Safe Magnetic Resonance (MR) Imaging of Patients with MR Conditional Implants and Devices

How formal and *de facto* standards drive innovation in medical imaging: a case study.

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***Abstract*—Coexistence of advanced (medical) technologies requires new, cross-sectorial approaches to standards. This case study describes how clinical needs fuelled two decades of disruptive innovation and technology development in medical device industry (passive implants, active implants, and magnetic resonance imaging, MRI). The role of visionaries, the value of standards development working groups as discussion platforms between users, industry and regulators, and the support from public-private partnership programs in evaluating new concepts and fostering new enterprises are discussed. It is shown that development of a formal standard has provided for the introduction of disruptive functionality by one MRI vendor. This *de facto* product standard sets the pace for further formal standardization in regulatory and technology developments. An outlook is provided to describe further standards and technology development needs in a complex scene of strict regulations (MDR and FDA), clinical consensus guidelines, and a highly competitive industrial landscape.**

***Index Terms*—Magnetic Resonance Imaging, MRI, MR Conditional, Implants, pacemaker, ICD, DBS, Safety**

I. Introduction

The aging population will cause a steep increase in incidence of musculoskeletal, cardiovascular and neurological diseases, as well as diabetes and cancer [1]. Treatment of many chronic conditions often involves placement of implants, such as vascular stents, hip or knee replacement, spine stabilization devices, pacemakers, ICDs, deep brain or vagal nerve stimulators, or leverages body-worn devices such as insulin pumps. Patients depending on such devices are likely to develop another medical condition over the remainder of their life time [1], for which they will require access to non-invasive medical imaging, esp. Magnetic Resonance Imaging (MRI). Exposure of treatment devices to the non-ionizing radiation electromagnetic fields of the MRI poses serious dangers to patients, and can destroy the function of the implant.

II. MRI And Implant Safety

This section provides a brief overview of the basic principles of MRI, and how its technologies relate to specific risks for patients with implants.

The human body primarily consists of water, whose protons' magnetization can be used to visualize organ structure and function using the magnetic resonance phenomenon [2]. To this end, the body is placed in a strong, uniform magnetic field (approx. 100,000x the earth magnetic field). Spatial information is encoded by fast switching of localized magnetic fields, and RF excitation with different timings. Such pulse sequences generate contrasts reflecting different biophysical environments. Each of these fields constitutes safety risks [3], particularly in the presence of implants [4], [5], see Figure 1.

The static magnetic field is always on, and can turn small objects into dangerous projectiles. Force

and acceleration is especially high around the entry of the magnet bore, where the fringe field is characterized by a steep gradient. In active implants, the magnetic field may disturb powering of the device, or switch pacemakers to non-therapeutic mode, even at low field strengths below 1 mT.

Active field gradients can cause malfunction through rectified voltages, vibrations and heating. Significant, rapid heating and voltage rectification can also result from the necessary RF exposures. In addition, Electromagnetic Interference (EMI) could result from the intense exposures at relatively low and varying frequencies [4], [5].

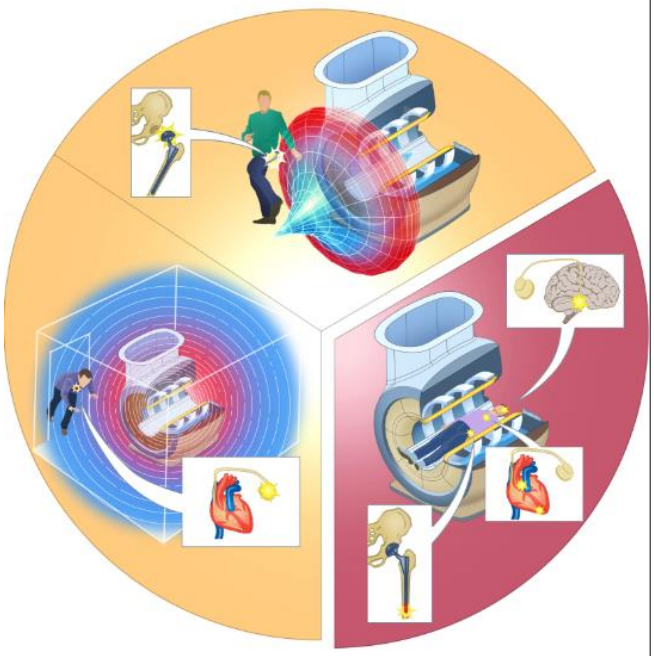

Figure 1 Overview of the risks associated with the use of implants near or inside an MRI system

Left side: The magnet is always on, and potentially endangers the patient by causing a malfunction in the implant. For example, a pacemaker may stop pulsing beyond a magnetic field of 0.5 mT (5 Gauss), or an implant may be dislodged when approaching the façade of the MRI magnet due to the local high spatial field gradient.
Right side: Strong time-varying electromagnetic fields are present when imaging data is acquired. These fields add risks related to heating (tissue burns), vibration, and implant malfunction.

III. Stakeholders and Standards Landscape

Where practice of medicine and medical device industry is highly regulated, advancement of safe medical care results from a complex interplay of academia, industry, consultancy and test businesses, government, and professional and industrial associations. Over the past two decades, innovation was mainly driven from the US and some European countries. To appreciate the dynamics in technology adoption and standards development, consider the following set of stakeholders, and their influencing of the standards landscape:

A. Academia

The need to scan patients presenting with complex diagnostic questions is initially managed at academic hospitals. Safety assessments to support (off-label) scanning of patients with stents and passive implants were performed by local medical physicists, and their methods were published in peer-reviewed scientific journals. Such publications were instrumental in initiating standards development, for example through ASTM, the American Society for Testing and Materials.

B. Industry

MRI manufacturers, such as Siemens, GE, Philips and Toshiba, have generally contra-indicated scanning patients with implants, to reflect the high-risk safety profile, and associated legal and regulatory concerns. Patient safety of the MR equipment by controlling output levels is ensured through compliance with IEC 60601-2-33 [6], the particular standard for basic safety of MRI Medical Electrical Equipment.

Manufacturers of active implants, such as Medtronic, Abbott (St Jude Medical), Boston Sci, and Biotronik, have responded to pressures from clinic and competition to enable MRI for patients with pacemakers, though investment decisions reflected the low number of customers demanding solutions. Medium-size enterprises have also been active in providing MR Conditional solutions, both for passive (hip, knee) and active implants (hearing aids). Standards related to passive implants are maintained by ASTM and ISO. Product standards for active implants are primarily developed by ISO, but also AAMI, the Association for the

Advancement of Medical Instrumentation engaged in such standards. Table 1 provides an overview of applicable standards, their owning organizations, and dates of publication and anticipated revision.

TABLE I. OVERVIEW OF STANDARDS RELATED TO MR CONDITIONAL IMPLANTS

	Standard description		
***Owne*r**	***ID and Topic***	***Date of Release***	***Planned Revision Date***
ASTM	F2052 (Magnetic Force)	2015	
	F2119 (IQ artifacts)	2007	2019
	F2182 (RF Heating)	2011	2019
	F2213 (Magnetic Torque)	2006	
ASTM IEC	F2503 / IEC 62570 (marking of devices)	2013	2019
ISO	TS 10974 (Active Implant test methods)	2012	2018 2022
	14708-1 (requirements for Active Implants)	2014	
	14708-2 (requirements for pacemakers)	2005	AAMI PC76 2019
	14708-3 (requirements for neurostimulators)	2017	
IEC	60601-2-33	2015	2019

C. Consultancy and Test Companies

Newly developed test approaches, and supporting evidence for regulatory submissions, are provided by independent startup companies. This includes services to the medical community such as databases of implants and their operational conditions. These companies also provide dedicated training courses and online support for understanding MR Conditional safety concepts.

D. Government

Regulators ensure device labeling based on well-established (standardized) test methods. Especially US FDA has encouraged inter-sectorial industrial alignment to develop uniform labeling terminology. Their Guidance Document on passive implants [7] provides an example of non-consensus standard setting.

E. Associations and Societies

Development of device standards and test methods is scattered over multiple organizations. Passive implants are largely covered by ASTM, active implanted devices by ISO, and large medical equipment by IEC. Additional specific standards are developed by the Medical Imaging Trade Association (MITA, part of NEMA), or as part of AAMI, the Association for the Advancement of Medical Instrumentation. Implant manufacturers also collaborate in AdvaMed, and provided a position paper for MR Conditional implant scanning through MTAA, the Medical Technology Association of Australia.

Connection with end users is essential to understand usability, to avoid complexity, and to deploy technology solutions. Connection to the Society of Magnetic Resonance Technologists (SMRT) provides a first sanity check for the feasibility of MR Conditional product labeling propositions. Since 2014, the American Board of Magnetic Resonance Safety (ABMRS) is another key player, promoting harmonized safety concepts for MR Conditional scanning.

Major challenges in developing international standards have been the formation of joint working groups, both formal and informal, for common and shared understanding of needs, vocabulary, and interfaces; requirements on translations; and potential divergence from inter-sectorial consensus when developing vertical standards. Monitoring all activities is often not justifiable for many stakeholders in the ecosystem.

IV. HISTORICAL OVERVIEW

This section provides some insights how key actors found each other in developing formal and *de facto* standards. It shows that a seminal product, establishing a *de facto* standard, can be more impactful and effective than a consensus formal standard. The product(s) would, however, never have existed without the efforts spent to develop the formal standard. The focus is on ISO TS 10974 [5] and IEC 60601-2-33 [6], for scanning patients with active implants. It intends to highlight the need for and benefit of open, face-to-face conversations, forced convergence, and unconstrained competition.

A. The Role of Visionaries

Development of technology and standards can often be attributed to a few recognized, and easily

named, individuals. They grasped societal and technology needs and translated it into action. Such visionaries happened to be at the right place at the right time, but also contributed to building networks and trust. Importantly, their employers (universities, government agencies, and companies) enabled and supported them to open-mindedly find new ways of collaboration to the benefit of patients.

Though mentioning names is risky, establishing a joint working group (JWG) between ISO and IEC Technical Committees (ISO/TC150, Subcommittee SC6, and IEC/TC62B, maintenance team MT40) to develop safety guidance of MR Conditional Active Implanted Medical Devices (AIMDs) would never have happened without the leadership of Curt Sponberg (Medtronic, ISO SC6) and Hans Engels (Philips, IEC MT40).

B. Pivotal Meetings

The JWG was created in 2007 at the European Congress of Radiology in Vienna. A third edition of IEC 60601-2-33, the particular standard for MRI safety, was in the making. It was realized by the key stakeholders that control of RF-induced heating of implants through reported whole-body SAR at MR scanners was associated with too much (inter-vendor) variability. The need to introduce a new UI parameter, B1rms, was consolidated at the final review 2009 in Zürich. This, however, only covered part of the complexity of safety related interactions. It also needed a repair of the standard in 2015, since MR manufacturers could only commit to control B1+rms.

Initial meetings of the JWG focused on identification of hazards and appropriate tests for especially the active fields (RF and gradients) on active devices. Where MR vendors resisted introduction of additional control options related to gradient switching, a side-gathering over lunch during the 2009 meeting in Maastricht decided to explore possibilities for additional output restriction options on the User Interface of the MR equipment. This shows the importance of informal networks for standards development, outside the formal parts of the scheduled meetings. The dynamics of follow-up meetings is described in the next sub-section.

Effects of the static magnetic field and its spatial gradient (SFG) had already been covered by ASTM standards for passive implants. Nevertheless, a lot of confusion existed in terminology and abbreviations, which was addressed in a Public Hearing organized at the FDA premises in 2010. That meeting created the necessary awareness and sense of urgency to implement a common language in device and equipment labeling, based on agreed and understood definitions. Assumptions in test methods were challenged, a revision of the associated ASTM standard initiated. Also, non-uniform representation of SFG in the technical documentation of MR systems was signaled, and resolved in Amendment 2 of the 3rd edition of IEC 60601-2-33 [6], published in 2015.

A schematic overview of standards development activities is shown in Figure 2.

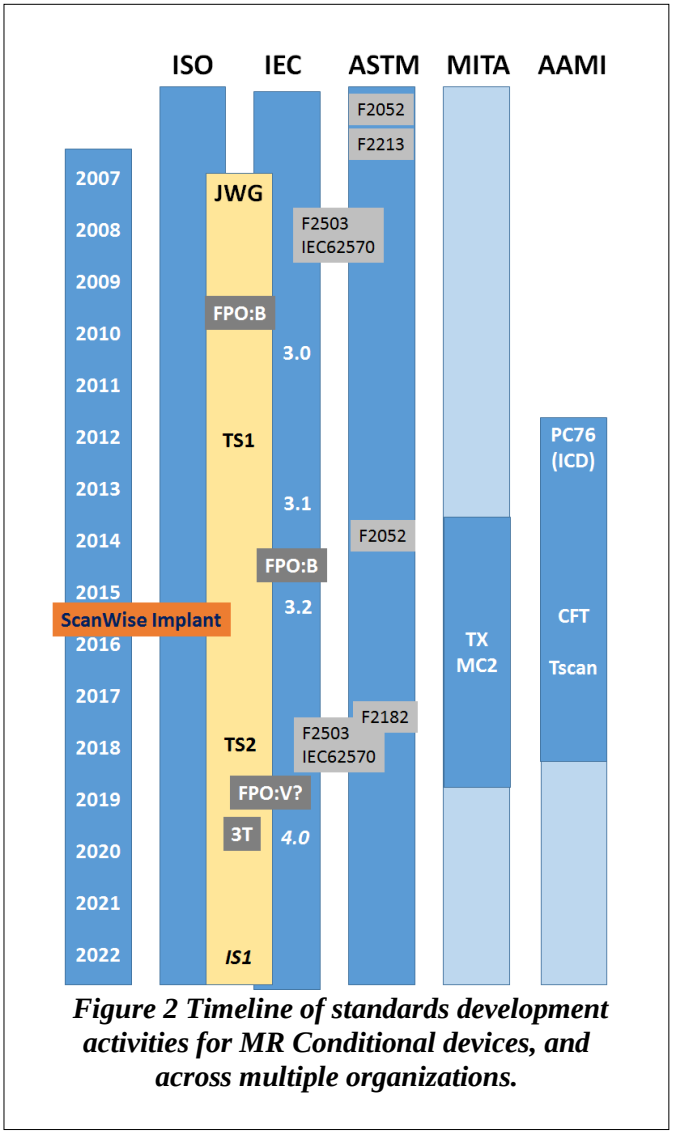

Figure 2 Timeline of standards development activities for MR Conditional devices, and across multiple organizations.

C. Establishing Requirements

A team of representatives from 10 manufacturers and several end users across the US and Europe developed a draft set of parameters that required output restrictions. Regular telephone conferences and rapid updates of draft specifications are key in such processes. Plenary biannual face-to-face meetings were used to confirm progress and decisions, with a lead time of more than three years.

Values for B1+ and dB/dt, and their time-averaged rms values, were selected for 1.5 T to be close to outputs at the "Normal Mode" of MR systems, the previously used test and labeling criteria for many implants. Foundational system-level simulations by Philips [8] established the clinical diagnostic impact of the agreed output levels. These simulations also revealed that existing control mechanism for gradient output (limiting peripheral nerve stimulation) were inadequate.

Usability requirements were central to defining how output restrictions could be applied. Adding multiple (new) parameters was considered too complicated, and a single radio button was preferred. Translation of the name/identification should be prevented, but developing a symbol through ISO is considered too complicated. As MR systems already implement a "controlled operating mode", the use of the word "mode" was deemed unacceptable. Where a single set of restrictions would be agreed upon, but extensions were foreseen, the identification should be extendible. And, while standardization was necessary, the implementation should be voluntary depending on MR manufacturer's business decisions. A summary of the positions of the several stakeholders was presented in 2015 at the AAPM meeting ([4], [9], and [10]). The need for simplification of both implant labeling and the MR user interface and workflow was clearly articulated in [10]. This should also cover the significant amount of existing implants.

After long deliberations, the identification FPO:B was chosen, where FPO would indicate Fixed Parameter Option (not to be translated), and B stands for Basic (allowing for more advanced extensions). The identification "fixed parameter" alludes to a single, pre-defined set of output restrictions. Use of the option requires explicit re-labeling of implants, and new software (and possibly hardware) for MR systems. FPO:B therefore does not help to reduce complexity in current medical practice, and an unmet need continues to exist for legacy implants.

D. ScanWise Implant As De Facto Standard

Philips actively contributed in the development of FPO:B requirements, and developed the necessary technology demonstrator [8] as part of a European subsidy project, MEDIATE. This included safety controls and workflow-supporting functionality to ensure image quality at reduced performance levels.

The inter-sectorial agreements concerning relevant parameters to control MR outputs for implant safety, the definitions of these parameters, and methods to demonstrate compliance that emerged from the formal standards development were essential for further product development.

Leveraging the ground-breaking capabilities developed for the FPO:B demonstrator, and taking into account the user needs to support current practice, development of appropriate controls to restrict outputs according to legacy implant labeling was a feasible path. This implementation, called ScanWise Implant [11], was brought to market in 2015, and has received regulatory approval across the world. Figure 3 provides an overview of the ScanWise Implant user interface. This product feature is currently recognized as the *de facto* standard for scanning MR Conditional implants.

An essential step in the development of ScanWise Implant was Usability Engineering, and validation of the User Interface with (non-expert) radiographers. Parameter order, interaction design, and visualization of feedback were adjusted in several iterations. Such specific designs are key to safety and usability, and are very difficult to achieve in the scope of developing consensus standards. In practice, it requires an industrial investment budget, and the rigor of Design Controls, to reach a safe and effective solution.

V. Lessons for Standards Development

A. The Value of a Testbed

A sufficient understanding of device interactions, failure modes, and root causes, was established by

an open mind set in the JWG. Vendors and research institutes shared their observations and insights. Dedicated simulations and experiments were conducted to establish requirements.

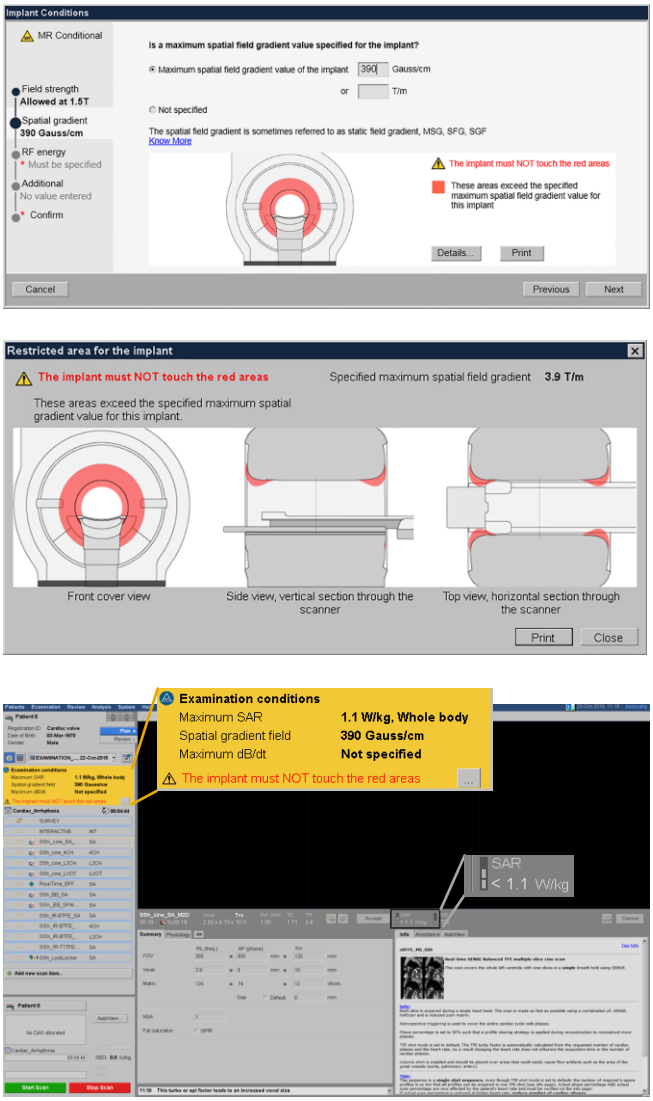

Figure 3 User Interface for ScanWise Implant.

Top: The magnet and safety exclusion zones are displayed. Bottom: Safety relevant parameters are always visible during image acquisition, in the yellow box

The number of participants of the JWG, esp. from implant vendors, grew rapidly as they realized the opportunity to learn more about MR technology and compatibility requirements.

Emerging standards must be consolidated early in the process, with a possibility to learn and iterate. ISO supports dealing with technical uncertainties by the concept of a Technical Specification (which can see two editions). This allows to strike a balance between developing solid standards, and gaining early experience. The ISO approach is provides more incentives to improve that the Technical Report approach used by IEC.

An apparent and remaining challenge is how to incorporate unproven concepts in established standards, such as IEC 60601-2-33 [6].

B. Matching Opportunity with Timeliness

The imposed timeline of IEC and ISO projects is beneficial to set priorities and to drive convergence. Development of ISO TS 1047 focused on 1.5 T. The additional complexity in RF interactions at 3.0 T would have prevented timely publication of the TS, without providing significant benefits.

The need for adequate stability periods of product standards does not allow rapid updates. Additions to the existing IEC 60601-2-33 standard [6] to prescribe how MR manufacturers would report or control outputs were aligned with the timeline for Ed. 3.2.

The MR manufacturers are now experimenting with an alternative path of standard development through MITA. This approach would allow shorter cycle times to establish guidance and handshakes within and across industrial sectors, without having immediate compliance implications. Its value still needs to be proven, in view of the long lead time to establish consensus, see Figure 2.

C. The Need to Consider Legacy Implants

Most existing (MR Conditional) implants have no, partial or incomplete labeling information. Passive implants will display (maximum allowed) main magnetic field strength (in tesla, T), static field gradient (in non-SI units, G/cm: Gauss per centimeter) and (whole body) SAR in W/kg. Active implants may add slew rate (in T/m/s or equivalently mT/m/ms, or the alternative dB/dt in T/s), or apply dual labeling for RF (SAR and B1+rms). In addition, clinical expert groups may have developed guidelines with parameter restrictions for off-label scanning of old active implants.

End users clearly expressed the desire to have an easy-to-use interface on MR systems to control the

settings in according with labels of legacy implant and supporting their existing medical practice [10]. No consensus could be reached in the IEC maintenance team to support development of such controls. Currently only Philips offers such capabilities as a regulatory-approved product.

Implant manufacturers and regulators like FDA recognized that a more flexible approach than FPO:B is required. Having seen the capabilities of ScanWise Implant [11], the community has effectively abandoned FPO:B before its implementation. This decision was confirmed in the JWG meeting in Vienna in 2016. Replacement of (optional) FPO:B is currently under investigation. Requirements in a future formal standard should better reflect and recognize existing products, and include real-world requirements for usability and safety experience. Whether developing a standard without real-world usability validation can still be supported should be reviewed in detail by IEC and ISO policy teams.

D. Moving Forward: Remove Complexity

Legacy products are the central concern for adoption of new and safer technologies. Regulators and manufacturers generally do not drive for solutions where the installed base is required to upgrade to newer levels of consensus standards of technology.

MR manufacturers could upgrade embedded software for their installed base to implement new labeling requirements on all systems. Such upgrades are not required by standards, and grandfathering reduces the level of safety consistency and imposes difficulties to ensure uniform education. As a result, and by example, adoption of B1+rms on MR scanner User Interfaces is seriously lagging behind the published IEC 60601-2-33 standard in 2010. Independent and slow technology evolution tends to support proliferation of complexity.

While all partners involved in MR Conditional implant labeling are committed to reduce complexity, disruptive re-labeling may be required to effectively do so. We probably cannot expect to see this happen unless government agencies take the lead. The MDR in Europe (enforced from 2020) may be such a hallmark. It does not allow for grandfathering, and this may disruptively enforce higher levels of standards compliance. The implant manufacturers and the MR manufacturers should consider the window of opportunity to align their MR Conditional labeling in this time frame.

E. Horizontal versus Vertical Standards

Development of a horizontal standard like ISO TS 10479 involves many stakeholders from industry, hospitals and legislators. A total of over 130 contacts are registered, and active participation in meetings is on average at a level of 50 persons. The different safety aspects and technologies, and the wide range of products to be covered in a horizontal standard lead to sometimes diffuse requirements and speed of convergence can be slow. The MR manufacturers were actively involved in providing information during development of the first edition of the TS, but their participation was deemed less important in the second edition. Actually, however, implant vendors decided to introduce exposure tables and test methods which were either inconsistent with MR system capabilities, could cause additional burden for MR manufacturers, or might imply inadequate safety coverage. Ensuring continuous engagement, and proactive information seeking and sharing for and between all stakeholders is essential to maintain trust and provide a high standard of safety.

Product specific, vertical, standards also need to be developed in a rapidly-innovating market segment like MR Conditional Active Implanted Medical Devices. A specific group in AAMI (PC76) is focused on developing a test standard including acceptance criteria for pacemakers and ICDs. MR manufacturers are not represented in this group, and cannot be participating in development of all vertical standards. It was found, however, that PC76 considered it necessary to deal with 2 new concerns not (fully) covered in the inter-sectorial Joint Working Group: Combined Field Test, and heating due to gradient switching (“solved” by proposing a total scan time limit in the label). An adequate model to discuss such new concerns that would affect MR system labeling and functionality has not been established.

VI. Public-Private Partnerships and Subsidies

Development of product standards is a recognized criterion in European subsidy grant programs, esp. those related to industrial innovation (EUREKA and ENIAC). Philips, academia, and test houses and consultancy companies have shown the benefit of such standards-development focus in subsidy grants. For ScanWise Implant, this included exploration of the requirements of co-existence of novel and complex devices and technologies, and active participation in multiple standards development teams.

Similar approaches should be encouraged for US grant schemes, and across the globe. IEC and ISO could be good liaisons in reviewing such activities and ensuring global alignment of efforts.

VII. Recommendations

a) Improved alignment of standards development activities across multiple organizations. Prevent local optimizations with intended or de facto exclusion of relevant stakeholders from project teams. Set up inter-organizational agreements for observer and reviewer roles without formal membership, between e.g. AAMI and IEC or ISO.

b) Develop approaches for diversification of normative and informative text in standards. Existing standards should allow for faster iteration cycles for new technology developments, with possibilities to test and withdraw. The option to split particular standards in a main standard and collaterals for specific technologies may be a feasible way forward that deserves further investigations.

c) Concordant with the critical role of Usability Engineering in safety and effectiveness, esp. for user interfaces and labeling, standards maintenance committees should be encouraged and supported to develop demonstrators and perform formal usability testing prior to proposing new user interface requirements. Formal liaising of IEC and ISO with EU and US grant agencies, and securing budgets for such activities, could significantly improve the quality and value of standards.

VIII. Conclusion

This case study provides an exemplary overview of the complexity of the standards development scene. Learnings from this example of medical devices and medical equipment can likely be extended to other sectors. Ambient technology poses ever higher requirements on coexistence, and single-device standards are insufficient to ensure safety in actual operational settings. Usability-driven solutions based on carefully evaluated demonstrators are crucial for development of sustainable standards, both *de facto* and formal.

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References

[1] K. Barnett, S.W. Mercer, M. Norbury, G. Watt, S. Wyke, and B. Guthrie, “Epidemiology of multimorbidity and implications for health care, research, and medical education: a cross-sectional study”. The Lancet. Vol. 380, pp 37–43, July 2012. DOI: http://dx.doi.org/10.1016/S0140-6736(12)60240-2

[2] D.W. McRobbie, E.A. Moore, M.J. Graves, and M.R. Prince, MRI from Picture to Proton, 3rd Ed., Cambridge (UK): Cambridge University Press, 2017.

[3] S.J. Kim, and K.A. Kim, “Safety issues and updates under MR environments”, Eur. J. Radiol. Vol. 89, pp 7-13, April 2017. DOI: http://dx.doi.org/10.1016/j.ejrad.2017.01.010.

[4] R. Venook, “Active Implants in MRI: The Implant Industry's Perspective”. 2015 AAPM Annual Meeting.

http://amos3.aapm.org/abstracts/pdf/99-28936-359478-114565.pdf.

[5] ISO/TS 10974:2012 “Assessment of the safety of magnetic resonance imaging for patients with an active implantable medical device”. https://www.iso.org/standard/46462.html

[6] IEC 60601-2-33:2010+AMD1:2013 +AMD2:2015 “Medical electrical equipment - Part 2-33: Particular requirements for the basic safety and essential performance of magnetic resonance equipment for medical diagnosis”. https://webstore.iec.ch/publication/22705.

[7] FDA Guidance Document 1685 (2014) “Establishing Safety and Compatibility of Passive Implants in the Magnetic Resonance (MR) Environment”. https://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/UCM107708.pdf

[8] J.S. van den Brink (2012) “D3.1.1 - User Interface for MR imaging with MR Conditional Implants and Devices”. https://itea3.org/project/workpackage/document/download/574/09039-MEDIATE-WP-3-D311UserinterfaceforMRimagingwithMRconditionalimplantsanddevices.

[9] M. Steckner, “Active Implants in MRI: The MRI Industry’s Perspective”. 2015 AAPM Annual Meeting. http://amos3.aapm.org/abstracts/pdf/99-28935-359478-114793.pdf.

[10] V. Kimbrell, “Active Implants in MRI: The MR Technologist's Perspective”. 2015 AAPM Annual Meeting. http://amos3.aapm.org/abstracts/pdf/99-28937-359478-114567-1137440862.pdf.

[11] J.S. van den Brink, C. Possanzini, M. van Meel, J.P. Groen, T. Geraedts, S. Last, J. Konijn, M. Mitra, P. Kaufholz, A.M.C. van Muiswinkel, P.R. Harvey (2016) “Simplify scanning of patients with MR Conditional implants”. https://www.usa.philips.com/b-dam/b2bhc/master/events/ISMRM2016/philips-scanwise-implant-whitepaper.pdf