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The quest for standards in medical imaging

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ABSTRACT

This article focuses on standards supporting interoperability and system integration in the medical imaging domain. We introduce the basic concepts and actors and we review the most salient achievements in this domain, especially with the DICOM standard, and the definition of IHE integration profiles. We analyze and discuss what was successful, and what could still be more widely adopted by industry. We then sketch out a perspective of what should be done next, based on our vision of new requirements for the next decade. In particular, we discuss the challenges of a more explicit sharing of image and image processing semantics, and we discuss the help that semantic web technologies (and especially ontologies) may bring to achieving this goal.

1. Introduction

1.1. Motivations

The expression "quest for standards" immediately suggests some mythical, rather unreachable goal: so we must first define which "Holy Grail" our quest for standards is trying to pursue.

Healthcare professionals, and especially physicians, have always been "knowledge workers", but this is more and more the case in the current context of the evolution of medicine. This term denotes that a significant part of their activity consists in processing information: collecting and selecting information concerning a patient (clinical data, biological data, genomic data, etc.), decision making – using basic knowledge (anatomy, physiology, biochemistry, etc.) and more or less formalized empirical knowledge (know-how) such as good practice recommendations, guidelines, etc. Of course, this general trend is becoming more and more prominent with the extraordinary development of information technology (IT).

All this information and knowledge processing is oriented toward one major goal, namely to take the most appropriate decisions, i.e., those maximizing the chances of curing the patient, while minimizing the risks inherent in any diagnostic or therapeutic action. This goal also requires close collaboration between all healthcare actors in charge of patient care. The use of computerized information facilitates this cooperation, both within and between clinical teams, especially when some sort of protocol-based work organization (workflow) is present.

Healthcare professionals in the imaging sector – especially radiologists – are fully concerned by this evolution, and they have often been pioneers of it, as a result of the digitalization of medical imaging. Radiologists are, above all, physicians, who must take into account a broad clinical context in order to make the best decisions and carry out the technical actions that constitute their daily work. To do so, they must be able to access, select, capture, interpret and communicate image information, which necessarily involves interacting with multiple equipment and information system components: ePrescribing systems, guidelines repositories, imaging equipment, image processing software, reviewing workstations, dictation systems, teleconferencing systems, etc. Most of these systems were developed as independent components and consequently have not necessarily been designed to interoperate with one another. Similarly, they were not designed from a functional point of view to be used as a whole by a single user. This is precisely where we find our "Holy Grail": the quest is thus to elaborate a set of rules such that all of these components of equipment and information systems can successfully interoperate, thereby giving the user the impression that they are components of a consistent whole, i.e., minimizing the need for multiple entries of the same information as well as useless storage and retrieval actions, and seemingly aware of the user's specific goals and context of operation. In practice, this requires the existence of rules because all these components are supplied by a variety of manufacturers, and

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each of them must be able to be easily replaced, when necessary, and to be selected solely based on its intrinsic qualities (the "best of breed" principle), rather than on factors involving hardware, format or protocol compatibility.

1.2. Definitions

Interoperation between system components involves two complementary and interdependent notions, namely "interoperability" and "integration". Both are given various meanings in the literature, so it is preferable to define here the precise meaning used in this paper.

Concerning "interoperability", we clearly refer to the definition that gained acceptance in the European health informatics community in the late 1990s [1,2]; it explicitly mentions the ability to re-use data to perform a task. Interoperability between two information system components denotes the capacity of one system to successfully re-use data provided by the other in order to apply to it some pre-defined automatic processing.

This definition, because it involves the functional aspect of the targeted processing, differs from others, which either limit themselves to simple connectivity (the ability to send and receive data), as well as from semantic interoperability, a notion that assumes some shared knowledge model behind the mere data. The term "interoperable" is sometimes used to qualify data, or data formats, without any clear definition of what is meant. In my opinion, the concept of interoperability should only be used to qualify information system components.

Integration is also a complex notion, involving several different levels of analysis (i.e., at the level of business, application and technology). Basically, integration refers to a "part-to-whole" relationship between a system and a collection of system components. Usually this relationship is not limited to a juxtaposition of components but rather involves dependencies between them. For example, one component may use information provided by others to complete its own specific task. This interaction raises the issue of interoperability of the components between which such a dependency exists. This is a necessary condition but is not sufficient for successful integration. Some common understanding of the data and processes, as well as common coordination mechanisms, may need to exist for all of the system's components in order to overcome their heterogeneity, their distribution across multiple physical platforms and their various choices in terms of dependence/autonomy tradeoffs.

In summary, the quest for standards discussed in this article aims to ensure the interoperability and integration of different equipment or information system components that support activities (primarily care delivery and research) in the medical imaging domain.

1.3. Origin and development of standards

We traditionally distinguish between three categories of standards.

"De jure" Standards: these are produced by official, international standardization bodies, such as ISO (the International Standards Organization) and CEN (Comité Européen de Normalization) or by the various national standardization bodies, e.g., the DIN (Deutsches Institut für Normung) in Germany, or AFNOR (Association Française de Normalisation) in France. International organizations act through country-based representatives, delegated by the national standardization bodies. Standards result from open processes, are publicly available and free of charge. Rules exist requiring that "de jure" standards be referred to in public tenders, such as those of the European Union. Bilateral agreements exist (such as the Vienna Agreement between ISO and CEN) to avoid duplication of work between official bodies. A common criticism made of official standardization bodies is that the time required to create standards is quite long, e.g., 4–10 years, thus causing problems in the IT domain, where technology evolves very rapidly.

Industrial standards: these standards are created by professional societies, for example, IEEE (Institute of Electrical and Electronics Engineers), by manufacturers' associations or by any sort of association of interested parties, for example, OASIS (Organization for the Advancement of Structured Information Standards), the W3C (World Wide Web Consortium), the Internet Engineering Task Force (IETF) or the DICOM Standards Committee and the Health Level 7 association (HL7) in the fields of biomedical imaging and biomedical informatics. These associations have standardized working procedures, more or less aligned with official bodies' procedures, which in general guarantee a certain openness. Depending upon each case, the resulting standards and related documentation may be publicly available or not. These standards development organizations usually function with a short- or mid-term vision.

"De facto" standards: these specifications do not stem from any kind of agreement between interested parties, whoever they may be. Their status as a standard or quasi-standard derives from their very broad diffusion and use. This is the case, for example, of the PDF format (Portable Document Format, Adobe™) or of the storage formats of some text processing software, such as RTF (Rich Text Format, Microsoft™).

General standards and domain-specific standards: one may make a distinction between standards that are general (i.e., that may be used in any application domain), and those that are relevant to one application domain only. For example, there are many general standards in the imaging domain, such as GIF (Graphics Interchange Format, CompuServe), JPEG (Joint Photographic Experts Group, ISO), TIFF (Tagged Image File Format, Adobe) and MPEG (Moving Picture Experts Group, ISO), that may potentially be used in specialized domains like biomedical imaging. There is also one domain-specific standard, the DICOM standard (described in detail below), which addresses the specific needs of the biomedical imaging domain. Besides these, many general standards exist for the Internet, such as HTML (Hypertext Markup Language), XML (eXtensible Markup Language), RDF(S) (Resource Description Framework), etc., as well as standard protocols like smtp (simple mail transfer protocol), http (hypertext transfer protocol), etc., created by associations like W3C and IETF. Domain-specific standards are developed to meet the specific needs of various domains like imaging, biological laboratories and clinical records, and these may of course use general standards. In the imaging domain, the major standard is the DICOM standard (presented below) but one should also mention HL7, which includes message specifications that are widely used in imaging departments to transmit orders, scheduling information, and reports related to imaging procedures.

The juncture between general standards and domain-specific standards is quite natural. The motivation for developing domain-specific standards arises from the realization that existing general standards are inadequate. In the imaging domain, for example, standard image formats like GIF or JPEG do not allow one to represent the medical context and acquisition parameters that are mandatory for proper understanding and interpretation of image content. Naturally, standards development organizations do their best to avoid "reinventing the wheel", so they make maximum use of general standards available at the time. Thus, the DICOM standard did not try to develop new image compression standards, and always relied on existing ISO standards, namely JPEG, JPEG 2000, and MPEG. These formats were "encapsulated" in DICOM

objects, which means that the ISO-compatible image bitstream is embedded into the DICOM syntax. This approach allows one to combine the advantages of a representation compatible with the most widespread hardware and software (to compress and decompress the images) and the availability of the medical and technical metadata that are necessary to properly manage and interpret the images. Similarly, the DICOM standard, whose initial exchange protocols were based on a specific message exchange (DICOM Message Service Elements or DIMSE) recently proposed extensions in order to use general standards related to mail exchange (DICOM MIME type) and Uniform Resource Identifiers (Web Access to DICOM persistent Objects, or WADO). This results from a concern to make the best use of the universal adoption of Internet technology. One should note that these extensions provide new communication capabilities that are complementary to existing ones, but they are not intended to replace them.

The juncture between the various domain-specific standards is much more problematic. The health informatics domain is covered by numerous standard development organizations, namely, CEN's Technical Committee 251 – "Health Informatics", ISO's Technical Committee 215 – "Health Informatics", the HL7 association and the DICOM Standards Committee, to cite only the major ones. Each has its own strategy and its own procedures, leading to a certain amount of overlap and, honestly speaking, to some confusion. Fortunately, these organizations are aware of that, and consult with each other in order to work in beneficial synergy, rather than in competition. Thus, a period of potentially diverging strategies between DICOM and TC 251 (1990–1993) was followed by a period of close collaboration (1994–1997), and then outright cessation by TC 251 of its activities in medical imaging, currently totally delegated to the DICOM Standards Committee. Similarly, in 2000, HL7 and TC 251 ended up signing a memorandum of understanding (MOU) to formalize their collaboration on definition of the HL7 RIM (Reference Information Model) and the development of HL7 Version 3, especially meant to take full advantage of TC 251 achievements, such as its message development methodology and its standards for electronic healthcare information architecture (CEN ENV 13606 EHRCOM "Electronic Healthcare Record Communication"). Finally, there is also a long history of collaboration between HL7 and the DICOM Standards Committee, especially through DICOM's Working Group 20 – "Integration of Imaging and Information Systems". This working group carries out harmonization work needed for, e.g., referencing HL7 structured documents in DICOM objects (DICOM Supplement 101, 2004), and conversely, referencing DICOM images in HL7 messages and documents, as well as translating DICOM structured reports into HL7 Clinical Document Architecture documents (DICOM Supplement 138, currently available for Public Comment).

The IHE initiative [3] (Integrating the Healthcare Enterprise) occupies a special position in this scenario. In point of fact, IHE is not a standards development organization and does not develop interoperability standards in the sense defined in Section 1.2. However, IHE develops technical specifications that facilitate system integration in healthcare enterprises, per our earlier definition of integration. It is complementary to organizations like HL7 and DICOM, and its added value is very substantial, from the perspective of both users and manufacturers.

The remainder of this paper is organized as follows: Section 2 describes the achievements of the DICOM Standards Committee and the IHE initiative. We then discuss their impact, at a functional level, for users. Section 3 introduces a forward-looking reflection, based on our perception of new needs and on the availability of new technology. Finally, Section 4 provides our conclusions, emphasizing the active role user communities should play in monitoring and pursuing this "quest for standards".

2. Achievements

2.1. DICOM achievements

2.1.1. Scope and content

The DICOM (Digital Imaging and Communication in Medicine) standard [4] is the result of a joint, 25-year effort, bringing together the imaging sector's major manufacturers and many professional societies in the fields of radiology, cardiology and other domains where imaging plays an important role. There are many good papers that discuss the content of the DICOM standard, e.g., [5], and the interested reader can easily refer to them, as well as to the standard itself. My goal here is to highlight a few salient characteristics that are meaningful with respect to our analysis of what the future of this effort should be.

In terms of scope, the DICOM standard currently covers five major aspects (of course, this is not a comprehensive list):

- Network image communication, based on the "Storage" and "Query and Retrieve" service classes, "image" being used here in a very broad sense, embracing images of any modality, waveforms, radiotherapy information objects, some results of image processing such as spatial registration results (i.e., matrices and deformation fields), and segmentation results.
- Network structured reports interchange (DICOM SR), using the same "Storage" and "Query and Retrieve" services.
- Image and structured reports interchange using physical media, e.g., compact disks (CD) and digital versatile disks (DVD).
- Image management, based on services such as "Modality Worklist", "Storage Commitment", "Performed Procedure Step", and "General purpose worklist", aiming at facilitating the organization of tasks between an application entity in charge of scheduling (mostly a radiology information system and/or an image manager), and application entities that execute those tasks: image acquisition, image analysis (e.g., Computer Assisted Detection analysis or CAD), reporting, transcription, etc.
- Image and structured reports interchange and referencing based on web technologies: e-mail attachments (DICOM Supplement 54), and Uniform Resource Identifiers (Web Access to DICOM persistent Objects, or WADO service, defined in DICOM Part 18, introduced in DICOM Supplement 85).

This scope is very broad, especially due to the numerous imaging modalities and to the intrinsic complexity and rapid evolution of the technology involved, especially for image acquisition (e.g., for magnetic resonance imaging). This requires an astute, rigorous methodology for the management and maintenance of the standard. In particular, this methodology must identify the appropriate tradeoffs so that common mechanisms and data structures can be defined and applied consistently across the whole standard, while leaving enough flexibility to enable introducing specific solutions to address very specific issues that may be required for some modalities, and must introduce new mechanisms – re-usable ones, in so far as possible – when this seems relevant. To be able to find such tradeoffs was – in my view – one of the greatest successes of DICOM and especially of Working Group 6 "Core standard", in charge of ensuring the long-term consistency of the standard. For its strategy, the DICOM Standards Committee relies on Working Group 10 "Strategic advisory", which anticipates new requirements. From a practical viewpoint, the standard evolves by means of three different procedures: (1) the publication of "Supplements", which introduce new services in the standard; (2) "Change Proposals" (or CPs), which allow one to quickly remedy isolated inconsistencies and needs for clarification; (3) "retirements", which simplify the standard by retiring those parts that are obsolete and/or have

never been implemented. It is important to emphasize that the evolution of the standard is managed in such a way as to guarantee backward compatibility, so that extensions and corrections never compromise the proper functioning of any existing implementation; for example, in the context of an existing service, optional data elements should not be changed to mandatory, because this would "break" any implementations that had chosen not to provide those data elements. Thus, new needs are usually addressed by introducing new services that progressively replace the older ones; for example, Enhanced MR, Enhanced CT and Enhanced PET are destined to replace previous services, some of which date back to the initial publication of DICOM 3.0 in 1993. As a result of this backward compatibility principle, there is no notion of "version" of a standard; references to publication dates exist only to facilitate adequate management of the standard's documentation.

The major part of the DICOM standard specifies data exchange services (called "SOP Classes", for Service Object Pairs), based on which application entities can exchange information. Each SOP Class has two basic aspects: a specification of an information object (called IOD, for "Information Object Definition" – for example, CT image IOD, MR image IOD, etc.), and a specification of an exchange mechanism, e.g., based on message exchange. It is meaningful to highlight that, among the 3500 pages of the standard (2008 edition), definitions of information objects definitions (Part 3) alone amount to around 1000 pages, meaning 30% of the standard, and terminology-related aspects (Part 16) amount to around 800 pages, meaning 23% of the standard (Table 1). Comparatively, message exchange (Part 7) and data encoding (Part 5) aspects – which are often considered the complex parts of DICOM – are only 124 pages and 108 pages long, respectively (meaning less than 7% of the standard, for both of them), and they have undergone almost no change since their initial publication in 1993.

Hence, the essential part of the standard concerns the semantics of images and associated parameters, as well as observations made by observers – whatever they are – human observers or automatic algorithms. The structuring of information relies on information models (represented using the entity-relationship formalism), but these are quite limited and their actual use in the standard's design and implementation is almost non-existent. The structuring of data elements differs for images or structured report observations. The basic structure used for images is a list of "modules", with each module being a simple aggregate of data elements that describe a single conceptual entity; however, this may be a complex aggregate due to embedded "sequences of items". The basic structure used for structured report observations uses another level of structuring with a tree structure (called SR tree) [6]. In this structure, a node (called "content item") represents an item of information (such as a measurement made on an image), and a relationship between two nodes in an elementary observation, such as stating on which image this measurement was made. Each node has a name that is coded, i.e., represented with a triplet (code value, code meaning, coding scheme designator) chosen from a terminology resource. Observation semantics are captured through the typing of content item nodes and the typing of relationships. Tables 2 and 3 show in detail the different types of nodes and relationships. In addition, the standard defined a notion of "Template" that represents a SR sub-tree specification, properly identified using a Template identifier (or TID), and thus easily re-usable in various SR objects' specifications.

The standard specifies explicitly what interoperability is expected between two application entities. This is documented in the definition of services (definition of each SOP Class), where the roles of each entity – service provider or service user – are specified: expected behaviors of both entities, mandatory and optional data elements, etc. The "interoperability contract" lies in the "Conformance statement", a document any manufacturer must provide for each product for which it claims conformity to the DICOM standard. Such documents must provide precise information, following a document structure specified in DICOM Part 2 "Conformance". This Part 2 may also include special provisions related to specific DICOM services that the manufacturer must document. The data contained in Conformance statements are, in principle, sufficient to allow an integrator or information system architect to pre-determine whether two system components are able to interoperate. In effect, DICOM does not claim to guarantee interoperability, but just to facilitate it.

2.1.2. Appraisal of DICOM achievements

Functional appraisal: The DICOM standard is undeniably the standard of biomedical imaging. It finally became prominent in the fields of radiology, cardiology, nuclear medicine, radiotherapy and dentistry. It continues its development in ophthalmology, visible light imaging like endoscopy, pathology, as well as surgery and veterinary medicine. However, its implementation primarily involves the exchange of acquired data produced by imaging equipment. DICOM's success in the domain of image processing is more mitigated: for example, extensions for segmentation and spatial registration results have yet to be widely implemented. Similarly, the substantial efforts devoted to security enhancements have received little interest up to now. The success of Structured reports has also been spotty; they were widely implemented in the context of CAD analysis (Computer Assisted Detection), especially for Chest CAD and Mammography CAD, as well as for highly specialized procedure reports such as those in ultrasound (gynecology/obstetrics, intravascular ultrasound) and cath labs (procedure logs). In contrast, it cannot be said that DICOM SR was successfully used for the implementation of ordinary reports, e.g., to record and transcribe a vocal interpretation and to manage references to relevant images or to specific measurements.

Technical appraisal: The question here is to assess the quality of the interoperability contributed by the use of the DICOM standard. Very contradictory statements exist on this subject. There is no doubt that, during its first years of use (between 1993 and 2000), users may have been disappointed by the many difficulties they had to face. In my view, one can lay the blame for this on four causes: (1) poor implementation of the standard, sometimes (but not always) related to insufficient clarity of the standard itself; (2) excessive and inappropriate use of service classes like Secondary Capture, instead of regular classes like CT Image Storage or XRay Angio Storage; (3) insufficient training and information of sales personnel, "pushing" DICOM compatibility as a magic "Open Sesame" word, whereas it requires a precise analysis and understanding of the needs of the communicating applications; and finally, (4) a poor understanding and inadequate use of exchanged information ("the users-computer specialists gap"). However, those difficulties must be kept in perspective, given the wide-scale deployment of DICOM in Picture Archiving and Communication Systems (PACS). Nevertheless, such problems are real and hard to solve, especially due to the multiple actors involved (a hospital's IT department, manufacturers), and to the difficulty of locating the right DICOM-knowledgeable persons, those who have the skills required to both determine the origin of the problem and propose a solution.

Another aspect that merits emphasis here is the fact that, in many industrial PACS, image exchange between image storage systems and workstations does not rely on DICOM services, but rather on some proprietary protocol. As a consequence, connecting a new PACS workstation from another manufacturer to the current system may be simply impossible, or lead to unacceptable image transfer performances. In fact, manufacturers often suggest that their customers choose between performance or openness, with performance being associated with the use of proprietary protocols, and openness – i.e., the use of standard protocols – with poor

Table 1
The various parts of the DICOM standard and their relative importance (in pages and in percentages): these figures support the statement that the essential part of the standard lies in the definition of information semantics (Parts 3 and 16).

DICOM Part	Title	No. of pages	Percentage
Part 1	Introduction	21	0.58%
Part 2	Conformance	342	9.52%
Part 3	Information Object Definitions	1097	30.54%
Part 4	Service Class Specifications	288	8.02%
Part 5	Data Structures and Encoding	108	3.01%
Part 6	Dictionary	106	2.95%
Part 7	Message Exchange	124	3.45%
Part 8	Network Communication Support for Message Exchange	56	1.56%
Part 10	Media Storage and File Format for Media Interchange	34	0.95%
Part 11	Media Storage Application Profiles	76	2.12%
Part 12	Media Formats and Physical Media for Media Interchange	55	1.53%
Part 14	Grayscale Standard Display Function	55	1.53%
Part 15	Security and System Management Profiles	80	2.23%
Part 16	Content Mapping Resource	831	23.13%
Part 17	Explanatory Information	297	8.27%
Part 18	Web Access to DICOM Persistent Objects (WADO)	22	0.61%
	Total:	3592	

Table 2
The different kinds of content item nodes in DICOM Structured Reporting.

Content item node	Description
CONTAINER	This node simply contains other content item nodes (those that are related using the CONTAINS relationship)
TEXT	Free text, without any presentation attributes
PNAME	Person name, e.g. "Smith^John^^Dr"
DATETIME	Concatenated date and time
DATE	Calendar date
TIME	Time of day
NUM	Numeric value of a measurement, with the mention of a unit of measurement
IMAGE	A reference to one DICOM Image; may mention a Presentation State associated with the image
WAVEFORM	A reference to one DICOM Waveform
COMPOSITE	A reference to one Composite SOP Instance that is not an Image or Waveform, e.g., a Structured Report
UIDREF	Unique identifier (UID) of a DICOM entity
SCOORD	Spatial coordinates of a geometric region in an Image, such as a polyline, or a circle
TCOORD	Temporal coordinates of a specific instant in a time series
CODE	Code value, taken from a terminological resource

performance levels. I personally think that this is a dishonest and reprehensible approach, and it denotes the persistence of out-dated protection strategies of industry aiming to lock their customers in their proprietary products.

2.2. IHE achievements

The IHE initiative brings answers to integration issues. As explained earlier, not all interoperability issues between information system components can be addressed solely based on rules concerning bilateral exchanges between peer-components. Hence, additional rules and constraints must be agreed on that concern the whole set of components involved in a given domain of activity. This is precisely what IHE does.

This kind of needs arose from a number of undertakings in the field of image management and PACS workflow in the early nineties, both by manufacturers, especially Philips [7], and Siemens [8], and by academic projects such as EurIPACS/MIMOSA [9]. The impetus for IHE came from two American professional societies in 1988: the Radiological Society of North America (RSNA) and the Healthcare Information and Management Systems Society (HIMSS), followed in 2001 by European actors, then Japanese ones. One can find excellent articles (e.g., [10,11]) and a very complete web site that describe in detail the IHE's concepts and achievements, and the interested reader can easily refer to them. My goal here is simply to clarify the relation to standards. IHE is not a standardization body, and consequently does not create standards in the sense defined earlier in this article. However, IHE specifies, from among all the

Table 3
The different kinds of relationships in DICOM Structured Reporting.

Content item node	Description
CONTAINS	A source content item contains target content items
HAS OBS CONTEXT	The target content items denote the observation context of the observation contained in the source content item
HAS CONCEPT MOD	The target content items add post-coordinated descriptions of a concept represented in the source content item
HAS PROPERTIES	The target content items describe properties of the source content item
HAS ACQ CONTEXT	The target content items describe the conditions of acquisition of information referred to in the source content item (usually Images or Waveforms)
INFERRED FROM	This relationship denotes an inference between the source content item and the target content item, e.g., a measurement (NUM) inferred from a region of interest (SCOORD)
SELECTED FROM	This relationship relates a region of interest (SCOORD) or temporal coordinate (TCOORD) to the Image or Waveform from which it was selected

possible options, a particular way to organize integration in a given activity domain, and it is laid out in a document called the IHE Technical Framework.

This kind of activity is somewhat analogous to the development of standards, and in fact the provisions contained in the IHE Technical Framework can be used in the same way as standards. In particular, they can be referred to in technical appendices of tenders to assist – in a way that complements and simplifies the reference to standards – in defining integration and interoperability constraints. Thus, in practice, IHE provides a "language" by which to specify integration conditions, through the notions of "Integration profile", "Actor", "Transaction" and "IHE integration statements". Definitions of these notions are given in Table 4.

This language is complementary to traditional interoperability standards, either domain-specific ones (e.g., DICOM services, HL7 message or document formats), or general ones such as ebXML protocols (electronic business XML, a family of services for the remote call-up of services, through the web, based on the Simple Object Access Protocol), or KERBEROS in the field of security. IHE has agreed not to develop standards, but instead coordinates its activities with standardization bodies, e.g., to suggest the definition of new standards that may be needed to develop some new, acutely needed integration profile.

IHE obtained its first successes in the fields of radiology and PACS, especially with the "Scheduled Workflow" and "Patient Information Reconciliation" integration profiles, then went on to develop many additional ones dedicated to nuclear medicine, cardiology, laboratories, etc.

Among the numerous profiles available today, one should highlight those addressing the communication between healthcare enterprises, such as Cross-Enterprise Document Sharing (XDS), and its XDS-I extension for imaging, as well as Cross-Enterprise Document Media Interchange (XDM) which may play an important role for teleradiology.

3. The future of standardization in medical imaging

3.1. New challenges

It is now necessary to broaden our reflection, by considering a larger context encompassing new requirements engendered by the evolution of biomedical imaging, especially the necessary articulation between care delivery and biomedical research – both basic and applied.

A first aspect that needs to be stressed is the movement toward quantitative imaging, according to which images should no longer be seen as visual representations of the internal anatomy of the patient, or as a representation of some physiological process such as uptake and clearance, but as measurements corresponding to well-defined quantities and obtained through reproducible procedures, thus minimizing intra and inter-equipment variability. This movement more or less affects all imaging modalities, especially Computed Tomography (CT), Positron Emission Tomography (PET), and Magnetic Resonance Imaging (MRI) [12].

This evolution will clearly affect care delivery, in the sense of providing a more scientific means of practicing medicine, in which decisions will be based more and more on objective criteria measured in patients using new investigative techniques and, for care delivery, protocols that are consistent with the most recent scientific knowledge. This evolution is becoming a reality and calls for close articulation between care delivery and basic and applied research (translational medicine). Information technology and knowledge management are important factors in the materialization of this evolution.

As far as imaging is concerned, the forerunners of this evolution in systems and methodology appeared 10 years ago in the field of oncology, with the development of well-systematized approaches for human therapeutic clinical trials through the use of image-derived measurements as "surrogate" endpoints (e.g., RECIST, in the field of solid tumors). Such methodologies involve the use of linear measurements, e.g., based on CT, of the diameter of lesions, or the measurement of Standardized Uptake Values (SUV) in Single-Photon Emission Tomography (SPECT) or PET to assess metabolic activity.

This kind of approach is bound to be applied very broadly through the notion of "imaging biomarker" [13], especially for drug development. Such "imaging biomarkers" are derived from image data through image processing, and they may depict some structural characteristics of biological tissues or organs, or their normal or pathologic functioning, or their evolution over time [14]. The term "imaging biomarkers" provides an analogy with biological biomarkers, obtained through the biological analysis of a tissue sample. All imaging modalities are involved, and significant results can be expected in diagnosis, disease progression and therapeutic effect monitoring in many pathologies, especially cancer, degenerative nervous system diseases (e.g., Alzheimer's disease, Parkinson's disease), or in acute diseases (cerebral infraction), orthopedic diseases (rheumatoid arthritis), to cite only the major ones. The related issues, and especially the relationship to the development of standards, were extensively discussed at a workshop entitled "Imaging as a biomarker", organized in 2006 by the American National Institute of Standards and Technology (NIST), in cooperation with American regulatory agencies (Food and Drug Administration), research agencies, manufacturers, and professional societies. The minutes and presentations of this interesting workshop are available to the public [15,16].

Moreover, everyone is aware of the tremendous progress made during the 10 last years by genomic and proteomic methods, and of the availability of various gene expression profiling techniques to identify groups of genes that may explain the variability of clinical outcomes and the varying sensitivity and resistance to drug-treatment one finds in treating cancer. Today, modern *in vivo* imagery can deliver "imaging traits" that reflect the structural and molecular properties of tissues [17]. Although it is still not possible to attach a unequivocal biological meaning to each "imaging trait", it is now possible – as pioneering studies such as [18] have made quite clear in liver cancer – to highlight a systematic relationship between the imaging appearance of the tissues, called a "radiophenotype"(in the particular case of primary liver tumors), and the underlying gene expression patterns, and that this relationship could be inscribed in a very limited number of traits. Such new approaches – known as "radiogenomics", offer very promising perspectives for quantitative biomedical imaging.

The broadest and most efficient use of these techniques requires that they be applicable to any data, regardless of which equipment instance they were acquired on, and that has important implications for standardizing imaging methodology, especially:

- acquisition protocols, or even imaging equipment itself (to transform the machines into real measurement instruments) in order to provide standard measurements;
- image pre-processing, to take into account corrections such as non-uniformity of the B0 and B1 magnetic field in MRI;
- image processing, to extract meaningful "imaging biomarkers" and "imaging traits" that will contribute to subsequent data analysis and/or actual decision making.

At the same time, new efforts are needed to better document those acquisition and image processing processes. Metadata (i.e., data describing image data itself) must be defined, to be associated

Table 4
The key notions of IHE.

IHE key notion	Explanation
IHE Integration Profile	An abstraction gathering into a functional whole a number of interactions between information system components that collectively highlight their capacity to address specific clinical needs.
IHE Actor	An abstraction modeling the functional components of the healthcare institution: the notion of Actor focuses on those functions solely associated with integrating information system components. The IHE definition of actors should not be seen as an attempt to comprehensively describe the architecture of a healthcare information system.
IHE Transaction	An abstraction of the interactions among actors that transfer the required information through standards-based messages.
IHE Integration Statement	A document published by a manufacturer to describe the conformance of a particular product to the specifications in the IHE Technical Framework. It documents which IHE Integration Profiles are supported by the product and the role(s) that it implements, i.e., which IHE Actor(s). Such documents are designed to facilitate communication between integrators and manufacturers to determine whether and to what extent communications might be supported between products.

with the images and with the imaging biomarkers and imaging traits from which they were derived, in order to refer, for example, to standard protocols, standard image processing tools, etc. In coming years, this should become one of the tasks of actors in imaging-domain standardization.

Some of the challenges of future standardization should thus, in my view, concern two aspects, discussed in the two next sections: (1) the sharing of image semantics and the sharing of the meaning of any derived information, especially moving towards precise definition, validation and wide-scale adoption of the most interesting "imaging biomarkers" and "imaging traits", and (2) the sharing of processing tools that implement the extraction of imaging traits and imaging biomarkers.

3.2. Sharing of image semantics: possibilities and limitations of current standards

The DICOM standard, and especially DICOM SR, already provides interesting capabilities, which are described by David Clunie in [19]. Personally, I believe that the new, emerging needs that we evoked previously call for more powerful solutions. I would argue that Semantic Web (SW) technologies, and especially ontologies, may be of significant help in expressing image semantics and sharing it in a much broader way. I strongly recommend that interested readers who wish to understand what these technologies are read the excellent paper by Horrocks [20]. For a broad understanding of what ontologies may bring to biomedical research, one can refer to [21], an article written by members of the Semantic Web Health Care and Life Sciences (HCLS) Interest Group of W3C. What seems really important to me is that image semantics must be able to be shared – not only within the biomedical imaging community (which is already achievable with DICOM as it is), but also far beyond, in order to make them accessible to researchers from other communities. Highlighting similarities between various diseases, animal models of those diseases, associating observations made at different scales, analyzing how different results can be interpreted based on the physical properties or the chemical composition of contrast agents or molecular imaging probes, are all instances of applications that require cross-domain analysis and therefore justify the use of the semantic web approaches and technologies.

Basically, what needs to be done is to define image annotations – very similar to current DICOM metadata – in order to represent the basic characteristics of the images, such as acquisition parameters and the key information concerning the various types of processing applied to it (reconstruction, filtering, etc.). The fundamental difference with current DICOM metadata is that – in the semantic web framework – annotations are expressed in languages such as RDF or Ontology Web language (OWL) and must refer to explicit knowledge models provided in ontologies. Ontologies provide extensible vocabularies of terms, defined in a formal language, such as OWL, and especially its OWL-DL variant based on Description Logics. Description logics is a subset of First Order Logic, which offers excellent properties in terms of reasoning. Many highly optimized reasoners are available today that can be used to execute arbitrarily complex queries and that exploit the knowledge structure defined in the ontologies (especially the definitions of the object classes) to retrieve information from RDF or OWL data repositories (e.g., image annotations, instances of the ontologies' classes) [20]. Such capabilities cannot be achieved using existing DICOM image metadata, nor using DICOM SR observations, since SR content item nodes and SR relationships, for example, currently do not have formal semantics.

Extending the DICOM standard to express image metadata and structured reports using the semantic web languages is an undertaking which may seem monumental. Based on our experience from the NeuroBase and Neurolog projects, supported by the French Ministry of Research and the National Research Agency, we are well aware of the extent and difficulty of the task at hand [22]. Nevertheless, I believe this is feasible since – as explained above – the core of the DICOM Standard (Part 3 and 16) concerns the definition of information semantics, and consequently one already knows *what* has to be expressed (this usually is the most difficult part of the work). This semantic has to be formulated differently, in a more formal way, using semantic web methods and languages. In practice, this means integrating existing ontologies (when they exist) and developing new ones (if necessary). Of course, such work cannot be compared with the old debate on migrating DICOM syntax to XML, since the latter was limited to a syntax issue, whereas reference to ontologies calls into question how knowledge is structured in the domain covered by DICOM, which is much more ambitious and difficult to achieve.

Recent undertakings, such as Dirk Marwede's work in Leipzig [23], and the "Annotation and Image Markup" project (AIM) set up by David Channin and Daniel Rubin in the context of the CaBIG initiative [24] (Cancer Biomedical Informatics Grid, National Cancer Institute), undeniably go into this direction, although the latter currently seems to be situated somewhere between a simple information model and a genuine ontology [25,26].

In my view, one of the major difficulties in this extension of DICOM lies in the articulation with other terminological resources referred to in the standard, especially SNOMED and RadLex. The re-engineering of SNOMED toward a genuine ontology-based construct is in progress, but its huge size (more than 300,000 concepts) makes its feasibility highly challenging. This problem raises the issue of the design of domain- or application-ontologies that span multiple domains and therefore require the integration of multiple ontologies that may have been conceived by various groups according to different philosophical and modeling approaches. There is no general methodology to address this problem. However, the use of "foundational ontologies" such as DOLCE (Descriptive Ontology for Language and Cognitive Engineering) or BFO (Basic Formal

Ontology) – whose role is precisely to describe the upper-level entities and relationships and to express the basic principles governing their modeling – may provide some help [27]. As for RadLex, it seems necessary to me to clarify its specific position, which lies somewhere between a terminology and an ontology. There is doubtless a need to model some concepts of radiological practice, which do not yet belong to any standard terminology and have little chance to be included in SNOMED. However, the methodology for developing a simple list of terms clearly differs from the one required to build a real ontology on which one aims to perform reasoning. For example, it is quite clear that the use of the 'is a' relationship in many terminologies is not rigorous enough to enable automatic inferences as it can be expected when using a real ontology [28,29].

3.3. Sharing of processing tools

The second aspect deals with the sharing of processing tools. In the most current practice, processing capabilities are equipment-dependent, which means that if a user needs a specific capability not provided by standard PACS workstations, he may need to acquire new equipment, including hardware and basic infrastructure software, in addition to the specific capability he needs. This results in additional costs, space taken up needlessly in reading rooms, and, above all, complex procedures to organize the processing, i.e., retrieve the data to be processed and save the results. Moreover, when a complex processing workflow must be applied, as in some clinical trials, this problem may become really cumbersome. The idea of clearly distinguishing infrastructure components – which provide access to the images (to read or to write them) – from actual image processing components thus seems highly relevant. Its implementation in a multi-vendor environment requires standards defining how a given infrastructure component (or "hosting system") can interact with one or more specialized processing components ("hosted application" or "plug-in"). This objective, i.e., the design of a such standard, is the one being pursued since 2006 by DICOM Working Group 23 "Application Hosting".

The initial efforts of this working group focused on the definition of a standard interface to launch an application, allow it to access the images to be processed (represented in DICOM syntax, or using an XML-based abstract model) and to save the images or other results resulting from this processing. DICOM Supplement 118, which specifies this standard Application Programming Interface, is currently available for Public Comment. A trial use period may follow to validate the proposed solutions, which are completely new in the DICOM arena.

This constitutes a first step. In point of fact, there are increasing needs for the sharing of image processing tools, both in the context of clinical research (we mentioned previously the extraction of imaging biomarkers and imaging traits), but also for daily care delivery, with the development of CAD. Actually, enabling the broadest interoperability between infrastructure components (e.g., PACS workstations) and specialized applications should stimulate the development of such applications and facilitate their broad use by clinicians.

This evolution clearly meets requirements expressed in the context of infrastructure projects like BIRN (Biomedical Informatics Research Network) [30] and CaBIG in the USA, as well as in Europe with projects like the European project @Neurist [31] and the French project NeuroLog [32].

In spite of the security issues it raises, the problem of access to and the orchestration of distributed services (on the Internet) will need to be addressed. General standards (such as the Business Process Execution Language, OASIS) will become available, but a fundamental question will – here, too – be that of sharing the semantics of data processing (through the semantic definition of the processing, the semantic definition of input and output data, the definitions of pre-conditions and post-conditions, etc.). This is the next step toward semantic interoperability, which is the key feature needed to enable wide-scale, successful re-use. Ontologies will certainly be of some help in achieving this sharing.

4. Discussion/conclusion

The "quest for standards" goes ever onward. The most basic needs of the imaging domain have now been met, thanks to the DICOM standard, and thanks to initiatives such as IHE, that fully embraced this problem of integration and managed to contribute pragmatic solutions forg a very broad range of applications for diagnosis and therapy, including interventional radiology and cardiology, image-guided surgery, radiotherapy, etc. They also support the transfer of images to research environments for advanced quantitative analysis. However, one cannot say that DICOM is widely used in research labs except to receive the images from the hospital PACS. Images are usually converted into other image formats such as Analyze (Mayo Clinic) or Nifti [33], that are deemed simpler to use and better suited to rendering processed images, but certainly not sufficient for successfully sharing images between different research organizations. The same thing can be said about image annotations: although DICOM SR has achieved some success in the context of care delivery and CAD, its use is still limited in research projects, where XML-based approaches are often preferred. Thus, the sharing of images and related data in the context of research, especially processed data and image-related observations, remains an open question.

One may regret that manufacturers are still tempted to confront users with a difficult dilemma: choosing between performance (using proprietary protocols) or openness (using standard ones) with degraded levels of performance. Additional efforts are needed on the manufacturers' side to reconcile performance and openness, both of which users have a right to. It is also the latter's responsibility – as customers – to stand their ground on this issue.

A lot has been achieved, but much still remains to be done, especially in domains like surgery, where complex workflows exist involving many actors and types of equipment (image guidance, vital signs monitoring, robots, etc.).

As for the future, it holds new challenges related to the emergence of quantitative imaging, and to new needs in the context of translational medicine – as expressed in the CaBIG initiative, or in research projects of the neuroimaging domain. They demand that images be useable outside imaging departments, in a form that makes them fully exploitable and is associated with rich annotations documenting in a complete and precise way their nature, content, and how they were obtained. Most general technologies are already available to do so, especially semantic web technologies, but substantial work remains to be done to re-express image-related information using ontologies. This is not an easy task, and above all is difficult to organize due to an unavoidable overlap of connex domains. More than ever, it requires the collaboration of all related communities – manufacturers, medical professional societies, and of course physicists, for the adequate capture of physics-related aspects.

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