2010)	Recommended minimum criteria for the validation of various aspects of the DNA profiling process	[92]
ENFSI DNA WG (2010)	Training DNA staff: concept training document	[93]
ENFSI DNA WG (2010)	Contamination prevention guidelines	[94]
ENFSI DNA WG (2014)	DNA database management: review and recommendations	[95]
Interpol (2009)	Interpol handbook on DNA data exchange and practice	[96]
NIST/NIJ (2013)	Biological evidence preservation handbook: best practices for evidence handlers	[97]
UK Forensic Regulator (2012)	The interpretation of DNA evidence	[98]
UK Forensic Regulator (2014)	Forensic science providers: codes of practice and conduct	[99]
UK Forensic Regulator (2014)	DNA analysis: codes of practice and conduct	[100]
UK Forensic Regulator (2014)	Allele frequency databases and reporting guidance for the DNA-17 profiling	[101]
UK Forensic Regulator (2014)	DNA contamination detection—the management and use of staff elimination DNA databases	[102]
UK Forensic Regulator (2014)	Forensic science providers: validation	[103]
IFSA (2014)	Minimum requirements for DNA collection, analysis, and interpretation: a document for emerging laboratories	[104]

is also enabled by standard data formats and core DNA testing regions. One of the primary reasons that DNA is on a more solid scientific foundation compared to many of the other forensic disciplines is a community-wide use of standard methods and materials to produce quality measurements [70].

Organizations involved in developing standards and guidelines for forensic DNA include SWGDAM in the United States and Canada started in 1988 (see Table 3 and earlier discussion), the European Network of Forensic Science Institutes (ENFSI) DNA Working Group started in 1995, and the UK Forensic Science Regulator started in 2008 [71]. In addition, the International Society for Forensic Genetics (ISFG) DNA Commission regularly publishes recommendations on DNA polymorphisms, allele nomenclature, non-human DNA, disaster victim identification, and interpretation of DNA mixtures [72]. It is expected that the OSAC subcommittees which are focused on DNA methods and interpretation will begin producing new technical standards and guidelines in the near future that will be available world-wide.

### 6.1. Documentary standards

Documentary standards with technical specifications are created by standard developing organizations (SDOs). International standards organizations include the International Organization for Standardization (ISO) [73], the International Electrotechnical Commission (IEC) [74], and the International Telecommunication Union (ITU) [75]. Within the United States, the American National Standards Institute (ANSI) founded in 1918 [76] serves as coordinator of the U.S. private sector led standards system and organizes U.S. representation to ISO and IEC.

ANSI regularly publishes *Essential Requirements for Due Process* [77]. These essential requirements emphasize openness, lack of dominance, balance of interest, coordination and harmonization, public notification of standards development, appropriate consideration of views and objections raised, evidence of a consensus vote, an appeals mechanism, and written procedures for methods used in standards development [77].

Once technical documentary standards are developed they can be used by accrediting bodies as a means to assess adherence of an audited laboratory to defined written processes. This conformity assessment for laboratory testing is most often performed with ISO/IEC 17025 and supplemental documents. Forensic DNA laboratories in the United States and elsewhere are commonly accredited to ISO/IEC 17025 with the FBI Quality Assurance

Standards serving as the primary supplemental document. A primary incentive for U.S. forensic DNA laboratories to adhere to the FBI's Quality Assurance Standards is that access to the National DNA database and federal grant funds are contingent on successfully being accredited to these standards.

### 6.2. ISO/IEC 17025

International standard ISO/IEC 17025 (current version 2005 is often written ISO/IEC 17025:2005) covers general requirements for the competence of testing and calibration laboratories [78]. The focus of the document is on management requirements (Section 4) and technical requirements (Section 5). The technical requirements include topics such as method validation (Section 5.4), measurement traceability (Section 5.6), and reporting the results (Section 5.10).

Currently three accrediting bodies accredit forensic DNA laboratories in the United States using ISO/IEC 17025:2005. These three accrediting bodies are the American Society of Crime Laboratory Directors/Laboratory Accreditation Board (ASCLD/LAB) [79], ANSI-ASQ National Accreditation Board (ANAB, formerly Forensic Quality Systems or FQS) [80], and the American Association for Laboratory Accreditation (A2LA) [81]. Previously a number of forensic laboratories were accredited under a "Legacy Program" with ASCLD/LAB, but all new accreditations are now under the ASCLD/LAB International Accreditation Program that utilized ISO/IEC 17025. ASCLD/LAB, ANAB, and A2LA utilize the FBI Quality Assurance Standards as supplemental information when accrediting forensic laboratories in the area of DNA analysis.

### 6.3. FBI Quality Assurance Standards

Although laboratories internationally may consider the FBI's policies and actions, specific requirements exist for U.S. forensic DNA laboratories. As mentioned above, within the United States, all accredited laboratories using the national DNA database or desiring federal grant funding have to adhere to the FBI's Quality Assurance Standards (QAS) [29,30,82]. The most recent version of the QAS went into effect in September 2011 although a recent addendum was made for rapid DNA testing in December 2014 [82]. The QAS require regular inspection audits by accrediting bodies, continuing education of laboratory staff, semiannual proficiency tests of analysts, performance validation of methods, use of traceable measurement standards, and technical review of results.

**Table 9**

Summary of ISFG DNA Commission recommendations, which are available at <http://www.isfg.org/Publications/DNA+Commission>.

Source (Date)	Document Title	Reference
ISFG (1989)	Recommendations of the Society for Forensic Haemogenetics concerning DNA polymorphisms	[105]
ISFG (1992)	1991 Report concerning recommendations of the DNA Commission of the International Society for Forensic Haemogenetics relating to the use of DNA polymorphisms	[106]
ISFG (1992)	Recommendations of the DNA Commission of the International Society for Forensic Haemogenetics relating to the use of PCR-based polymorphisms	[107]
ISFG (1994)	DNA recommendations—1994 report concerning further recommendations of the DNA Commission of the ISFH regarding PCR-based polymorphisms in STR (short tandem repeat) systems	[108]
ISFG (1997)	Further report of the DNA Commission of the ISFG regarding the use of short tandem repeat systems	[109]
ISFG (2000)	Guidelines for mitochondrial DNA Typing	[110]
ISFG (2001)	Recommendations on forensic analysis using Y-chromosome STRs	[111]
ISFG (2002)	Paternity Testing Commission: recommendations on genetic investigations in paternity cases	[112]
ISFG (2006)	Update of the recommendations on the Use of Y-STRs in forensic analysis	[113]
ISFG (2006)	Recommendations on the interpretation of mixtures	[114]
ISFG (2007)	Recommendations regarding the role of forensic genetics for disaster victim identification (DVI)	[115]
ISFG (2007)	Recommendations on biostatistics in paternity testing	[116]
ISFG (2011)	Recommendations regarding the use of non-human (animal) DNA in forensic genetic investigations	[117]
ISFG (2012)	Recommendations on the evaluation of STR typing results that may include drop-out and/or drop-in using probabilistic methods	[118]
ISFG (2014)	Revised and extended guidelines for mitochondrial DNA typing	[119]

**Table 10**

Summary of dates and activities around selection and application of core forensic DNA markers (short tandem repeats, STRs) in Europe and the United States.

European Dates	U.S. dates	Activity
Early 1990s	Early 1990s	Initial STR papers [122–125]
1995	1994	DNA Identification Act authorizes FBI to develop a national DNA database
		UK National DNA database began with 6 STRs (SGM) [126]
	1997	Selection of U.S. CODIS core 13 STR loci [127,128]
	1998	U.S. National DNA Index System (NDIS) launched
1998		Initial Interpol European Standard Set (ESS) 4 STR loci [131]
1999		ESS increased to 7 STRs; UK goes to 10 STRs (SGM Plus) [131]
2004		EDNAP degraded DNA interlaboratory study conducted [131]
2005		EDNAP/ENFSI recommend new loci [131]
2005		Agreement for European data sharing (Prüm treaty) [131]
2006		Letters to editor announce proposed new loci [129,130]
2007–2008		Prototype kits developed and tested
2009		ENFSI votes to expand ESS to 12 STR loci [131]
2010		New STR kits released to meet European requirements
	2010	FBI Core STR Working Group begins considering expanding U.S. core loci
2011		Implementation of expanded ESS 12 required in Europe
	2011	Expanded CODIS set proposed [132]
	2012	New STR kits released to meet U.S. requirements; U.S. population data collected [134]
	2013–2014	FBI consortium validation project test of 24 plex STR kits
	2015	New CODIS 20 core loci announced [133]
	2017	Implementation expanded CODIS 20 required in the U.S. [133]

There are 17 topics covered in the revised (and original) QAS: (1) scope, (2) definitions, (3) quality assurance program, (4) laboratory organization and management, (5) personnel, (6) facilities, (7) evidence/sample control, (8) validation, (9) analytical procedures, (10) equipment calibration and maintenance, (11) reports/documentation, (12) review, (13) proficiency testing, (14) corrective action, (15) audits, (16) safety, and (17) outsourcing.

#### 6.4. DNA guidance documents

Table 8 summarizes documentary standards and guidelines available to aid forensic DNA analysis efforts. The currently available guidance documents come from SWGDAM, the ENFSI DNA Working Group, the UK Forensic Regulator, and the International Forensic Strategic Alliance (IFSA). Strict adherence to guidelines is typically not considered essential in laboratory accreditation audits. Guidelines typically define best practices using words such as “should” or “may” rather than “shall” or “must”.

For most of the past three decades, the Scientific Working Group on DNA Analysis Methods (SWGDAM) and its predecessor TWGDAM have produced helpful guidelines on training, validation, missing persons casework, and interpretation of autosomal short tandem repeats (STRs), mitochondrial DNA, and Y-chromosome STRs (see <http://www.swgdam.org>). SWGDAM consists of around 20 members and an equal number or more invited guests that meet semiannually, typically in January and July, through funding from the FBI Laboratory. Tony Onorato from the FBI Laboratory is the current chair of SWGDAM. Table 8 includes citations to the most recent versions of SWGDAM guidelines.

The ENFSI DNA Working Group is one of now 17 working groups in ENFSI (see <http://enfsi.eu>). This group meets at least once a year, typically in April, and consists of about 100 representatives from 35 European countries (see <http://www.enfsi.eu/about-enfsi/structure/working-groups/dna>). A number of invited guests also contribute to the discussions and work products. The current chair of the group is Roman Hradil from the Institute of Criminalistics in Prague, Czech Republic. Subgroups cover topics such as DNA analysis and interpretation, quality assurance, DNA databases, automation and expert systems, and forensic biology.

ENFSI guidelines have been created for minimum validation requirements [92], DNA staff training [93], and contamination prevention [94]. The ENFSI DNA Working Group website also includes reports on criminal cases solved by DNA mass screens, DNA legislation in Europe, a survey of DNA databases in Europe, and a document on DNA database management. Since its first edition in 2008, the ENFSI DNA Database Management document is revised each April by Kees van der Beek from the Netherlands Forensic Institute. The 2014 document is 88 pages long with 33 recommendations and questions provided for audit purposes [95].

Table 9 summarizes publications from the International Society for Forensic Genetics (ISFG) DNA Commission. ISFG recommendations help standardize allele nomenclature and methods for DNA typing and interpretation. It is expected that many of these standards and guidelines will be considered for the OSAC Registry of Standards and Registry of Guidelines discussed earlier.

#### 6.5. Quality manufacturing standards

Standards efforts should lead to improved working methods. An important concern with sensitive methods is the possibility of DNA contamination in disposable plastic-ware and other reagents used in forensic laboratories. A 2010 publication coordinated European, North American, and Australian/New Zealand positions regarding manufacturers of disposable plastic-ware and other reagents [120]. This publication advocates that manufacturers: (1) utilize automation in manufacturing lines, (2) minimize interaction of staff with manufacturing lines, (3) ensure products are protected from staff using personal protective equipment, (4) utilize clean rooms for production, (5) perform QC checks with adequate sensitivity, (6) conduct post-manufacture DNA contaminant destruction, (7) perform QC checks on post-production treatment(s), and (8) maintain staff elimination databases for screening DNA results as needed [120].

From earlier efforts in Australia and the UK, an international standard is in the process of being developed to help ensure quality results from products used in DNA testing. Manufacturers are already preparing to implement quality standards based on what will eventually become ISO/IEC 18385 “Minimizing the risk of DNA contamination in products used to collect and analyze biological material for forensic purposes” [121].

## 7. Data standards

Standardizing data formats is essential for effectively comparing information among laboratories. First, the same core set of DNA markers need to be examined in order to compare results among different testing laboratories. Second, the description of DNA marker results needs to be consistent from test to test. This is referred to as allele nomenclature. Third, if computer databases are used to share data, then information needs to be in a common data format in order to share it and make sense of what is being transmitted. Each of these data standardization issues is briefly discussed below.

### 7.1. Core markers

For DNA typing markers to be effective across a wide number of jurisdictions, a common set of standardized markers must be used. Table 10 summarizes time frames and activities for core loci selection and expansion efforts in Europe and the United States. The initial groups of STR loci that are commonly used in human identity testing were characterized and developed either in the laboratory of Dr. Thomas Caskey at the Baylor College of Medicine [122,123] or at the Forensic Science Service (FSS) in England [124,125].

The UK began their National DNA database in April 1995 using six STRs (TH01, vWA, FGA, D8S1179, D18S51, and D21S11) [126], and Europe adopted the early UK DNA markers plus D3S1358 as their initial European Standard Set (ESS) of seven core STR loci. In November 1997 the United States settled on a set of 13 core STR markers to use with the FBI's Combined DNA Index System (CODIS) software and about a year later launched the National DNA Index System (NDIS) [127,128]. The CODIS 13 core loci include the seven ESS loci plus D16S539, TPOX, CSF1PO, D5S818, D7S820, and D13S317 [128]. Because D16S539 is part of many STR typing kits, there are typically eight loci that overlap between U.S. and European DNA tests. Over the past two decades, NDIS has grown to more than 10 million DNA profiles. Several European national DNA databases now exceed 1 million DNA profiles (see [95]). Due to concerns with potential adventitious matches when comparing within and between large DNA databases, the number of required loci have been expanded in recent years.

In April 2009 the ENFSI DNA Working Group adopted five additional STRs (D1S1656, D2S441, D10S1248, D12S391, and D22S1045) as part of their extended core [129–131]. An FBI-sponsored CODIS Core Loci Working Group began work in May 2010 and recommended an expanded set of loci in 2011 [132]. Following an extensive validation study, an expanded set of 20 required STR loci was announced in 2015 with the goal to require implementation of the new 20 CODIS Core Loci by January 1, 2017 [133]. The additional seven markers are the five new STRs used in Europe (see above) plus D2S1338 and D19S433 that are widely used in commercial STR kits. Variability of these STR markers in U. S. population has been studied and published by NIST [134]. Thus, when needed, future comparisons among DNA profiles containing the expanded CODIS core and the expanded ESS will have 15 DNA markers in common.

### 7.2. Allele nomenclature

Uniform designation of STR allele calls in forensic DNA typing is achieved by comparison of the DNA fragment sizes in DNA profiles to common allelic ladders available in commercial kits that measure the same DNA region. For traceability purposes, these kit allelic ladders can be calibrated with physical reference materials prepared by NIST (see below). Common strategies and formats for

STR allele designation have been defined by ISFG (see [108,109,113]) and described in more detail elsewhere [135].

### 7.3. Standard data formats

Data storage and transmission standards to aid software developers have long been championed by NIST for interchange of biometric information. The ANSI/NIST-ITL (American National Standards Institute/National Institute of Standards and Technology-Information Technology Laboratory) Standard Data Format provides record types that include biometric fingerprint, iris, dental, voice information, and DNA. Within the 623 page document that makes up the December 2013 version of the ANSI/NIST-ITL standard, there are 24 pages that cover DNA records. Codes are provided for 64 autosomal STR loci, 64 X-STRs, and 135 Y-STRs as well as 88 DNA kits from the three major manufacturers. This data format standard is regularly revised (see [http://www.nist.gov/itl/iad/ig/ansi\\_standard.cfm](http://www.nist.gov/itl/iad/ig/ansi_standard.cfm)).

## 8. Physical reference standards

Physical standards or reference materials enable calibration of test results from core DNA markers to a common allele nomenclature. Reference DNA samples are crucial to the validation of any DNA testing procedure. Standard 9.5.5 in the revised Quality Assurance Standards states: "The laboratory shall check its DNA procedures annually or whenever substantial changes are made to the protocol(s) against an appropriate and available NIST standard reference material or standard traceable to a NIST standard" [82]. NIST supplies several DNA standard reference materials (SRMs) to enable validation of a laboratory's measurement capabilities as well as calibration of instrumentation and methods (see Table 7.7 in [70]).

The most widely used NIST DNA reference material for STR typing measurements is SRM 2391c, which in its latest revision provides six DNA samples with certified genotype values for 25 autosomal STR loci and 29 Y-chromosome STR loci [136]. Further reference and information genotypes are available for 27 additional autosomal STR loci, 12 X-chromosome STRs, and 30 insertion/deletion markers [136]. A DNA quantitation reference material is also available (SRM 2372 [137]). Further information on STR markers used in forensic DNA typing is available on the NIST STRBase website [138].

Lessons learned from the benefits of DNA standards and certified reference materials have helped other forensic science disciplines. For example, the firearms and toolmark community have worked with NIST since 1998 to create a standard bullet (SRM 2460) and a standard cartridge case (SRM 2461). Use of these SRMs has led to improved software algorithms and interoperability across forensic laboratories performing ballistics measurements [139]. Experiences with developing DNA documentary standards may also aid ongoing efforts in other forensic science disciplines (e.g., [18]). Hopefully future efforts in documentary and physical reference standard development will be more collaborative across forensic science disciplines as the OSAC activities described earlier move forward.

## Acknowledgments

Numerous NIST and DOJ colleagues provided input and suggestions to this manuscript including Susan Ballou, Andrew Bruck, Richard Cavanagh, Mike Coble, Jennifer Huergo, John Paul Jones, Robin Jones, Jonathan McGrath, Toni Roberts, Nelson Santos, Tania Simoncelli, Becky Hill Steffen, Mark Stolorow, Melissa Taylor, Robert Thompson, Peter Vallone, and Shannan Williams. Points of view in this document are those of the author and do not

necessarily represent the official position or policies of the U.S. Department of Justice or the National Institute of Standards and Technology. Certain commercial equipment, instruments, and materials are identified in order to specify experimental procedures as completely as possible. In no case does such identification imply a recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that any of the materials, instruments, or equipment identified are necessarily the best available for the purpose.

## References

- [1] National Academy of Sciences, Strengthening Forensic Science in The United States: A Path Forward, National Academies Press, Washington, D.C. 2009.
- [2] K.M. Pyrek, Forensic Science Under Siege: The Challenges of Forensic Laboratories and the Medico-legal Death Investigation System, Elsevier Academic Press, San Diego, 2007.
- [3] B.L. Garrett, Convicting the Innocent: Where Criminal Prosecutions Go Wrong, Harvard University Press, Cambridge, MA, 2011.
- [4] S.A. Cole, Forensic science and wrongful convictions: from exposure to contributor to corrector, *N. Engl. Law Rev.* 46 (2012) 711–736.
- [5] R.B. Stacey, Report on the erroneous fingerprint individualization in the Madrid train bombing case *Forensic Sci. Commun.* 7. Available at: [http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/special\\_report/2005\\_special\\_report.htm](http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/special_report/2005_special_report.htm), 2005 (accessed 25.03.15).
- [6] U.S. Department of Justice, Office of Inspector General, A Review of the FBI's Handling of the Brandon Mayfield Case. March 2006 Report. Available at: <http://www.justice.gov/oig/special/s0601/final.pdf>, 2006 (accessed 25.03.15).
- [7] H.T. Edwards, The National Academy of Sciences Report on Forensic Sciences: what it means for the bench and the bar. Presentation at the Superior Court of the District of Columbia Conference on The Role of the Courts in an Age of Developing Science & Technology, Held in Washington, D.C. May 6, 2010. Available at: [http://www.law.yale.edu/documents/pdf/alumni\\_affairs/stith\\_edwards\\_nas\\_report\\_forensic\\_science.pdf](http://www.law.yale.edu/documents/pdf/alumni_affairs/stith_edwards_nas_report_forensic_science.pdf), 2010 (accessed 13.03.15).
- [8] Charter of the Subcommittee on Forensic Science, Committee on Science, National Science and Technology Council. Available at: <https://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic-science-subcommittee-charter.pdf>, 2015 (accessed 13.03.15).
- [9] Renewed Charter of the Subcommittee on Forensic Science. Available at: [https://www.whitehouse.gov/sites/default/files/sofs\\_charter\\_2012\\_signed.pdf](https://www.whitehouse.gov/sites/default/files/sofs_charter_2012_signed.pdf), 2015 (accessed 13.03.15).
- [10] Charter of the Inter-agency Working Group on Accreditation and Certification. Available at: <https://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic-science-accred-cert.pdf>, 2015 (accessed 13.03.15).
- [11] Charter of the Inter-agency Working Group on Standards, Practices and Protocols. Available at: <https://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic-science-stand-pract-prot.pdf>, 2015 (accessed 13.03.15).
- [12] Charter of the Inter-agency Working Group on Education, Ethics and Terminology. Available at: <https://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic-science-education-ethics.pdf>, 2015 (accessed 13.03.15).
- [13] Charter of the Inter-agency Working Group on Research, Development, Testing and Evaluation. Available at: <https://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic-science-rdte.pdf>, 2015 (accessed 13.03.15).
- [14] Charter of the Inter-agency Working Group on Outreach and Communication. Available at: <https://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic-science-outreach-comm.pdf>, 2015 (accessed 13.03.15).
- [15] National Science and Technology Council, Committee on Science, Subcommittee on Forensic Science, Strengthening the Forensic Sciences. Available at: [https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/strengthening\\_the\\_forensic\\_sciences\\_may\\_-\\_2014.pdf](https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/strengthening_the_forensic_sciences_may_-_2014.pdf), 2015 (accessed 25.03.15).
- [16] M.R. DuRose, K.A. Walsh, A.M. Burch, Census of Publicly Funded Forensic Crime Laboratories, 2009, U.S. Department of Justice, Bureau of Justice Statistics, August 2012. Available at <http://www.bjs.gov/content/pub/pdf/cpffc109.pdf>, 2009 (accessed 25.03.15).
- [17] NIST/DOJ press release (15 February 2013). Department of Justice and National Institute of Standards and Technology Announce Launch of National Commission on Forensic Science. Available at: <http://www.nist.gov/oles/doj-nist-forensic-science021513.cfm> or <http://www.justice.gov/opa/pr/department-justice-and-national-institute-standards-and-technology-announce-launch-national>, 2013 (accessed 25.03.15).
- [18] J.M. Butler, The National Commission on Forensic Science and the Organization of Scientific Area Committees, Proceedings of the International Symposium on Human Identification. Available at <http://www.promega.com/products/pm/genetic-identity/ishi-conference-proceedings/25th-ishi-oral-presentations/>, 2014 (accessed 13.03.15).
- [19] Federal Advisory Committee Act. Information available at: <http://www.gsa.gov/faca>, 2015 (accessed 25.03.15).
- [20] NCFCS 2013 Charter. Available at: [http://www.facadatabase.gov/download.aspx?fn=Charters/83353\\_Charter\\_\(2013-05-03-10-42-45\).pdf](http://www.facadatabase.gov/download.aspx?fn=Charters/83353_Charter_(2013-05-03-10-42-45).pdf), 2013 (accessed 25 March 2015).
- [21] T.B.P.M. Tjin-A-Tsoi, Trends, Challenges and Strategy in the Forensic Science Sector, March 2013. Available at: [http://www.forensicinstitute.nl/about\\_nfi/](http://www.forensicinstitute.nl/about_nfi/), 2013 (accessed 25.03.15).
- [22] M.M. Houck, R.A. Riley, P.J. Speaker, T.S. Witt, FORESIGHT: a business approach to improving forensic science services, *Forensic Sci. Policy Manag.* 1 (2009) 85–95.
- [23] M. Houck, P.J. Speaker, A.S. Fleming, R.A. Riley, The balanced scorecard: sustainable performance assessment for forensic laboratories, *Sci. Justice* 52 (2012) 209–216.
- [24] J. Peterson, M. Hickman, Forensic science practice in the united states, in: D. H. Ubelaker (Ed.), *The Global Practice of Forensic Science*, Wiley-Blackwell, Hoboken, NJ, 2015, pp. 301–334 (Chapter 28).
- [25] SWGDAM, History of DNA QA Standards and SWGDAM, January 2013 presentation available at: <http://www.swgdam.org/History%20of%20QA%20%20SWGDAM%20Jan%202013.pdf>, 2013 (accessed 07.04.15).
- [26] J. Kearney, et al., Guidelines for a quality assurance program for DNA restriction fragment length polymorphism analysis, *Crime Lab. Dig.* 16 (2) (1989) 40–59.
- [27] J. Kearney, et al., Guidelines for a quality assurance program for DNA analysis, *Crime Lab. Dig.* 18 (2) (1991) 44–75.
- [28] B. Budowle, et al., Guidelines for a quality assurance program for DNA analysis, *Crime Lab. Dig.* 22 (2) (1995) 20–43.
- [29] DNA Advisory Board for Federal Bureau of Investigation, Quality assurance standards for forensic DNA testing laboratories, *Forensic Sci. Commun.* 2(3). Available at: <http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/july2000/codispre.htm/codis2a.htm>, 2000 (accessed 07.04.15).
- [30] DNA Advisory Board for Federal Bureau of Investigation. Quality assurance standards for convicted offender DNA databasing laboratories, *Forensic Sci. Commun.* 2(3). Available at: <http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/july2000/codispre.htm/codis1a.htm>, 2000 (accessed 07.04.15).
- [31] D.E. Adams, K.L. Lothridge, Scientific working groups, *Forensic Science Communications* 2(3). Available at: <http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/july2000/swgroups.htm>, 2000 (accessed 25.03.15).
- [32] OSAC website: <http://www.nist.gov/forensics/osac/index.cfm>, 2015 (accessed 27.04.15).
- [33] Forensic OSAC public workspace: <https://workspace.forensicosac.org/kws/public>, 2015 (accessed 27.04.15).
- [34] OSAC Catalog of Standards and Guidelines: <http://www.nist.gov/forensics/osac/standards-guidelines-catalog.cfm>, 2015 (accessed 27.04.15).
- [35] White House Office of Science and Technology Policy, Strengthening Forensic Science: A Progress Report, February 2014. Available at: [http://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic\\_science\\_progress\\_2-14-14.pdf](http://www.whitehouse.gov/sites/default/files/microsites/ostp/forensic_science_progress_2-14-14.pdf), 2015 (accessed 27.04.15).
- [36] National Institute of Justice, The Impact of Forensic Science Research and Development, April 2015 (accessed 27.04.15).
- [37] Forensic Technology Center of Excellence, Project Update to the National Institute of Justice: NIJ R&D Portfolio Management and Technology Transition Support Report Summary, July 2014. Available at: <https://rti.connectsolutions.com/p9gbz920bwc>, 2014 (accessed 27.04.15).
- [38] NIJ Forensic Science Research and Development Projects: <http://nij.gov/topics/forensics/pages/forensic-awards.aspx>, 2015 (accessed 27.04.15).
- [39] M.K. Taylor, et al., Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach, February 2012. Available at: [http://www.nist.gov/manuscript-publication-search.cfm?pub\\_id=910745](http://www.nist.gov/manuscript-publication-search.cfm?pub_id=910745), 2012 (accessed 27.04.15).
- [40] S.M. Ballou, et al., The Biological Evidence Preservation Handbook: Best Practices for Evidence Handlers, April 2013. Available at: <http://nvlpubs.nist.gov/nistpubs/ir/2013/NIST.IR.7928.pdf>, 2013 (accessed 27.04.15).
- [41] National Science Foundation, Dear Colleague Letter: National Science Foundation and National Institute of Justice Collaboration in the Social, Behavioral and Forensic Sciences, October 2012. Available at: <http://www.nsf.gov/pubs/2013/nsf13007/nsf13007.pdf>, 2012 (accessed 27.04.15).
- [42] National Science Foundation, Dear Colleague Letter: Forensic Science – Opportunity for Breakthroughs in Fundamental and Basic Research and Education, August 2013. Available at <http://www.nsf.gov/pubs/2013/nsf13120/nsf13120.pdf>, 2013 (accessed 27.04.15).
- [43] National Science Foundation and the National Institute of Justice, Dear Colleague Letter – I/UCRCs in Areas Relevant to the Forensic Sciences, May 2014. Available at: <http://www.nsf.gov/pubs/2014/nsf14066/nsf14066.pdf>, 2014 (accessed 27.04.15).
- [44] J.J. Koehler, J. Meixner, Workshop on Cognitive Bias and Forensic Science: Northwestern University School of Law, September 23–24. Available at: <https://northwestern.app.box.com/s/y5fmlmf7jdvd58s3uuxvh1j6vdqzq4>, 2010 (accessed 27.04.15).
- [45] Science on Location: Forensic Science on the Move, Strengthening Forensic Science Through Connections with the Analytical Sciences: A Report from a National Science Foundation Supported Workshop Held December 3–4, 2012 in Arlington, Virginia. Previously available at: <https://www.chem.purdue.edu/docs/ForensicWorkshopFinalReport.pdf>.

- [46] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 55 (5) (1983) 19R–31R.
- [47] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 57 (5) (1985) 175R–187R.
- [48] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 59 (12) (1987) 162R–174R.
- [49] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 61 (12) (1989) 95R–109R.
- [50] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 63 (12) (1991) 148R–164R.
- [51] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 65 (12) (1993) 293R–310R.
- [52] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 67 (12) (1995) 273R–294R.
- [53] T.A. Brettell, R. Saferstein, *Forensic science, Anal. Chem.* 69 (12) (1997) 123R–143R.
- [54] T.A. Brettell, K. Inman, N. Rudin, R. Saferstein, *Forensic science, Anal. Chem.* 71 (12) (1999) 235R–255R.
- [55] T.A. Brettell, K. Inman, N. Rudin, R. Saferstein, *Forensic science, Anal. Chem.* 73 (12) (2001) 2735–2743.
- [56] T.A. Brettell, N. Rudin, R. Saferstein, *Forensic science, Anal. Chem.* 75 (12) (2003) 2877–2890.
- [57] T.A. Brettell, J.M. Butler, R. Saferstein, *Forensic science, Anal. Chem.* 77 (12) (2005) 3839–3860.
- [58] T.A. Brettell, J.M. Butler, J.R. Almirall, *Forensic science, Anal. Chem.* 79 (12) (2007) 4365–4384.
- [59] T.A. Brettell, J.M. Butler, J.R. Almirall, *Forensic science, Anal. Chem.* 81 (12) (2009) 4695–4711.
- [60] T.A. Brettell, J.M. Butler, J.R. Almirall, *Forensic science, Anal. Chem.* 83 (12) (2011) 4539–4556.
- [61] Interpol, 17th Interpol International Forensic Science Managers Symposium, Lyon, 8th–10th October 2013, Review Papers (edited by Prof. Niamh Nic Daeid). Available at <http://www.interpol.int/content/download/21910/206602/version/1/file/IFSMReviewPapers2013.pdf>, 2013 (accessed 27.04.15).
- [62] Annotated Bibliographies of Foundational Forensic Science Research as Supplied by a Scientific Working Group or Other Professional Organization: <http://www.nist.gov/forensics/workgroups.cfm#B>, 2015 (accessed 21.04.15).
- [63] SWGFAST Response to the Research, Development, Testing & Evaluation Inter-Agency Working Group of the National Science and Technology Council, Committee on Science, Subcommittee on Forensic Science: <http://www.nist.gov/forensics/upload/Annotated-Bibliography-latent-print-analysis.pdf>, 2015 (accessed 29.04.15).
- [64] Forensic Science Assessments: A Quality and Gap Analysis: <http://www.aas.org/page/forensic-science-assessments-quality-and-gap-analysis>, 2015 (accessed 29.04.15).
- [65] Scientific Literature in Support of Forensic Science and Practice NCFS views document: [http://www.justice.gov/sites/default/files/ncfs/pages/attachments/2015/02/25/scientific\\_literature\\_views\\_document\\_as\\_adopted\\_1\\_30\\_15.pdf](http://www.justice.gov/sites/default/files/ncfs/pages/attachments/2015/02/25/scientific_literature_views_document_as_adopted_1_30_15.pdf), 2015 (accessed 29.04.15).
- [66] Technology Transition Workshops at the NFSTC: [http://projects.nfstc.org/tech\\_transition/](http://projects.nfstc.org/tech_transition/), 2015 (accessed 29.04.15).
- [67] NIJ Forensic Technology Center of Excellence: <https://www.forensiccoe.org/>, 2015 (accessed 29.04.15).
- [68] Forensics@NIST. <http://nist.gov/oles/forensics-2012.cfm>, 2012 (accessed 29.04.15).
- [69] Forensics@NIST. (accessed 29.04.15).
- [70] J.M. Butler, *Quality assurance and validation, Advanced Topics In Forensic DNA Typing: Methodology*, Elsevier Academic Press, San Diego, 2012:167–211 (Chapter 7).
- [71] J.M. Butler, *Forensic DNA advisory groups: dab, swgdam, enfsi, and bsag*, in: J. A. Siegel, P.J. Saukko (Eds.), *Encyclopedia of Forensic Sciences*, second ed., Elsevier Academic Press, San Diego, 2013, pp. 339–343.
- [72] ISFG DNA Commission publications: <http://www.isfg.org/Publications/DNA+Commission>, 2015 (accessed 21.03.15).
- [73] International Organization for Standardization (ISO): <http://www.iso.org/iso/home.html>, 2015 (accessed 04.05.15).
- [74] International Electrotechnical Commission (IEC): <http://www.iec.ch/>, 2015 (accessed 04.05.15).
- [75] International Telecommunications Union (ITU): <http://www.itu.int>, 2015 (accessed 04.05.15).
- [76] American National Standards Institute (ANSI): <http://www.ansi.org>, 2015 (accessed 04.05.15).
- [77] American National Standards Institute. ANSI Essential Requirements: Due process requirements for American National Standards. Available at: <http://www.ansi.org/essentialrequirements>, 2015 (accessed 04.05.15).
- [78] ISO/IEC 17025:2005. General Requirements for the Competence of Testing and Calibration Laboratories. Available at: <http://www.iso.org>, 2015 (accessed 04.05.15).
- [79] American Society of Crime Laboratory Directors/Laboratory Accreditation Board. <http://www.ascl-d-lab.org/>, 2015 (accessed 04.05.15).
- [80] ANSI-ASQ National Accreditation Board. <http://anab.org/>, 2015 (accessed 04.05.15).
- [81] American Association for Laboratory Accreditation (A2LA). <http://www.a2la.org/>, 2015 (accessed 04.05.15).
- [82] Revised FBI. QAS for Forensic and Databasing Laboratories and accompanying audit documents. Available at: <http://www.fbi.gov/about-us/lab/biometric-analysis/codis> (accessed 04.05.15).
- [83] SWGDAM (2010). Interpretation Guidelines for Autosomal STR Typing by Forensic DNA Testing Laboratories. Available at: [http://swgdam.org/Interpretation\\_Guidelines\\_January\\_2010.pdf](http://swgdam.org/Interpretation_Guidelines_January_2010.pdf) (accessed 04.05.15).
- [84] SWGDAM (2012). Validation Guidelines for DNA Analysis Methods. Available at: [http://swgdam.org/SWGDAM\\_Validation\\_Guidelines\\_APPROVED\\_Dec\\_2012.pdf](http://swgdam.org/SWGDAM_Validation_Guidelines_APPROVED_Dec_2012.pdf) (accessed 04.05.15).
- [85] SWGDAM. Interpretation Guidelines for Mitochondrial DNA Analysis by Forensic DNA Testing Laboratories. Available at: [http://swgdam.org/SWGDAM%20mtDNA\\_Interpretation\\_Guidelines\\_APPROVED\\_073013.pdf](http://swgdam.org/SWGDAM%20mtDNA_Interpretation_Guidelines_APPROVED_073013.pdf), 2012 (accessed 04.05.15).
- [86] SWGDAM. Mitochondrial DNA Nomenclature Examples Document. Available at: [http://swgdam.org/SWGDAM\\_Mitochondrial\\_DNA\\_Nomenclature\\_Examples\\_EB\\_APPROVED\\_05052014.pdf](http://swgdam.org/SWGDAM_Mitochondrial_DNA_Nomenclature_Examples_EB_APPROVED_05052014.pdf), 2012 (accessed 04.05.15).
- [87] SWGDAM (2013). Training Guidelines. Available at: <http://swgdam.org/SWGDAM%20Training%20Guidelines%20APPROVED%20January%202013.pdf>, 2013 (accessed 04.05.15).
- [88] SWGDAM (2014). Guidelines for Missing Persons Casework. Available at: [http://swgdam.org/SWGDAM\\_Guidelines\\_for\\_MP\\_Casework\\_APPROVED\\_01092014.pdf](http://swgdam.org/SWGDAM_Guidelines_for_MP_Casework_APPROVED_01092014.pdf), 2014 (accessed 04.05.15).
- [89] SWGDAM. Interpretation Guidelines for Y-Chromosome STR Typing. Available at: [http://swgdam.org/SWGDAM\\_YSTR\\_Guidelines\\_APPROVED\\_01092014\\_v\\_02112014\\_FINAL.pdf](http://swgdam.org/SWGDAM_YSTR_Guidelines_APPROVED_01092014_v_02112014_FINAL.pdf), 2014 (accessed 04.05.15).
- [90] SWGDAM. Guidelines for STR Enhanced Detection Methods. Available at: <http://swgdam.org/SWGDAM%20Guidelines%20for%20STR%20Enhanced%20Detection%20Methods%20FINAL%20100614.pdf>, 2014 (accessed 04.05.15).
- [91] SWGDAM. Guidelines for the Collection and Serological Examination of Biological Evidence. Available at: <http://swgdam.org/SWGDAM%20Guidelines%20for%20Biological%20Evidence%20APPROVED%201152015.pdf>, 2015 (accessed 04.05.15).
- [92] ENFSI DNA Working Group. Recommended Minimum Criteria for the Validation of Various Aspects of the DNA Profiling Process. Available at: [http://www.enfsi.eu/sites/default/files/documents/minimum\\_validation\\_guidelines\\_in\\_dna\\_profiling\\_-\\_v2010\\_0.pdf](http://www.enfsi.eu/sites/default/files/documents/minimum_validation_guidelines_in_dna_profiling_-_v2010_0.pdf), 2010 (accessed 04.05.15).
- [93] ENFSI DNA Working Group. Training DNA. Staff: Concept Training Document. Available at: [http://www.enfsi.eu/sites/default/files/documents/recommendations\\_for\\_the\\_training\\_of\\_dna\\_staff\\_-\\_v2010\\_0.pdf](http://www.enfsi.eu/sites/default/files/documents/recommendations_for_the_training_of_dna_staff_-_v2010_0.pdf), 2010 (accessed 04.05.15).
- [94] ENFSI DNA Working Group. Contamination Prevention Guidelines. Available at: [http://www.enfsi.eu/sites/default/files/documents/dna\\_contamination\\_prevention\\_guidelines\\_for\\_the\\_file\\_contamination\\_prevention\\_final\\_-\\_v2010\\_0.pdf](http://www.enfsi.eu/sites/default/files/documents/dna_contamination_prevention_guidelines_for_the_file_contamination_prevention_final_-_v2010_0.pdf), 2010 (accessed 04.05.15).
- [95] ENFSI DNA Working Group. DNA Database Management: Review and Recommendations. Available at: [http://www.enfsi.eu/sites/default/files/documents/enfsi\\_2014\\_document\\_on\\_dna-database\\_management\\_0.pdf](http://www.enfsi.eu/sites/default/files/documents/enfsi_2014_document_on_dna-database_management_0.pdf), 2014 (accessed 04.05.15).
- [96] Interpol Handbook on DNA Data Exchange and Practice. Available at: <http://www.interpol.int/content/download/8993/66934/version/6/file/HandbookPublic2009.pdf>, 2015 (accessed 04.05.15).
- [97] Biological Evidence Preservation Handbook: Best Practices for Evidence Handlers. Available at: <http://www.nist.gov/forensics/evidence-management.cfm>, 2015 (accessed 04.05.15).
- [98] P. Gill, J. Guinness, S. Iveson, *The interpretation of DNA evidence (including low-template DNA)*. Available at: <https://www.gov.uk/government/publications/the-interpretation-of-dna-evidence>, 2012 (accessed 04.05.15).
- [99] UK Forensic Regulator. Forensic Science Providers: Codes of Practice and Conduct. Available at: <https://www.gov.uk/government/publications/forensic-science-providers-codes-of-practice-and-conduct-2014>, 2014 (accessed 04.05.15).
- [100] UK Forensic Regulator (2014). DNA Analysis: Codes of Practice and Conduct. Available at: <https://www.gov.uk/government/publications/dna-analysis-codes-of-practice-and-conduct>, 2014 (accessed 04.05.15).
- [101] UK Forensic Regulator. Allele frequency databases and reporting guidance for the DNA-17 profiling. Available at: <https://www.gov.uk/government/publications/allele-frequency-databases-and-reporting-guidance-for-the-dna-17-profiling>, 2014 (accessed 04.05.15).
- [102] UK Forensic Regulator. DNA contamination detection –the management and use of staff elimination DNA databases. Available at: <https://www.gov.uk/government/publications/dna-contamination-detection>, 2014 (accessed 04.05.15).
- [103] UK Forensic Regulator. Forensic Science Providers: validation. Available at: <https://www.gov.uk/government/publications/forensic-science-providers-validation>, 2014 (accessed 04.05.15).
- [104] International Forensic Strategic Alliance. Minimum requirements for DNA collection, analysis, and interpretation: a document for emerging laboratories. International Forensic Strategic Alliance. Available at: [http://www.enfsi.eu/sites/default/files/documents/IFSA/ifsa\\_dna\\_mrd\\_2014.pdf](http://www.enfsi.eu/sites/default/files/documents/IFSA/ifsa_dna_mrd_2014.pdf), 2014 (accessed 04.05.15).



- [105] B. Brinkmann, et al., Editorial: Recommendations of the Society for Forensic Haemogenetics concerning DNA polymorphisms, *Forensic Sci. Int.* 43 (1989) 109–111.
- [106] B. Brinkmann, et al., Editorial: 1991 report concerning recommendations of the DNA Commission of the International Society for Forensic Haemogenetics relating to the use of DNA polymorphisms, *Forensic Sci. Int.* 52 (1992) 125–130.
- [107] W. Bär, et al., Editorial: recommendations of the DNA Commission of the International Society for Forensic Haemogenetics relating to the use of PCR-based polymorphisms, *Forensic Sci. Int.* 55 (1992) 1–3.
- [108] W. Bär, et al., DNA recommendations—1994 report concerning further recommendations of the DNA Commission of the ISFH regarding PCR-based polymorphisms in STR (short tandem repeat) systems, *Int. J. Leg. Med.* 107 (1994) 159–160.
- [109] W. Bär, et al., DNA recommendations—further report of the DNA Commission of the ISFH regarding the use of short tandem repeat systems, *Int. J. Leg. Med.* 110 (1997) 175–176.
- [110] A. Carracedo, et al., DNA Commission of the International Society for Forensic Genetics: guidelines for mitochondrial DNA typing, *Forensic Sci. Int.* 110 (2000) 79–85.
- [111] P. Gill, et al., DNA Commission of the International Society of Forensic Genetics: Recommendations on forensic analysis using Y-chromosome STRs, *Forensic Sci. Int.* 124 (2001) 5–10.
- [112] N. Morling, et al., Paternity Testing Commission of the International Society of Forensic Genetics: recommendations on genetic investigations in paternity cases, *Forensic Sci. Int.* 129 (2002) 148–157.
- [113] L. Gusmão, et al., DNA Commission of the International Society of Forensic Genetics (ISFG): an update of the recommendations on the use of Y-STRs in forensic analysis, *Forensic Sci. Int.* 157 (2006) 187–197.
- [114] P. Gill, et al., DNA Commission of the International Society of Forensic Genetics: recommendations on the interpretation of mixtures, *Forensic Sci. Int.* 160 (2006) 90–101.
- [115] M. Prinz, et al., DNA Commission of the International Society for Forensic Genetics (ISFG): recommendations regarding the role of forensic genetics for disaster victim identification (DVI), *Forensic Sci. Int. Genet.* 1 (2007) 3–12.
- [116] D.W. Gjetson, et al., ISFG: recommendations on biostatistics in paternity testing, *Forensic Sci. Int. Genet.* 1 (2007) 223–231.
- [117] A. Linacre, et al., ISFG: recommendations regarding the use of non-human (animal) DNA in forensic genetic investigations, *Forensic Sci. Int. Genet.* 5 (2011) 501–505.
- [118] P. Gill, et al., DNA Commission of the International Society for Forensic Genetics: recommendations on the evaluation of STR typing results that may include drop-out and/or drop-in using probabilistic methods, *Forensic Sci. Int. Genet.* 6 (2012) 679–688.
- [119] W. Parson, et al., DNA Commission of the International Society for Forensic Genetics: revised and extended guidelines for mitochondrial DNA typing, *Forensic Sci. Int. Genet.* 13 (2014) 134–142.
- [120] P. Gill, D. Rowlands, G. Tully, I. Bastisch, T. Staples, P. Scott, Manufacturer contamination of disposable plastic-ware and other reagents –an agree position statement by ENFSI SWGDAM, and BSAG, *Forensic Sci. Int. Genet.* 4 (2010) 269–270.
- [121] K. Pearson, A. Glebs, E. McCombs, Manufacturing High-Quality Forensic Tools –Promega Quality Standards, Profiles in DNA. Available at: <http://www.promega.com/resources/profiles-in-dna/manufacturing-high-quality-forensic-tools-promega-quality-standards/> 2010 (accessed 04.05.15).
- [122] A. Edwards, A. Civitello, H.A. Hammond, C.T. Caskey, DNA typing and genetic mapping with trimeric and tetrameric tandem repeats, *Am. J. Hum. Genet.* 49 (1991) 746–756.
- [123] H.A. Hammond, L. Jin, Y. Zhong, C.T. Caskey, R. Chakraborty, Evaluation of 13 short tandem repeat loci for use in personal identification applications, *Am. J. Hum. Genet.* 55 (1994) 175–189.
- [124] C.P. Kimpton, P. Gill, A. Walton, A. Urquhart, E.S. Millican, M. Adams, Automated DNA profiling employing multiplex amplification of short tandem repeat loci, *PCR Methods Appl.* 3 (1993) 13–22.
- [125] A. Urquhart, C.P. Kimpton, T.J. Downes, P. Gill, Variation in short tandem repeat sequences—a survey of twelve microsatellite loci for use as forensic identification markers, *Int. J. Leg. Med.* 107 (1994) 13–20.
- [126] D.J. Werrett, The national DNA database, *Forensic Sci. Int.* 88 (1997) 33–42.
- [127] B. Budowle, T.R. Moretti, S.J. Niezgoda, B.L. Brown, CODIS and PCR-based short tandem repeat loci: law enforcement tools, Proc. 2nd European Symp. Hum. Ident. Available at: <http://www.promega.com/~media/files/resources/conference%20proceedings/ishi%2002/oral%20presentations/17.pdf>, 1998 (accessed 04.05.15).
- [128] J.M. Butler, Genetics and genomics of core short tandem repeat loci used in human identity testing, *J. Forensic Sci.* 51 (2006) 253–265.
- [129] P. Gill, L. Fereday, N. Morling, P.M. Schneider, The evolution of DNA databases—recommendations for new European STR loci, *Forensic Sci. Int.* 156 (2006) 242–244.
- [130] P. Gill, L. Fereday, N. Morling, P.M. Schneider, New multiplexes for Europe—amendments and clarification of strategic development, *Forensic Sci. Int.* 163 (2006) 155–157.
- [131] P.M. Schneider, Expansion of the European Standard Set of DNA Database Loci—the Current Situation, Profile in DNA 12, 6–7. Available at: <http://www.promega.com/resources/profiles-in-dna/2009/expansion-of-the-european-standard-set/>, 2009 (accessed 04.05.15).
- [132] D.R. Hares, Expanding the CODIS core loci in the United States, *Forensic Sci. Int. Genet.* 6 (2012) e52–e54 [erratum in *Forensic Sci. Int. Genet.* 6(2012) e135].
- [133] D.R. Hares, Selection and implementation of expanded CODIS core loci in the United States, *Forensic Sci. Int. Genet.* 17 (2015) 33–34.
- [134] J.M. Butler, C.R. Hill, M.D. Coble, Variability of new STR loci and kits in U.S. population groups, Profiles in DNA. Available at: <http://www.promega.com/resources/profiles-in-dna/2012/variability-of-new-str-loci-and-kits-in-us-population-groups/>, 2012 (accessed 04.05.15).
- [135] J.M. Butler, Short tandem repeat (STR) loci and kits, *Advanced Topics In Forensic DNA Typing: Methodology*, Elsevier Academic Press, San Diego, 2012:99–139 (Chapter 5).
- [136] National Institute of Standards and Technology, Certificate of Analysis for Standard Reference Material (SRM) 2391: PCR-Based DNA Profiling Standard. Available at: [https://www-s.nist.gov/srmors/view\\_cert.cfm?srn=2391C](https://www-s.nist.gov/srmors/view_cert.cfm?srn=2391C), 2015 (accessed 04.05.15).
- [137] M.C. Kline, D.L. Diewer, J.C. Travis, M.V. Smith, J.W. Redman, P.M. Vallone, A.E. Decker, J.M. Butler, Production and certification of NIST Standard Reference Material 2372 Human DNA Quantitation Standard, *Anal. Bioanal. Chem.* 394 (2009) 1183–1192.
- [138] NIST STRBase website: <http://www.cstl.nist.gov/strbase/>, 2015 (accessed 04.05.15).
- [139] J. Song, T.V. Vorburger, S. Ballou, R.M. Thompson, J. Yen, T.B. Renegar, A. Zheng, R.M. Silver, M. Ols, The National Ballistics Imaging Comparison (NBIC) project, *Forensic Sci. Int.* 216 (2012) 168–182.
- [140] Forensic Death Investigation Symposium: <http://www.nij.gov/topics/law-enforcement/investigations/death-investigation/symposium/Pages/welcome.aspx>, 2015 (accessed 19.05.15).
- [141] National Science and Technology Council, Achieving Interoperability for Latent Fingerprint Identification in the United States (April 2015). Available at: [https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/latent\\_fingerprint\\_report\\_may\\_2015.pdf](https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/latent_fingerprint_report_may_2015.pdf), 2015 (accessed 19.05.15).