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Development of the international standard for functional near-infrared spectroscopy as medical equipment [Invited]

HIROSHI KAWAGUCHI[1,*] AND HIDEO EDA[1,2]

[1]Human Informatics and Interaction Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Central 2, 1-1-1, Umezono Tsukuba 305-8568, Japan
[2]Department of Electronics and Computer Engineering, Hiroshima Institute of Technology, 2-1-1, Miyake, Saeki-ku, Hiroshima, 731-5143, Japan
*hiroshi.kawaguchi@aist.go.jp

Abstract: Functional near-infrared spectroscopy (fNIRS) is widely used in academia and medicine, especially in human brain science. The international standard for the basic safety and essential performance of the fNIRS equipment as a medical device was established by the International Electrotechnical Commission (IEC) and published as IEC 80601-2-71. In this review, the authors, who are experienced project leaders in developing and revising the fNIRS standard, provide information on the development of the standard, including the process to date and expectations for the research community. The review will guide future experts in fNIRS standard revisions and relevant standard development.

1. Introduction

Functional near-infrared spectroscopy (fNIRS) is used in various academic research areas, including human brain science, and medicine, to measure brain function [1]. In Japan [2], China [3], and the United States (US) [4], fNIRS is commercially available as a medical device. Notably, fNIRS is used to identify epileptic foci and assist in the differential diagnosis of psychiatric disorders under the public insurance system in Japan [5]. fNIRS must meet certain safety and performance standards to avoid undue risk to patients during medical applications.

A premarket application must be submitted to the regulatory authorities in accordance with the laws and regulations of each country before marketing a medical device. For example, in Japan, the Pharmaceuticals and Medical Devices Agency, an independent administrative agency under the jurisdiction of the Ministry of Health, Labor, and Welfare, processes applications for approval under the Act on Pharmaceuticals and Medical Devices. In Europe, the Medical Device Regulation provides the regulatory framework, whereas in the US, the Food and Drug Administration serves as the regulatory authority.

Regulatory authorities usually employ standards for better regulation. National standards, established by many countries, are often cited in medical device marketing audits. The Japanese Industrial Standards (JIS), set by the JIS Committee (JISC), are also known as the certification standards for medical devices. Although JIS is essentially a voluntary standard, it can be regarded as a mandatory standard in practice as it is used for medical device certifications. The Agreement on Technical Barriers to Trade (TBT) [6], established by the World Trade Organization, ensures that compliance with the national standards for industrial goods and procedures does not hamper international trade. Therefore, TBT stipulates principles for establishing national standards based on international standards, ensuring transparency [7].

The manufacturers of fNIRS equipment are the major users of the standard. While the sale of fNIRS equipment as medical devices is currently low, it is predicted to increase. fNIRS equipment, first marketed for research use in Japan, is now manufactured and sold in many

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countries. Fortunately, the international standard for the fNIRS equipment has already been established by the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) and published as IEC 80601-2-71 [8]. Manufacturers of fNIRS equipment can enter the global medical device market by ensuring that their products comply with the international standard. As fNIRS technology gains widespread use as a medical device worldwide, adherence to this standard will become increasingly important.

Although regulatory authorities and manufacturers are the primary users of the fNIRS standard, it also benefits researchers in the fNIRS community. Generally, standards ensure that products and services perform as expected [9,10]. The fNIRS standard specifies the basic safety and essential performance criteria for fNIRS equipment, based on various tests developed through expert consultations within the fNIRS community. Equipment that complies with the standard provides users with high-quality data. For researchers involved in the technical development of fNIRS, the standard offers additional benefits. Standards facilitate the dissemination of techniques; therefore, if fNIRS techniques that are valuable in medical practice are included in the standard, these techniques are likely to spread globally.

The fNIRS standard affects stakeholders in many different capacities. Even the readers of this manuscript might be involved in developing the standard in the future. Generally, standards must be revised as technology evolves. Depending on the medical applications, developing new standards might be necessary. Documents summarizing the current development and revision of fNIRS standards are available, but limited in Japanese [11,12]. This review aims to inform the academic community about the international standard for fNIRS, IEC 80601-2-71. In particular, it intends to guide readers interested in revising the current fNIRS standard and developing other standards related to fNIRS. The status of the fNIRS standard development has been presented based on the experience of the current project leader (HK) and the former convenor and project leader (HE). Furthermore, the potential contributions of the future revisions of the standards to academia will be described.

Since the fNIRS standard is copyrighted, this paper will not address its specifics. Moreover, the authors have presented this manuscript as researchers introducing the standard activities to academia. Therefore, the personal views expressed in this manuscript are independent of our positions in the standardization organizations.

2. Development of international standards–an overview

The IEC and ISO are the international bodies that review the fNIRS standard. IEC deals with electrical engineering, electronics, and related technologies, while ISO establishes international standards for various products, services, processes, materials, and systems. The two are nongovernmental, nonprofit organizations headquartered in Geneva, Switzerland.

IEC and ISO develop their standards by working with national bodies worldwide [13,14], which only serve as representatives of the IEC and ISO and are responsible for international voting and the dispatch of technical experts. In Japan, JISC is the national body for IEC and ISO. Member organizations with voting rights in ISO and IEC are called P-members (participating members), while those participating as observers are called O-members (observing members). In practice, standards are reviewed by Technical Committees (TCs), subdivided into committees for each technical field [15,16]. Each TC may establish Sub Committees (SC) and Working Groups (WG) to handle various aspects of its work.

The ISO/IEC directives define the development process for international standards [17,18]. Generally, this process includes six sequential stages: proposal, preparation, committee, introduction, approval, and publication [19,20]. Newly proposed work items in the proposal stage are discussed by P-members and registered in the work plan if they meet the adoption conditions. In the preparation stage, a working draft document is prepared, which is updated after discussion with the experts during the committee, inquiry, and approval stages. At the publication stage,

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the document is published as an international standard. Documents registered at the committee, inquiry, and approval stages are circulated to the national bodies to obtain their comments and vote on their suitability as drafts for the next stage. After reviewing all the comments collected from national bodies, the experts attach their responses before the next international voting. Depending on the outcome of the vote, the next stage might be skipped.

An individual can be involved in developing standards as a member of a national body or as an international expert. In Japan, fNIRS standards are considered for commenting and voting on documents circulated by ISO and IEC through the industry associations for medical and electrical devices, respectively. Additionally, an ISO or IEC expert registered through a national body can directly participate in developing the international standard.

3. International standard for fNIRS

3.1. Position of the fNIRS standard in the IEC 60601 series

The fNIRS standard is included in the IEC 60601 series [21], which is the most important and widely applied international technical standard that specifies basic safety requirements and essential performance for medical devices and systems. This series mainly comprises general, collateral, and particular standards. The general standard, denoted as 60601-1, contains requirements concerning basic safety and essential performance that are generally applicable to medical electrical equipment [22]. For certain types of medical electrical equipment, these requirements are either supplemented or modified by the special requirements of a collateral or particular standard. Publications developed in IEC committees are numbered "IEC 60601-x-y," whereas those developed jointly by IEC and ISO committees are numbered "IEC/ISO 80601-x-y" if the IEC or ISO are the technical leads, respectively [23]. Collateral standards (x = 1) address special aspects ("y" numbering) not fully covered by the general standard. Particular standards (x = 2) are defined for specific medical devices ("y" numbering) and may modify or exclude parts of the general or collateral standards as necessary. Namely, the fNIRS standard IEC 80601-2-71 is a particular standard within the IEC 60601 series, developed by IEC and ISO committees under the technical lead of IEC. Moreover, any standard may cite another closely related standard. For example, the fNIRS standard cites a standard on laser safety. Thus, one standard might be related to various others. Therefore, when developing or revising a standard, attention should be paid to revisions of related standards.

The fNIRS standard was developed by the Joint Working Group (JWG) of the IEC and ISO (Table 1), which includes experts dispatched by the respective national bodies of the IEC and ISO. Currently, the main participants are manufacturers of fNIRS equipment, and physics and engineering researchers from the academic community. The JWG has been developing a standard for pulse oximeters (ISO 80601-2-61) [24] for many years and is currently managing three standards: the fNIRS standard and those for cerebral tissue oximeter equipment (ISO 80601-2-85) [25].

Table 1. Committees and JWGs developing the fNIRS standard

IEC	TC 62	Medical equipment, software, and systems
	SC 62D	Particular medical equipment, software, and systems
	JWG 5	Oximeters
ISO	TC 121	Anesthetic and respiratory equipment
	SC 3	Respiratory devices and related equipment used for patient care
	JWG 10	Oximeters

Particular standards are developed for each application rather than for the principle of measurement of medical equipment. The scope of a particular standard is clearly defined at the

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beginning of the document. In other words, if the scope can be clearly separated from existing standards, new standards can be developed to open new markets. Among the three medical devices mentioned in the previous paragraph, pulse oximeters are clearly different from the other two in terms of the measurement principle, while fNIRS and cerebral tissue oximeters have similar measurement principles. For example, a continuous wave NIRS device with two channels at different emission and detection intervals would be included in the scope of IEC 80601-2-71 if it was a medical fNIRS device with a short channel and in the scope of ISO 80601-2-85 if it was a medical device for measuring absolute cerebral oxygen saturation by applying spatially resolved spectroscopy. Another example includes the use of two electrocardiogram standards: electrocardiogram monitoring equipment (IEC 60601-2-27) and portable electrocardiogram systems (IEC 60601-2-47).

3.2. Development of the fNIRS standard

Like other IEC and ISO standards, the fNIRS standard was developed in the sequential stages, as mentioned above. Table 2 displays the development and process of fNIRS standards based on the experience of the authors regarding the stages indicated in the directives. The following sections outline the actual development process of the first and second editions.

Table 2. Actual development and revision process of the fNIRS standard[a]

Project stage	Important events (Month, Year)	
	First Edition	Second Edition
Proposal stage	Nuremberg meeting (Sep 2011) PWI submission (Nov 2011) Registration as work item (Mar 2012)	N/A
Preparatory stage	Kyoto meeting (Jun 2012) WD preparation (2012–13)	WD preparation (2020–22)
Committee stage	CD approval (Feb 2013)	CD approval (Mar 2022)
Enquiry stage	CDV approval (May 2013)	Phantom campaign (2023–24) CDV approval (Nov 2023)
Approval stage	FDIS approval (Jul 2014)	FDIS registration (Jun 2024)
Publication stage	IS publication (Jun 2015)	IS publication (TBD)
Review	Voting (Sep 2020)	(TBD)

[a]PWI: preliminary work item, WD: working draft, CD: committee draft, CDV: Committee Draft for Vote, FDIS: final draft international standard, IS: international standard, N/A: not applicable, TBD: to be determined.

3.2.1. First edition

The development of NIRS equipment in Japan started in the 1980s. When the data from devices sold by several Japanese manufacturers were compared, a non-negligible bias was found, mainly due to algorithm differences and molar absorption coefficients when calculating hemoglobin concentration changes. An initial standardization was initiated in Japan to solve this problem. First, a Japanese domestic project group was established in 2003 within the Japan Electronics and Information Technology Industries Association (JEITA) to formulate a JIS. Careful discussions were held to avoid any significant impact on the strategies of each manufacturer. Resultantly, the testing method was standardized rather than the equipment itself. After over eight years of discussions among several Japanese manufacturers and researchers, the JEITA standard AE-5010 was finally published as an industry standard, which was withdrawn from publication after the international fNIRS standard was established.

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The first draft of the international fNIRS standard was a careful English translation of the JEITA standard. The committee for preparing the international standard was formed in Japan based on the JEITA project group. Japan communicated its plan to submit a new proposal at the IEC international meeting in Nuremberg (Germany, September 2011). At that time, a US participant, who was not active in the fNIRS community, mentioned considering the development of an international standard for a similar device at the ISO. The chairman acted as an intermediary, and a joint project between the Japanese (IEC side) and the US (ISO side) proposals was suggested, which Japan agreed to. In November 2011, Japan submitted a preliminary work item, and the IEC project was approved with the participation of the five IEC and ISO P-members after an international vote. Simultaneously, the ISO side submitted a new work item proposal, and a joint project with the ISO was established under the IEC lead.

Although launched as a joint project between the IEC and ISO, the working drafts (WDs) of the Japanese and American proposals on the IEC and ISO sides, respectively, differed in content. Therefore, the handling of these two WDs was discussed at the first JWG meeting, held during the ISO meeting in Kyoto, Japan. The meeting room was arranged on short notice to facilitate this discussion. At the first meeting, separating the IEC from the ISO proposal was agreed upon, with the IEC proposal being the first WD for fNIRS. The IEC and ISO central secretariats approved this decision. The IEC proposal, approved by an international ballot in 2012 with the IEC taking the lead, proceeded to the committee stage, while the US proposal was to be developed as a separate joint project. After passing each development stage, the Japanese proposal was published in 2015 as IEC 80601-2-71, while the US proposal was published in 2021 as ISO 80601-2-85.

3.2.2. Second edition

As a rule, periodic ISO reviews must be conducted at least once every five years to update the standards. The fNIRS standard was subjected to an international ballot for periodic review in September 2020 and was voted "Confirmed" (status quo). However, the IEC 60601 series was revised simultaneously, and the secretary suggested waiting for the revision of the general standard before working on its second edition. When the draft was being prepared for the second edition, the main discussion was about the essential performance and the description of alarm systems related to it. After discussion in the JWG, a committee draft (CD) was circulated in November 2022.

National bodies provided over 160 comments on the CD. Standards experts must consider the responses to all comments and incorporate them into the draft, if necessary. The task is known as comment resolution. Before the pandemic, intensive discussions were conducted for comment resolution via face-to-face meetings for 3–4 days about twice a year, which became difficult later. Considering the time difference between the international experts, offline works and online meetings were combined to facilitate effective discussions and comment resolution. In addition to the offline works, three online meetings (6 hours in total) and a one-day hybrid meeting (held in conjunction with the international conference fNIRS2022) were conducted to reach an international consensus on all but about 10 comments related to the performance evaluation tests using a phantom.

When the first edition of the fNIRS standard was published, mostly Japanese manufacturers participated in these discussions. However, manufacturers from various countries have recently started providing fNIRS equipment for research purposes. Although European manufacturers have been involved in developing the standard, which include several performance tests, their lack of experience in these tests was recognized as a problem. Therefore, a phantom campaign, an international round-robin test, was conducted to allow European manufacturers to test the performance evaluation phantom developed in Japan when the first edition was developed and measure it on their equipment. Despite the limited conditions and timeframe during the pandemic,

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European manufacturers could make a positive impression through the phantom campaign, which yielded interesting findings on phantom characteristics that will be presented in a separate paper.

After the phantom campaign, an international consensus was formed on comments on the tests using a phantom in two online meetings, and the CDV was registered. All P-members voted in agreement, and the CDV was approved. The comments received from each country in the CDV circular were agreed upon within the JWG at the time of writing and are being prepared for circulation in the FDIS.

4. Expectations of academia from the standpoint of standard developers

4.1. Utilization of the standard

In addition to being cited as criteria in applications for medical device approval, standards have several functions, including the specification of technical levels, technique dissemination, and technical level improvement. The fNIRS standard includes equipment performance testing. For example, the standard describes tests to determine if the device can detect weak changes in the detected light intensity and if any signal crosstalk occurs between channels. These tests can clearly define the performance of the device. In other words, a device that complies with the fNIRS standard must meet certain technical levels. In research, if a manufacturer provides fNIRS-standardized equipment to the market, the fNIRS data quality will be at a certain level or higher. The use of this equipment by researchers will improve the data quality and enhance the research level.

International standards are also crucial for disseminating techniques. The clarity of the test method will help define the performance required for the device. This will facilitate the entry of new manufacturers, contributing to market expansion. As more manufacturers enter the market and develop devices with various functions, the fNIRS industry will grow in the healthcare industry, including medicine and scientific research.

4.2. Development of measurement techniques and their incorporation into standard development

The test methods for evaluating the performance of fNIRS equipment are key to developing the standard. Recently, fNIRS equipment has become increasingly modularized to make it more compact and wearable. Some relatively new equipment uses optodes integrating the light source and detector [26,27]. Current standard tests often use a phantom, which is suitable for conventional equipment with separate emission and detection optodes. However, this approach is not applicable to integrated optodes. Therefore, equipment that cannot separate emission and detection optodes does not comply with the current standard.

Future revisions must add new tests to the standard or update existing tests to ensure compliance with the standard. Specifically, new phantom tests must be developed. However, the phantom test in the standard should be designed to be as fair as possible so as not to favor or disadvantage some fNIRS equipment. For example, phantoms should be made of a medium whose absorption is mostly independent of the wavelength. Additionally, phantoms should not be manufactured using state-of-the-art methods and materials but universal ones that anyone can easily manufacture. The development of new phantoms that meet these requirements and their inclusion in future standards is strongly encouraged, and the research community is expected to contribute to this effort.

Various contaminants, typified by scalp hemodynamics, are mixed with brain activity in fNIRS signals [28,29], which cannot be eliminated by the tests included in the current standards. Therefore, incorporating such a technique in the standard would be an effective way to make it universal and improve the quality of fNIRS signals. Developing fair test methods would improve the measurement reliability of fNIRS equipment through the standard.

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4.3. Participation in the standard development

Standard development requires the cooperation of members with diverse expertise. The phantom campaign of the standard revision process is a good example of collaboration between standards development and academia, as opinions from an academic standpoint proved valuable in developing and discussing the standard. The involvement of academia has provided new scientific findings on the optical properties and design of the phantom used in the standard. In addition to benefiting the fNIRS community, these findings will also be useful for other biomedical NIRS techniques. In addition, international academic collaboration was strengthened through the phantom campaign. During this campaign, researchers from different countries got to collaborate, enabling future standard revisions. Even countries without their own manufacturers are encouraged to contribute to developing the international standard by providing their comments from an academic standpoint.

The medical application of fNIRS is still in its infancy. Once specific medical applications are determined, the expected performance of the equipment can be clearly defined in the standard. The development of standards requires the cooperation of medical experts. Moreover, the development of the aforementioned test methods should be supported by engineering experts with a broad and deep understanding of the manufacturers who developed them and the details of the relevant techniques.

Although medical and engineering are examples, academicians from various fields can participate in developing standards as members of national bodies or experts in international standardization bodies. If you are interested in standards, please contact your national body first. The list of national bodies can be found on the web pages [13,14], which also provides their contact information. If you are directly involved in developing an international standard, registering as an expert in Geneva first is essential. You may obtain registration information by contacting your national bodies. We welcome expert participation from various backgrounds who can contribute fairly and equitably to building an international consensus.

5. Concluding remarks

This review summarizes the current situation of the international standard IEC 80601-2-71 for fNIRS as a medical device, the development process to date, and expectations for the research community. We expect that the fNIRS equipment newly introduced into the market in compliance with international standards will exceed a certain level of performance. Compliance with standards will allow manufacturers to claim the validity of their equipment performances and provide users access to reliable equipment. The authors strongly hope that the continued revision of the international standard through collaboration among various experts, such as physics and engineering researchers, fNIRS manufacturers, brain science researchers, and medical professionals, will increase the completeness and reliability of fNIRS as a measurement device and contribute to the development of medicine and brain science.

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