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Towards a Common Standard for Data and Specimen Provenance in Life Sciences

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45 The profound crisis of scientific reproducibility has its roots in the enhanced avail-
46 ability of large volumes of data that are produced at ever increasing velocity, which
47 in turn often leads to the dissolution of the control mechanisms that traditionally en-
48 sured the quality of data and processes [1–7]. At the same time the origin and history
49 of specimens used to generate research data often remains inexplicit. While consid-
50 erable effort has been put in the development of standards for specimen quality, the
51 actual documentation has been left to the discretion of the provider of the specimen.
52 As a result the situation is exacerbated by the lack of consistent and comprehensive
53 documentation of specimens, which could support the identification of suspected, or
54 proven use of, fabricated data or specimen of unclear origin. Hence, the urgent need
55 for the trustworthy documentation of the data lineage and specimens is evident, espe-
56 cially when considering the serious impact of irreproducible or even flawed scientific
57 results on health, economics, and political decisions [8–12].

58 It is generally accepted that the properties and quality attributes of specimens
59 used in the life sciences have significant impact on the reliability of data generated
60 in downstream analytical procedures [13–15]. Experts from multiple life sciences do-
61 mains have called for the improvement and standardization of the documentation
62 of research and scientific service processes [16–22]. This has led in turn to the pro-
63 gressive development and implementation of data management and other functional
64 tools, such as discovery services, access pipelines, and standardized data models, en-
65 abling the sharing of data and specimens [23–28]. In practice, however, there remains
66 a gap between the needs and the reality of the requirements specified in accepted
67 standards, including technical, operational and legal specifications needed to ensure
68 the trustworthiness and traceability of data and specimens. Electronic lab notebooks
69 (ELN) and laboratory information management systems (LIMS) adopted by research
70 organizations might be considered attempts to electronically manage research work-
71 flows and data to promote reproducibility and traceability. However, these systems
72 can not provide the degree of standardization an international standard would offer,
73 as they are often proprietary and not subject to certification. In an effort to remedy
74 these deficiencies in the provenance captured and reported, we are endeavoring to de-
75 velop an *international standard on provenance information system for the life sciences*
76 accepted by both academia and industry. Provenance information can be used to as-
77 sess the quality and reliability, and hence the reusability of the object, i.e. the data,
78 the metadata, the biological materials, or the specimens.

79 The need for an effort to address the issues in provenance was proposed to the In-
80 ternational Standards Organization (ISO) Technical Committee 276 “Biotechnology”
81 (ISO/TC 276) in 2017 and approved as a preliminary work item. In 2020, ISO/TC 276

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82 approved a new work item proposal to develop an international standard for biological
83 material and data provenance and registered it as a working draft (WD), ISO/WD
84 23494-1 *Provenance information model for biological specimen and data — Part 1: Gen-*
85 *eral requirements*. This standardization effort is in accordance with the FAIR princi-
86 ples, which provide high-level methodological recommendations, including guidance
87 on provenance.¹ As the FAIR principles themselves do not provide detailed instruc-
88 tions for the implementation of provenance standards and documentation, ISO/WD
89 23494 is intended for data provenance of biological samples and will be built on the
90 World Wide Web Consortium’s (W3C) PROV [29], a generic provenance informa-
91 tion standard that defines a general model, corresponding serializations² and other
92 supporting specifications to enable the interoperable exchange of provenance infor-
93 mation between data environments. W3C PROV serves as a framework that is adapt-
94 able and extensible to fit the needs of diverse domains. The W3C PROV standard
95 has already been adopted in life science research areas [30], e.g., for computational
96 workflows [31], pharmacologic pipelines [32], neuroscience [33, 34], microscopy ex-
97 periments [35], medical sciences [36] and health implementation care³ in HL7 FHIR
98 [37]. Unfortunately, these implementations occurred without coordination and the
99 resulting solutions are often incompatible, incomplete, expressed at different levels of
100 granularity, and do not use a consistent approach for creating a continuous chain of
101 provenance from the “source” to the resulting data. Instead of redefining the W3C
102 PROV concepts, we have identified gaps that need to be filled in order to develop a
103 distributed, fully technically and semantically interoperable provenance information
104 standard that covers a given specimen and its associated metadata, and describes its
105 uninterrupted history from its “source”. The “source” can include a complex, multi-
106 institutional environment and can be both the source specimen and data, but also
107 link to a specific biological entity, or environmental specimen collected at a given
108 time and location (*connectivity* requirement [38]). The main goals of the provenance
109 information standard are

- 110 (i) to support improved reproducibility of life-sciences research, to provide a
111 voluntary provenance framework enabling concordance of governments, busi-
112 nesses, academia and the international community
- 113 (ii) to achieve harmonization of documentation of specimens that is compliant
114 with international conventions, recognized ethical practices and legal require-
115 ments such as the Nagoya Protocol [39] and the Declaration of Taipei [40].
- 116 (iii) to enable decision-making about the fitness-for-purpose of particular spec-
117 imens and data, by collecting and linking provenance information from the
118 whole life-cycle of the object (from specimen collection and processing, through
119 data generation and analysis) as depicted in Figure 1.

120 The standard will enhance the trustworthiness of provenance information by includ-
121 ing requirements and guidelines on its integrity, authenticity, and non-repudiation
122 [41], to prevent the production and/or use of unreliable, flawed or fabricated data

¹ Principle R1.2: (Meta)data are associated with detailed provenance.

² As defined in ISO 21597-1:2020: encoding of an ontology or dataset into a format that can be stored, typically in a file.

³ <https://www.hl7.org/fhir/provenance.html>

123 (the potential harms of which have become evident during the COVID-19 pandemic
124 [2, 10]), as well as accidental or malicious modification of data. Since provenance
125 information may also include sensitive or personal data (related, e.g., to the health
126 condition of an individual), the standard aims to enable sensitive information to be
127 concealed and disclosed only under strictly controlled conditions, while preserving its
128 core properties of integrity, authenticity and non-repudiation. Additional advanced
129 application scenarios include tracking of provenance information to: (i) track research
130 error propagation, (ii) identify people affected by incidental research findings, (iii)
131 check compliance with applicable regulations, or (iv) support production of reference
132 material by maintaining full documentation of provenance (complementing work of
133 ISO/TC 334 [42]). For research concerned with highly regulated fields in life sci-
134 ences, such as development of medical products or drugs, the standardized proven-
135 ance model will also contribute to a level of accountability and auditability of re-
136 search organisations.

137 The proposed standard is designed to cover the majority of the organizations in-
138 volved in life-sciences research, both academic and industrial, government labs and
139 research centers. Included organizations are university and industrial research labo-
140 ratories, biobanks and biorepositories, culture collections, hospitals, research centres,
141 and private companies (e.g., pharmaceutical companies or lab reagent suppliers). The
142 broader audience includes not only research data producers, but also those publishing,
143 cataloguing, archiving or reusing research data [43]. The standard can also be adopted
144 by manufacturers and vendors of laboratory instruments – e.g., automation devices,
145 microscopes, sequencers, spectrometers – to enable automated standard-compliant
146 generation of provenance information. Automated generation of provenance infor-
147 mation will minimize human errors and the burden put on workers, both in terms
148 of effort and training. Provenance information generated automatically by devices
149 should be interoperable to enable automated integration and quality control as well
150 as validity checks demonstrating standard-compliant provenance. The standard is in-
151 tended to cover a wide range of research and applications in life sciences and for that
152 reason a modular structure has been used to enable extensibility to evolving require-
153 ments, processes, or technologies.

154 The current draft proposal ISO/WD TS 23494 1 is the first part of a planned series
155 of six parts, with the intent that each will become a distinct ISO standard:

- 156 1. *Provenance Information Management* defines the overall structure of the stan-
157 dard and provides general requirements on provenance information manage-
158 ment, thus enabling interconnections between the various components of prove-
159 nance information in distributed environments. It also specifies requirements
160 applicable to entities responsible for generating the provenance information.
- 161 2. The *Common Provenance Model* builds on the W3C PROV model, defining repre-
162 sentations of elements common to all stages of research, such as interlinking of
163 distributed components of provenance information by sender and receiver ob-
164 jects, the identification of physical and digital objects, and provisions for non-
165 repudiation. Provenance information patterns for common scenarios, such as
166 the compound processes, versioning of provenance information or documen-

167 tation of accountabilities. The model will also define mechanisms to embed or
168 reference entire records of provenance information.

169 3. *Provenance of Biological Materials* defines requirements and scope of the prove-
170 nance information documenting biological material or specimen acquisition,
171 handling and processing and builds on the Common Provenance Model. This
172 includes, but is not limited to, data on collection and collection procedure, trans-
173 port conditions, and documentation of legal and ethical basis (e.g. consent,
174 terms of access and benefit sharing). It will also provide mechanisms to refer-
175 ence Standard Operating Procedures (SOPs) and compliance with or deviations
176 from them. Referencing the widely accepted de-facto reporting standard for bi-
177 ological specimen quality SPREC [44] will also be enabled. Actual techniques
178 or practices for handling biological material are not specified in the standard, in
179 favor of technical specifications enabling consistent interoperable and machine-
180 actionable documentation of handling biological material. With the provenance
181 information provided, however, the standard facilitates the verification of com-
182 pliance with other pre-analytical ISO standards covering biobanking, analyti-
183 cal and processing methods, generation of reference material and related fields
184 (ISO 20387:2018, ISO 20184 series, ISO 20166 series, and ISO 20186 series).

185 4. *Provenance of Data Generation* defines the provenance of data generated from
186 the analysis or observation of biological material, e.g., sequencing, microscopy,
187 spectrometry, etc. Provenance information specific for diverse analytical or ob-
188 servational methods will be embedded in a way meeting the requirements of the
189 particular domain, but as well compliant with the provenance model standard
190 allowing seamless integration in a complete provenance chain.

191 5. *Provenance of Data Processing* defines provenance of computational aspects of
192 life sciences research (such as computational workflows based on CWLProv [31]
193 and RO Crate [45]).

194 6. *Security Extensions* define optional extensions supporting authenticity, integrity
195 and non-repudiation of provenance information, and hence its trustworthiness
196 and reliability. Demonstration of these properties will also be supported for
197 sensitive elements of provenance information.

198 The ISO standards development process responds to a market need and is based
199 on globally-relevant expertise. The product is a voluntary consensus standard de-
200 veloped through a multi-stakeholder process. ISO/WD 23494-1 has a proven market
201 need and has passed through the preliminary stages of the ISO voting process – as
202 a result, it is part of the ISO Work Programme. The document is under development
203 and will evolve along the multi-stage ISO standard development process. ISO/WD
204 23494-1 *Provenance information model for biological specimen and data – Part 1: Gen-
205 eral requirements* is currently at the working draft stage, and is anticipated to move
206 next to the committee draft (CD) stage. The document will be revised and reviewed
207 throughout the ISO project stages until final approval and publication. Part 2 of this
208 series, *Biotechnology – Provenance information model for biological material and data*

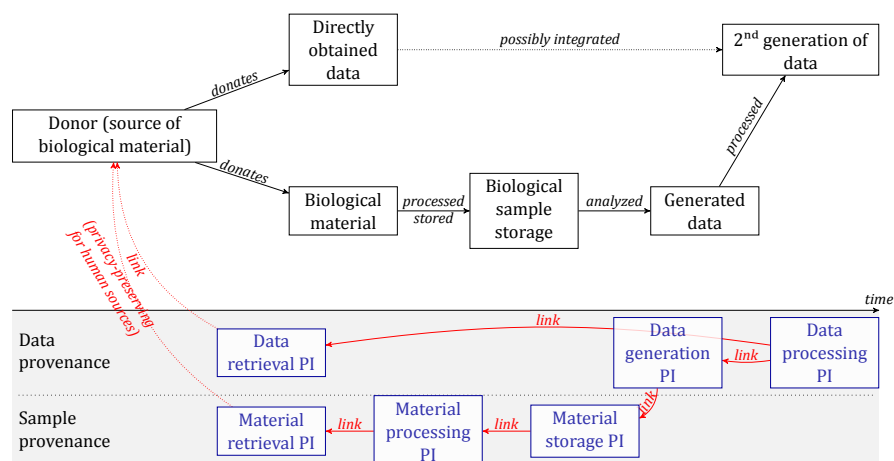


Figure 1: An overview of provenance chain. A sample obtained from a donor (or other source) is created and an initial set of provenance information (PI) is generated. As that sample moves through time and space, is processed and/or analyzed, additional provenance data is appended to the provenance chain for each new item. The chain can be extended as a complete unit of later stages of provenance or use unique identifiers to refer to early stages of provenance data.

209 — Part 2: Common provenance model, has been accepted by ISO/TC 276/WG 5 as pre-
 210 liminary work item ISO/PWI TS 23494-2 . The future documents in this series are in
 211 planning stages, but not yet submitted to ISO/TC 276/WG 5 . The standards develop-
 212 ment process builds on existing standards for collection and processing of specimens,
 213 analytical techniques and data generation and analysis, as well as use-cases from the
 214 biomedical domain. BBMRI-ERIC, which is also active in developing international
 215 standards for biobanking, has drafted use-cases for biological material provenance.
 216 Collaborations and ISO liasions with professional societies like the European, Middle
 217 Eastern and African Society for Biobanking (ESBB) and the International Society for
 218 Biological and Environmental Repositories (ISBER) have also contributed to the devel-
 219 opment of specimen provenance use cases. In addition, use cases on data generation
 220 and processing can come from subject matter experts and the scientific community
 221 including the European EOSC-Life project,⁴ Open Microscopy Environment, OME,⁵
 222 genetic data compression (ISO/IEC JTC1/SC 29/WG 08 MPEG-G) [46], clinical deci-
 223 sion support systems (Kings College London) and other life sciences domains such as
 224 biodiversity, marine biology and systems biology.

225 However, alternatives to ISO standards process⁶ exist—some community-based ef-
 226 forts have developed widely adopted specifications that have become *de facto* global

⁴ <https://www.eosc-life.eu/>

⁵ <https://www.openmicroscopy.org/>

⁶ <https://www.iso.org/developing-standards.html>

227 standards.⁷ The success of these examples lies, at least in part, in the pairing of a
228 specification with an accessible implementation that validates the utility of the spec-
229 ification and allows a broad community to explore integration into applications that
230 extend far beyond the initial target [50]. We believe that community-led and ISO-
231 based approaches for developing and delivering standards can complement each other
232 and that a combination of parallel efforts for developing a provenance chain standard
233 might ultimately be the most productive approach. As the provenance information
234 model development is grounded in the EOSC-Life project, collaboration with these
235 communities is already established. The ISO standard development is thus considered
236 as a standardized instance of a publicly available model developed in parallel under
237 auspices of EOSC-Life [51].

238 Another challenge is the continuous dissemination and periodic revision of the
239 standard once published. Though ISO standards are not “open access”, they can be
240 purchased for a moderate fee⁸ or accessed through institutional libraries, and, bar-
241 ring any patent restrictions, can be freely implemented, for instance, in Open Source
242 software. ISO standards can also include Open Source reference implementations as
243 specific normative or informative parts of the standards. ISO standards can be im-
244 plemented independently or based on such source code, in compliance with the rea-
245 sonable and non-discriminatory (RAND) licensing terms imposed by the ISO require-
246 ments. Such licensing terms, like for instance the one applied to all ISO/IEC/SC29
247 (MPEG) standards that are free from any charge for scientific and non-profit research
248 purposes, may or may not include licensing fees.

249 We would like to invite experts from biotechnology and biomedical fields to fur-
250 ther contribute to the standard, in particular to the provenance of biological speci-
251 mens, the data-generation and data-processing modules. Help is needed to develop
252 applications of the general modules and the development of specific use cases, as well
253 as direct contributions to the text of the standard itself. Contributions are possible
254 through a liaison organization, a national ISO body or by engaging with EOSC-Life
255 project events and calls.

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⁷ E.g., for on-line cryptography (RSA public keys [47]), scientific workflows (Common Workflow Language [48]) and bioimaging data formats (OME-TIFF [49]).

⁸ In some cases ISO standards can be obtained without any fee, e.g. <https://www.iso.org/covid19>

268 opinions in this paper are those of the authors and do not necessarily reflect the opin-
269 ions of the funders.

270 **Representation of communities** The co-authors team represents wide coverage
271 of life-sciences communities. PH, RW, CM, FF, HM, MP, JG come from human biobank-
272 ing and biomolecular resources communities, BBMRI-ERIC Research Infrastructure,
273 and are directly involved as experts in the ISO standardization process. KZ and JE
274 come from cancer research, biobanking and medical informatics and are long-term
275 contributors to data quality standardization efforts. TB, MCo lead development of the
276 BioSamples database at EMBL-European Bioinformatics Institute. IC and KE come
277 from marine biology and EMBRC Research Infrastructure. CG and SS-R have worked
278 with bioinformatics, CWL, RO-Crate and the original W3C PROV standards develop-
279 ments. JRS and JM come from bio-imaging communities and EUBioImaging Research
280 Infrastructure. VC, EF, and MCh come from health informatics. HN participates in
281 provenance standardization process as an expert from Japan, MS and JS as experts
282 from the U.S.A, and AK as an expert from Luxembourg. ME contributes to privacy
283 protection and provenance aspects. FB is a biobanking expert and chairing the ISBER
284 Biospecimen Science Working Group. AS is a biobanking expert and ESBB council-
285 lor. SL-G and CA are from NIST and convenor and secretary of ISO/TC 276/WG 3
286 "Analytical Methods". AM belongs to the tissue engineering and biomedical research
287 community. MM is a standard expert in the digital media, genomic sequencing and an-
288 notation data fields, and convenor of ISO/IEC SC29/WG 8 "MPEG Genomic Coding".
289 AC contributes to capture and handling of provenance within large organizations.

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