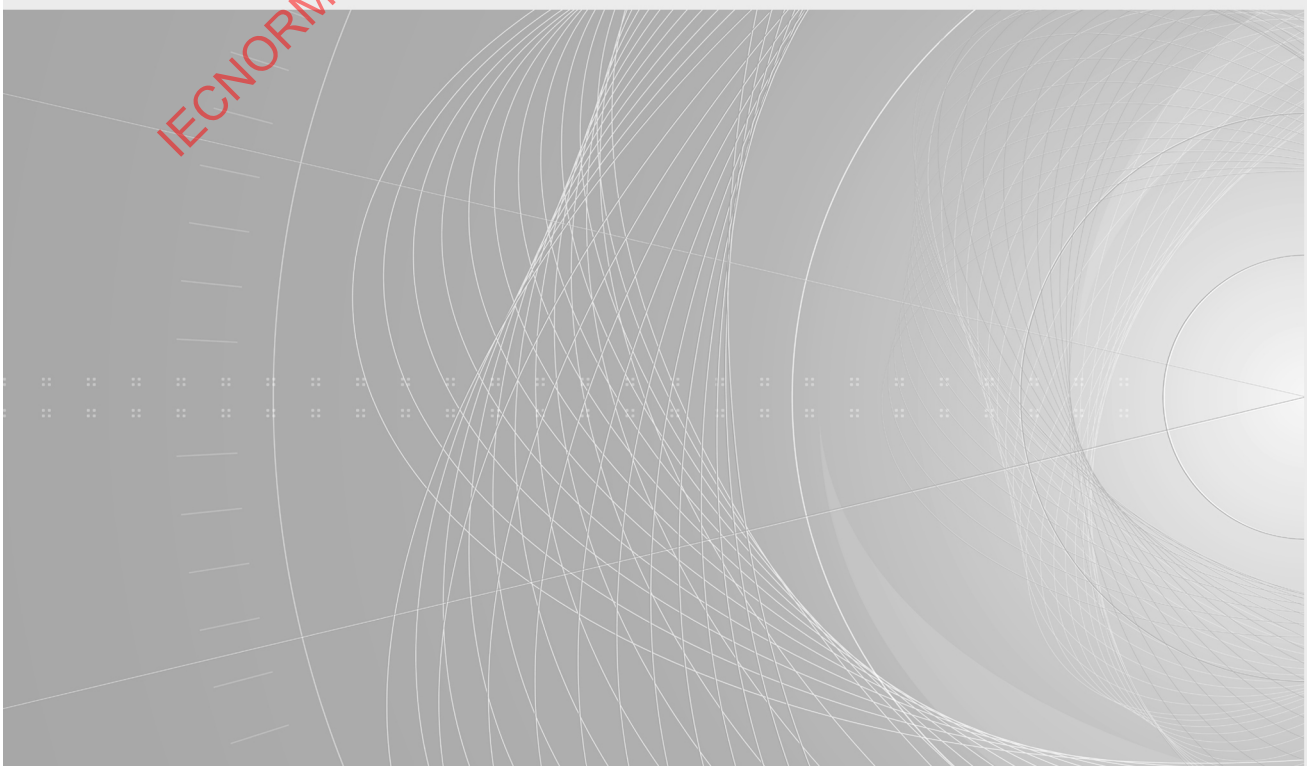
IEC TR 62926

Edition 1.0 2019-05

TECHNICAL REPORT

colour inside

Medical electrical system – Guidelines for safe integration and operation of adaptive external-beam radiotherapy systems for real-time adaptive radiotherapy



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MEDICAL ELECTRICAL SYSTEM –

GUIDELINES FOR SAFE INTEGRATION AND OPERATION OF ADAPTIVE EXTERNAL-BEAM RADIOTHERAPY SYSTEMS FOR REAL-TIME ADAPTIVE RADIOTHERAPY

FOREWORD

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IEC TR 62926, which is a technical report, has been prepared by subcommittee 62C: Equipment for radiotherapy, nuclear medicine and radiation dosimetry, of IEC technical committee 62: Electrical equipment in medical practice.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
62C/729/DTR	62C/737/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

In this document, the following print types are used:

- requirements and definitions: roman type;
- TERMS DEFINED IN CLAUSE 3 OR AS NOTED: SMALL CAPITALS.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Recent developments in RADIOTHERAPY using EXTERNAL BEAM EQUIPMENT (EBE) allow the delivery of doses to TARGET VOLUMEs with greater precision and accuracy than before, while also sparing surrounding critical structures to a higher degree. Three-dimensional or four-dimensional volumetric images are increasingly being used as PATIENT ANATOMY MODELs in RADIOTHERAPY TREATMENT PLANNING SYSTEMs (RTPSs) when simulating a dose distribution. The intended dose distribution is achievable when the four-dimensional location and shape of the TARGET VOLUME and organs at RISK (OARs) during TREATMENT match those of the TARGET VOLUME and OARs at the time of TREATMENT PLANNING. PATIENT anatomy and related physiology are subject to continuous changes as may result from respiration, cardiac motion, and digestive motion, both in the short and long term perspective during RADIOTHERAPY. These include changes in position, orientation, and deformation of the TARGET VOLUME.

Consideration for changes in anatomy or physiology during the course of RADIOTHERAPY, as well as during each fraction, is an important issue in modern RADIOTHERAPY. For example, lung tumours can exhibit translational and rotational changes which may result in underdosage of the TARGET VOLUME and overdosage of OARs. Techniques have been developed to reduce these RISKS by adapting the TREATMENT to the tumour as it moves in real-time. This can be achieved by instructing the EBE to perform a BEAM HOLD during translational motion of the TARGET VOLUME, by repositioning the PATIENT using a robotic PATIENT POSITIONER, by tilting or moving the RADIATION HEAD, by dynamically adapting the MULTILEAF COLLIMATORs (MLCs) of the EBE, or by changing the scanning field of LIGHT ION BEAM equipment operating in scanning mode.

During delivery of ADAPTIVE RADIOTHERAPY, the PATIENT anatomy or physiology is monitored and changes to TREATMENT PARAMETERS are allowed throughout the course of TREATMENT based upon the monitored information (see definition of ADAPTIVE RADIOTHERAPY). ADAPTIVE RADIOTHERAPY is increasingly being used to assure delivery of the prescribed ABSORBED DOSE distribution during intra-fractional changes of TARGET VOLUMEs. There are many different types of MOTION DETECTION EQUIPMENT (MDE) used to monitor intra-fractional organ changes. Some of these use imaging techniques, e.g. X-RAY BASED IMAGE-GUIDED RADIOTHERAPY, ULTRASOUND EQUIPMENT, and MAGNETIC RESONANCE EQUIPMENT, while others use surrogate parameters. Examples of equipment that use surrogate parameters include air flow meters, STRAIN GAUGEs, infrared sensors, optical surface mapping devices, and magnetic field sensors. In some cases, multiple MDEs are combined with a single EBE to monitor intra-fraction motion of multiple organs.

When ADAPTIVE RADIOTHERAPY includes intra-fraction monitoring of the TARGET VOLUME position and shape using an MDE, coordination between the MDE and the EBE is crucial to apply TREATMENT PARAMETER changes at the correct time. A MOTION COORDINATION FUNCTION (MCF) ensures that information about position and shape is appropriately linked to the TREATMENT PLAN, selects TREATMENT PARAMETERS, and sends ADAPTATION INSTRUCTIONs to the EBE. Integration and operation of the MDE, EBE, and MCF is essential to perform ADAPTIVE RADIOTHERAPY safely for a PATIENT with an intra-fractionally changing TARGET VOLUME. There are many possible combinations of EBEs, MDEs and MCFs. Each one can function independently or be integrated as a part of another. Because each function could be an independent piece of MEDICAL ELECTRICAL EQUIPMENT (MEE) and since the safety discussed in this document depends upon the safe integration and operation of the EBEs, MDEs, and MCFs, this combination will be dealt with as a MEDICAL ELECTRICAL SYSTEM. An adaptive external-beam RADIOTHERAPY system (AEBRS) consists of these three main pieces of equipment and respective functions.

The MCF part of an AEBRS can be software or a PROGRAMMABLE ELECTRICAL MEDICAL SYSTEM, and should be subject to the requirements of IEC 62304 or IEC 60601-1. The MDE can be components or systems which are not necessarily compliant with IEC 60601-1.

The reader's attention is drawn to ASTM F-2761 (a publication of the American Society for Testing and Materials) which describes an integrated clinical environment (ICE). The general requirements and the conceptual model of an ICE are described in F-2761. This document uses similar concepts and presents guidance for AEBRS RISK MANAGEMENT.

The reader's attention is also drawn to RADIATION PROTECTION N° 181 which contains general guidelines on RISK MANAGEMENT in external beam radiotherapy.

The concept of an AEBRS with representative information flow is shown in Figure 1.

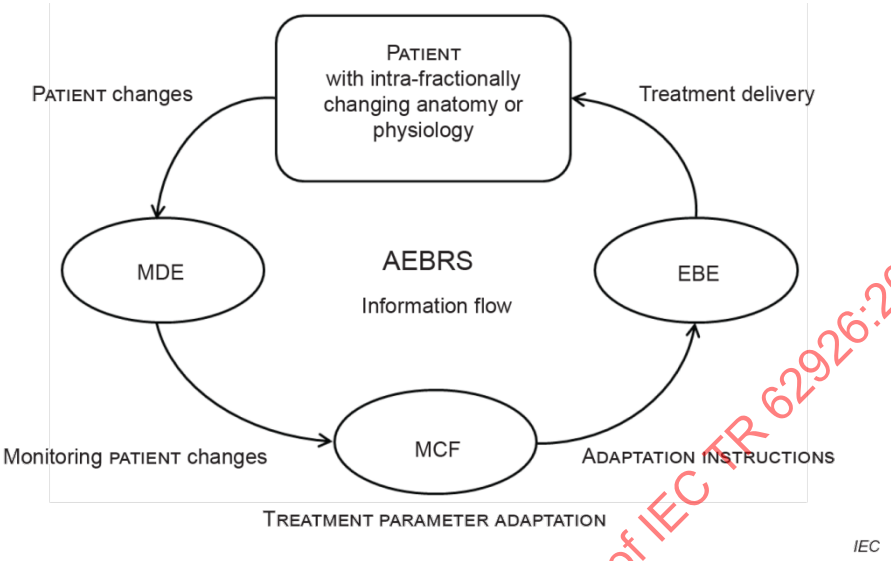

Figure 1 – Concept of AEBRS with information flow

This document provides guidelines for the safe integration and operation of an AEBRS for REAL-TIME ADAPTIVE RADIOTHERAPY. Since real-time monitoring of deformations of TARGET VOLUMEs is still a work-in-progress at this moment, this document addresses rigid TARGET VOLUMEs exhibiting intra-fractional translations and rotations. Deformations of TARGET VOLUMEs are not considered.

This document covers systems, whose configuration may be represented by Figure 2, where potential use of multiple MDEs in one AEBRS is reflected.

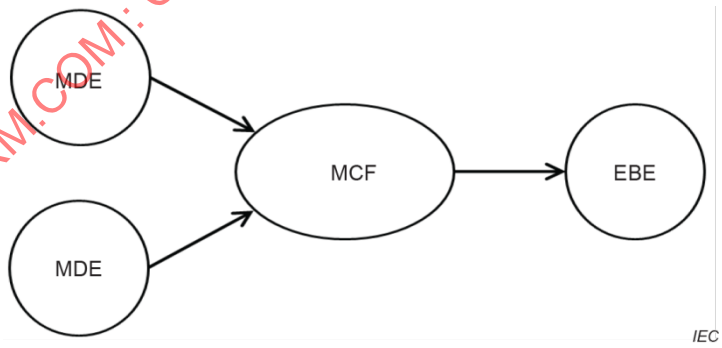

Figure 2 – Example of system configuration

Some EQUIPMENT for image or data acquisition and motion coordination is not covered by existing standards. Therefore, there are safety aspects that arise from the integration of various EQUIPMENT into an AEBRS that should be considered and that are not addressed by existing standards. Based on the considerations discussed above, guidelines should be developed to mitigate the RISKs arising from the integration and operation of ME EQUIPMENT and other various equipment (including non-ME EQUIPMENT) into an AEBRS, as shown in Figures 1 and 2.

This document discusses potential RISKs to be considered during the RISK ANALYSIS and provides recommendations for the safe integration and operation of an AEBRS. Since not all equipment may have an IEC/ISO standard, or an existing standard may not cover the use of the equipment as part of an AEBRS, this document also provides guidelines for individual pieces of EQUIPMENT that are part of the AEBRS. These guidelines are meant to enhance and not supersede requirements that may already exist.

Regarding existing standards, IEC 60601-2-68 includes requirements for X-ray-based MDE in an AEBRS. Requirements and recommendations in IEC 60601-2-68 are often applicable to an AEBRS where the MDE is other than an X-ray-based imaging device, such as optical, ULTRASOUND, or MAGNETIC RESONANCE IMAGING devices. For example, requirements addressing protection against electrical, mechanical, and RADIATION HAZARDs, or requirements addressing X-IGRT LATENCY, which is the time between initiation of image acquisition to delivery of the output signal by an MDE, are also applicable to non X-ray-based imaging devices. MANUFACTURERS or RESPONSIBLE ORGANIZATIONs who integrate an AEBRS for intra-fractionally moving rigid TARGET VOLUMEs should use IEC 60601-2-68 as guidance even when they utilize non X-ray-based imaging devices as MDE in the AEBRS.

Finally, this document addresses safety issues of the AEBRS without assuming specific clinical procedures. As with any testing within a clinical environment, the RESPONSIBLE ORGANIZATION should consider its clinical workflows and practices when devising tests for its facility.

MEDICAL ELECTRICAL SYSTEM –

GUIDELINES FOR SAFE INTEGRATION AND OPERATION OF ADAPTIVE EXTERNAL-BEAM RADIOTHERAPY SYSTEMS FOR REAL-TIME ADAPTIVE RADIOTHERAPY

1 Scope

This document provides guidelines for safe integration and operation of an adaptive external-beam RADIOTHERAPY system (AEBRS) for intra-fractionally moving rigid TARGET VOLUMEs, where required equipment can be sourced from one or several MANUFACTURERs. In particular it addresses guidelines to help ensure safe integration and operation for the PATIENT, OPERATOR, other persons and sensitive devices in the vicinity. In this document, the word "system" is hereafter used to refer to an AEBRS.

This document specifies the safety guidelines for a MANUFACTURER or RESPONSIBLE ORGANIZATION who integrates the AEBRS for intra-fractionally moving rigid TARGET VOLUMEs. If a RESPONSIBLE ORGANIZATION integrates an AEBRS, then it takes the role of MANUFACTURER and will be referred to as a MANUFACTURER throughout this document.

This document includes reference models of the AEBRS for intra-fractionally moving rigid TARGET VOLUMEs and HAZARDs which, at a minimum, are considered during the RISK ANALYSIS.

Although TARGET VOLUMES and OARs can deform during motion, adaptations in response to deformations of the TARGET VOLUME are out of the scope of this document. The scope is limited to rigid TARGET VOLUMEs exhibiting intra-fractional movements, both translational and rotational. While technical HAZARDs are discussed in this document, the RESPONSIBLE ORGANIZATION is reminded that clinical judgement is always employed when determining clinical usability and reviewing TREATMENT PARAMETER changes.

This document does not specifically address HAZARD mitigations for each of the HAZARDs mentioned in the document; however, some mitigations are given as examples in Clauses 4 and 5. All guidelines in this document are intended to be implemented in accordance with the general standard IEC 60601-1:2005 and IEC 60601-1:2005/AMD1:2012, with special attention to 4.2 of IEC 60601-1:2005 and IEC 60601-1:2005/AMD1:2012.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60601-1:2005, *Medical electrical equipment – Part 1: General requirements for basic safety and essential performance*
IEC 60601-1:2005/AMD1:2012

ISO 14971:2007, *Medical devices – Application of risk management to medical devices*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
ADAPTATION INSTRUCTION
instruction generated for TREATMENT PARAMETER ADAPTATION

3.2
ADAPTIVE RADIOTHERAPY
radiotherapy that monitors PATIENT anatomy or physiology and, based upon the monitored information, allows changes to TREATMENT PARAMETERs throughout the course of treatment

Note to entry: IMAGE GUIDED RADIATION THERAPY (IGRT) is one form of ADAPTIVE RADIOTHERAPY.

3.3
BEAM GATING
allowance or inhibition of IRRADIATION and related equipment movements according to the status provided by a BEAM GATING SIGNAL

[SOURCE: IEC 60601-2-64:2014, 201.3.204]

3.4
BEAM GATING SIGNAL
signal generated for the purpose of BEAM GATING

EXAMPLE Examples include a respiratory spirometer, electrocardiogram, optical sensor, etc.

[SOURCE: IEC 60601-2-64:2014, 201.3.205]

3.5
BEAM HOLD
condition during IRRADIATION in which the MEE has minimized the TREATMENT IRRADIATION output (approximating the IRRADIATION off condition)

NOTE 1 TO ENTRY: BEAM HOLD is not the same as INTERRUPTION OF IRRADIATION where the MEE is changed to the beam off state

NOTE 2 TO ENTRY: BEAM HOLD is a subcondition of IRRADIATION for the purpose of rapid transition to intended TREATMENT IRRADIATION output

Note 3 to entry: This is commonly used during gating, IMRT, etc.

[SOURCE: IEC 60601-2-1:20—, 201.3.208]

3.6
EXTERNAL BEAM EQUIPMENT
EBE
external RADIATION EQUIPMENT utilizing ELECTRON ACCELERATORS, LIGHT ION BEAM EQUIPMENT or RADIONUCLIDE BEAM THERAPY EQUIPMENT

Note 1 to entry: The note to entry concerning the origin of the abbreviation EBE applies to the French text only

[SOURCE: IEC 60601-2-68:2014, 201.3.207]

3.7
IRRADIATION
exposing of a living being or matter to RADIATION

Note 1 to entry: In RADIOLOGY, exposing of a living being or matter to IONIZING RADIATION.

Note 2 to entry: Examples of ionizing radiation include: x-rays, gamma-rays, electrons, neutrons, and light ions.

[SOURCE: IEC TR 60788:2004, rm-12-09, modified – moved examples of IONIZING RADIATION to a note.]

3.8
LATENCY
time interval between initiation of an event and its effect

[SOURCE: IEC 60601-2-1:20—, 201.3.232]

3.9
MANUFACTURER
natural or legal person with responsibility for the design, manufacture, packaging, or labelling of ME EQUIPMENT, assembling an ME SYSTEM, or adapting ME EQUIPMENT or an ME SYSTEM, regardless of whether these operations are performed by that person or on that person's behalf by a third party

Note 1 to entry: ISO 13485 defines "labelling" as written, printed or graphic matter

– affixed to a medical device or any of its containers or wrappers, or
– accompanying a medical device,
related to identification, technical description, and use of the medical device, but excluding shipping documents. In this standard, that material is described as markings and ACCOMPANYING DOCUMENTS.

Note 2 to entry: "Adapting" includes making substantial modifications to ME EQUIPMENT or an ME SYSTEM already in use.

Note 3 to entry: In some jurisdictions, the RESPONSIBLE ORGANIZATION can be considered a MANUFACTURER when involved in the activities described.

Note 4 to entry: Adapted from ISO 14971:2007, definition 2.8.

[SOURCE: IEC 60601-1:2005 and IEC 60601-1:2005/AMD1:2012, 3.55]

3.10
MOTION COORDINATION FUNCTION
MCF
function that evaluates and combines information provided by one or more MDEs to derive and adapt TREATMENT PARAMETERS

Note 1 to entry: The MCF can include a PREDICTION MODEL, a function generating ADAPTATION INSTRUCTIONS and a function for evaluating validity and deliverability of the ADAPTATION INSTRUCTIONS.

3.11
MOTION DETECTION EQUIPMENT
MDE
equipment that acquires data for monitoring changes in PATIENT anatomy or physiology

Note 1 to entry: This includes changes in position, orientation and deformation of the TARGET VOLUME, and changes in PATIENT setup or surface positioning.

3.12
MULTILEAF COLLIMATOR
MLC
a multi-element BLD capable of defining RADIATION FIELDS of irregular shapes

Note 1 to entry: The positions of the individual elements can either be static or can be changed dynamically during IRRADIATION.

[SOURCE: IEC 60601-2-1:20—, 201.3.233]

3.13
PREDICTION MODEL
algorithm that predicts changes, such as changes in PATIENT anatomy or physiology, based on information from one or more MDEs

Note 1 to entry: This includes predicting changes in position, orientation and deformation of the TARGET VOLUME.

3.14
RADIATION HEAD
structure from which the RADIATION BEAM emerges

[SOURCE: IEC TR 60788:2004, rm-20-06]

3.15
REAL-TIME ADAPTIVE RADIOTHERAPY
radiotherapy that, throughout therapeutic IRRADIATION, monitors PATIENT anatomy or physiology and based upon that information, allows autonomous adjustments of TREATMENT PARAMETERS throughout the therapeutic IRRADIATION without OPERATOR intervention

3.16
TREATMENT PARAMETER ADAPTATION
change of TREATMENT PARAMETERS based on monitored changes, such as changes in PATIENT anatomy or physiology

Note 1 to entry: BEAM GATING and tracking are examples of TREATMENT PARAMETER ADAPTATION.

3.17
X-IGRT LATENCY
time from initiation of image acquisition to delivery of output signal by X-IGRT EQUIPMENT to the EBE

Note 1 to entry: It is expected that the EBE should also state its LATENCY time from receiving a signal to providing the requested action.

Note 2 to entry: The X-IGRT LATENCY includes the hardware and software LATENCIES.

Note 3 to entry: Network transfer times vary from one installation to another as there are too many factors involved that are supplied by the user. Network transfer LATENCY therefore is not considered as part of the X-IGRT LATENCY time.

[SOURCE: IEC 60601-2-68:2014, 201.3.234, modified – In Note 1 to entry, "correction" was replaced by "requested action".]

4 General safety guidelines for an AEBRS for intra-fractionally moving rigid TARGET VOLUMES

4.1 TARGET VOLUMES addressed in this document

The effects of intra-fraction TARGET VOLUME translations, rotations and deformations on delivered dose distributions depend not only on the extent of these changes but also on the size and shape of the TARGET VOLUME and on changes in the surrounding tissues. For example, the dose distribution for a rotated small spheroid shaped target (e.g. a baseball shape) will not change much as the rotation angle increases, while the dose distribution can change significantly for a rotated long narrow cylinder target (e.g. a cigar shape) if rotated perpendicularly to its long axis.

The detection of TARGET VOLUME translations, rotations and deformations during the delivery of a single fraction is difficult without real-time volumetric imaging techniques. However, TARGET VOLUME changes can be predicted by combining 4D volumetric planning images with information from associated surrogate detectors such as orthogonal 2D imaging with implanted fiducial markers, spirometers, expansion belts, or PATIENT surface scanning

EQUIPMENT. Monitoring of deformations by volumetric imaging in real-time is still considered a work-in-progress at this moment. Therefore, it will not be addressed in this document.

The RESPONSIBLE ORGANIZATION should investigate the effects of translations, rotations and deformations and the clinical tolerances allowed for their PATIENT population and select the appropriate combination of sensors, software and other MEES. This document addresses safety issues associated with integrating these combinations but does not address the clinical applications.

4.2 Relationship between system configuration of an AEBRS, existing standards, and this document

4.2.1 General

The RISK arising from the integration of equipment in an AEBRS should be addressed by the MANUFACTURER and this should be done according to existing STANDARDs, where available.

Irrespective of the system configuration of an AEBRS, IEC 60601-1 and its collaterals always apply. Particular standards may exist to cover equipment integrated in an AEBRS. Examples of such particular standards are IEC 60601-2-1 and IEC 60601-2-64 for EBE, IEC 60601-2-68 for MCF or a combination of MCF and MDE, and IEC 60601-2-33 and IEC 60601-2-44 for MDE.

This document provides further guidance in implementing 4.2 and Clause 14 from IEC 60601-1:2005 and IEC 60601-1:2005/AMD1:2012.

The MANUFACTURER of an AEBRS should ask the MANUFACTURER of any MEE to be integrated to provide applicable conditions of interoperability and requirements for acceptability.

Mitigation of AEBRS RISKS is the responsibility of the integrating party, and the mitigation should be demonstrated by a completed Test Report Form for the IEC 60601-1 series of standards.

Compliance of the AEBRS can be documented by referencing the corresponding clauses or subclauses of existing standard(s) for the integrated devices.

NOTE 1 An example of MEEs covered by particular standards in the IEC 60601 series is illustrated when assessing the RISK associated with an AEBRS using LIGHT ION BEAM equipment as an EBE and utilizing X-ray RADIOSCOPY as an MDE. IEC 60601-2-64:2014 applies to the EBE and IEC 60601-2-68:2014 applies to the MDE and MCF.

NOTE 2 An example of an MEE not covered by IEC 60601 particular standards is illustrated when assessing the RISK associated with an AEBRS utilizing a 3D camera as MDE. The latter is not addressed by any of the standards in the IEC 60601-1 series.

Annexes A to C show examples of RISK MANAGEMENT of an AEBRSs as explained in 4.3.2.

4.2.2 Representative configurations of AEBRSs, their relationships to existing standards, and this document

4.2.2.1 General

Representative configurations of AEBRSs, their relationships to existing standards and this document are described in the following subclauses. The dotted line in each figure indicates the function or EQUIPMENT covered by the standard cited in each of the following paragraphs and figures. This document covers the entire system as described by the series of examples.

4.2.2.2 Relationship with standards for MOTION DETECTION EQUIPMENT (MDE)

Figure 3 shows an example of an AEBRS incorporating MDE that are addressed by particular standards (e.g. IEC 60601-2-33 for MRI, IEC 60601-2-68 for X-IGRT).

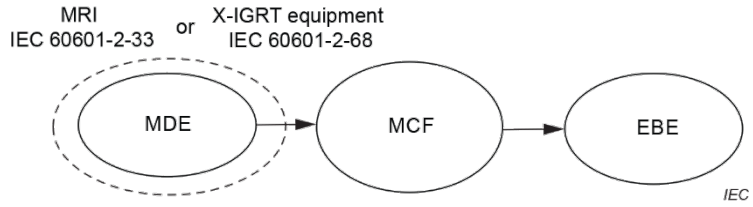

Figure 3 – AEBRS incorporating an MDE addressed by particular standards

Figure 4 shows an example of an AEBRS incorporating MDE (e.g. surface guided MOTION DETECTION EQUIPMENT) which is not addressed by a particular standard.

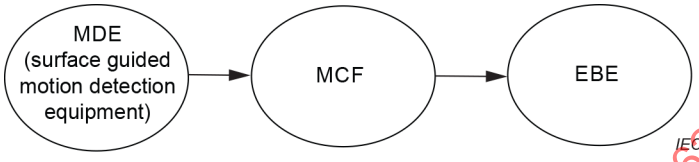

Figure 4 – AEBRS incorporating an MDE not addressed by a particular standard

4.2.2.3 Relationship with STANDARDS for MDE with an interface to MCF

An example of MDE with an interface to an MCF is shown in Figure 5. The figure shows an example of X-IGRT EQUIPMENT that incorporates an MCF. The particular standard addressing X-IGRT is IEC 60601-2-68.

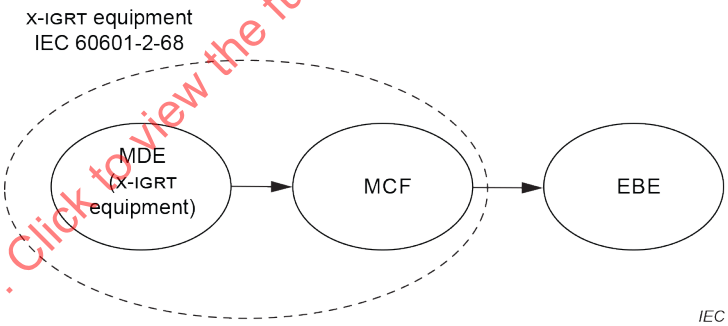

Figure 5 – AEBRS incorporating an MDE with an interface to an MCF

4.2.2.4 Relationship with STANDARDS for EBE with an interface to an MCF

An example of an EBE with an interface to an MCF is shown in Figure 6. The figure shows an ELECTRON ACCELERATOR or a LIGHT ION BEAM ME EQUIPMENT which is interfaced to an MCF. The standard addressing ELECTRON ACCELERATOR equipment is IEC 60601-2-1, and the standard addressing LIGHT ION BEAM ME EQUIPMENT is IEC 60601-2-64.

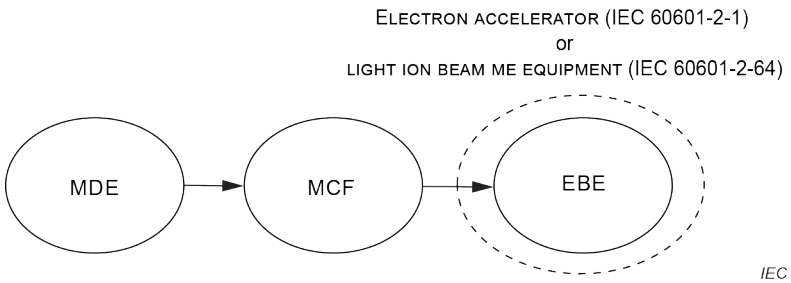

Figure 6 – AEBRS incorporating an MCF with an interface to an EBE

4.2.2.5 Relationship with the guideline for an interface between an MCF and an EBE

The interface between an MCF and an EBE is shown in Figure 7. The figure shows an example of a gating interface. An existing guideline addressing a gating interface is NEMA RT-1.

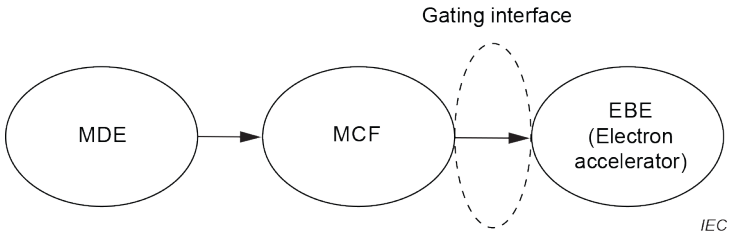

Figure 7 – AEBRS with a gating interface between an MCF and an EBE

4.2.2.6 A generic reference model of an AEBRS for intra-fractionally moving rigid TARGET VOLUMEs with information flow for a representative system

An adaptive external-beam RADIOTHERAPY system (AEBRS) for intra-fractionally moving rigid TARGET VOLUMEs is defined as consisting of an EXTERNAL BEAM EQUIPMENT (EBE), a MOTION DETECTION EQUIPMENT (MDE), and MOTION COORDINATION FUNCTIONS (MCFs). MDEs acquire data for monitoring the intra-fractional movement of the rigid TARGET VOLUME or an appropriate surrogate; an MCF performs the TREATMENT PARAMETER ADAPTATION according to the information provided by the MDE and sends ADAPTATION INSTRUCTIONS to the EBE; and the EBE delivers a TREATMENT to the PATIENT accordingly. Figure 1 shows the concept of the AEBRS and the information flow. A representative system configuration of an AEBRS is shown in Figure 2. In Figure 8, functions and information flow are shown using the representative system configuration of Figure 2.

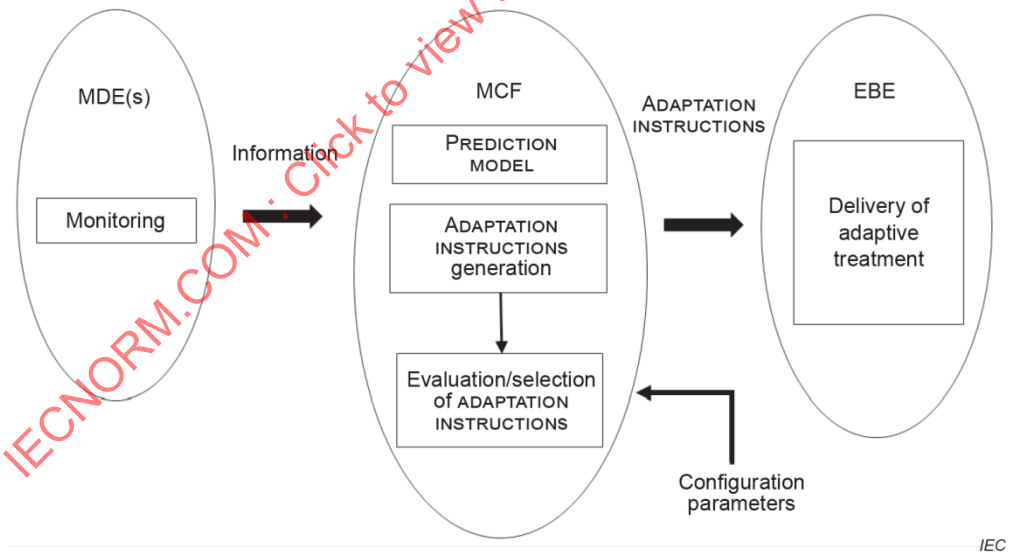

Figure 8 – Functions and information flow of an AEBRS

The AEBRS may incorporate multiple pieces of MOTION DETECTION EQUIPMENT (MDE). MDEs acquire data for monitoring the intra-fractional movement of the rigid TARGET VOLUME or an appropriate surrogate, which can be used to estimate the position of the TARGET VOLUME in three dimensions, registering both translations and rotations. This positional information is processed by the MCF. Deformations of the TARGET VOLUME are not covered in this document.

An MCF includes a PREDICTION MODEL, a function generating ADAPTATION INSTRUCTIONS, and a function for evaluating the validity and deliverability of the ADAPTATION INSTRUCTIONS. The MCF

may evaluate and combine information from multiple MDEs. The selected ADAPTATION INSTRUCTIONS are sent to the EBE.

The PREDICTION MODEL predicts the changes in rotational and translational position of the rigid TARGET VOLUME based on information from the MDE, and prior information generated by the PREDICTION MODEL.

The results of the prediction by the PREDICTION MODEL are used to generate ADAPTATION INSTRUCTIONS.

The validity and deliverability of the generated ADAPTATION INSTRUCTIONS are evaluated. ADAPTATION INSTRUCTIONS valid for TREATMENT PARAMETER ADAPTATION are selected and sent to the EBE for TREATMENT delivery.

The EBE executes TREATMENT delivery by applying the new TREATMENT PARAMETERS according to the ADAPTATION INSTRUCTIONS output by the MCF.

4.2.3 Representative AEBRS reference models

4.2.3.1 General

The function performed by the MCF of the AEBRS can be classified as a gating function or a tracking function. These are described in Figure 9 and Figure 10 respectively.

4.2.3.2 BEAM GATING system model

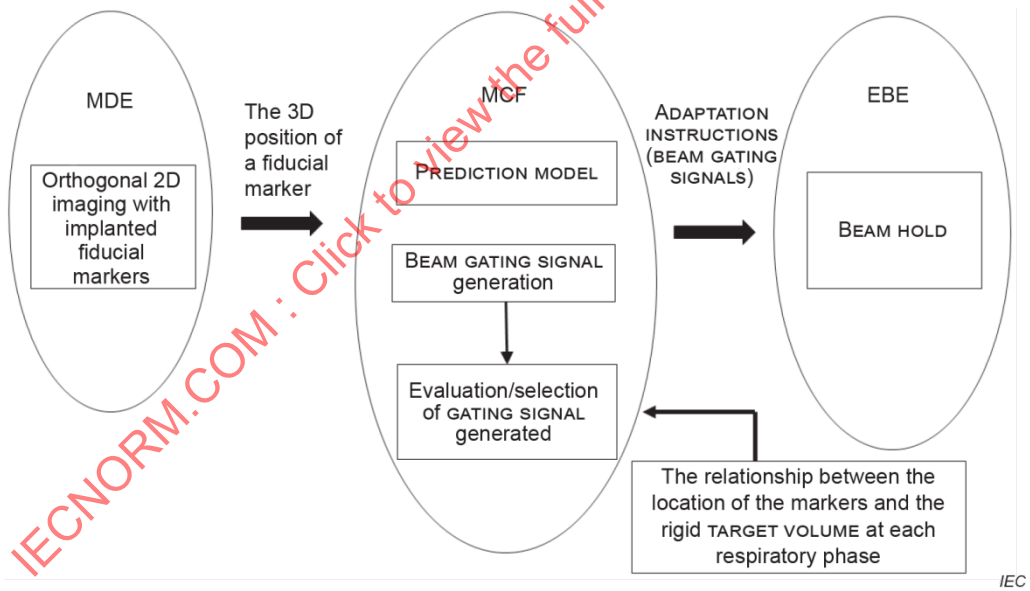

Figure 9 – BEAM GATING system for intra-fractionally moving rigid TARGET VOLUMES

Figure 9 shows an example of an AEBRS reference model; a BEAM GATING system for intra-fractionally moving rigid TARGET VOLUMEs. The configuration parameters describing the relationship between the location of internal fiducial markers and the rigid TARGET VOLUME at each respiratory phase is loaded into the MCF before the treatment. Orthogonal 2D imaging of internal fiducial markers is used as an MDE and the 3D position of a fiducial marker is transferred from the MDE to the MCF. In the MCF, a PREDICTION MODEL predicts the changes in position of the rigid TARGET VOLUME based on information from the MDE. The output of the PREDICTION MODEL is used to generate ADAPTATION INSTRUCTIONS, which are BEAM GATING SIGNALS in this case. After evaluation of the generated BEAM GATING SIGNALS, using pre-treatment established limits of allowed 3D position of the fiducial markers, valid BEAM GATING SIGNALS are sent to the EBE. In response, the EBE performs a BEAM HOLD or a beam resume.

4.2.3.3 Beam tracking system model

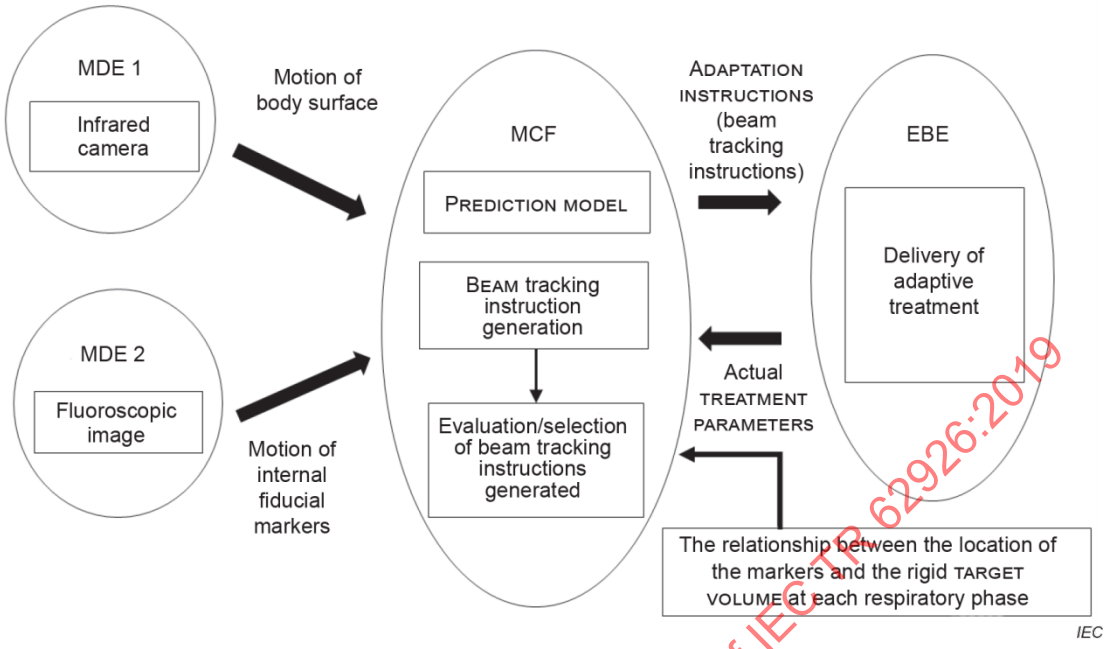

Figure 10 – Beam tracking system for intra-fractionally moving rigid TARGET VOLUMES

Figure 10 shows an example of a reference model of a beam tracking system for intra-fractionally moving rigid TARGET VOLUMEs. The configuration parameters relating the location of internal fiducial markers to that of the rigid TARGET VOLUME at each respiratory phase are loaded into the MCF before the treatment. The motion of the body surface detected by an infrared camera in MDE 1 is used to determine the respiratory phase. The motion of internal fiducial markers detected by fluoroscopy in MDE 2 is used to determine the position of the rigid TARGET VOLUME. These data are transferred from MDE 1 and MDE 2 to the MCF. The PREDICTION MODEL predicts the changes in position, including rotations and translations, of the rigid TARGET VOLUME based on the correlation model created by synchronization of the data from MDE 1 and MDE 2. The output of the PREDICTION MODEL is used to generate ADAPTATION INSTRUCTIONS, which are beam tracking instructions in this case. After evaluation of the beam tracking instructions, valid beam tracking instructions are sent to the EBE. The EBE performs TREATMENT delivery applying the TREATMENT PARAMETERS. The TREATMENT PARAMETERS actually used, such as beam direction, are sent back to the MCF from the EBE for verification.

4.3 RISK MANAGEMENT of an AEBRS

4.3.1 General

This document provides a guideline for the RISK MANAGEMENT PROCESS (defined in ISO 14971) of the AEBRS for intra-fractionally moving rigid TARGET VOLUMEs.

A minimum set of HAZARDs to consider for adaptive TREATMENT functions are given in Annex A.

Since RISK MANAGEMENT of an AEBRS often requires the understanding of the RESPONSIBLE ORGANIZATION and USER, the RESPONSIBLE ORGANIZATION and USERs should also review and adopt this guideline even when they are not involved in the integration of the AEBRS.

The MANUFACTURER who integrates the AEBRS should determine the criteria for RISK acceptability of an AEBRS. RISK MANAGEMENT of an AEBRS should be carried out by assignment of responsibilities and authorities for personnel who are able to analyze and review the combination of MDE, MCF, and EBE.

The RISK MANAGEMENT PROCESS of the AEBRS includes RISK ANALYSIS, RISK EVALUATION, RISK CONTROL, evaluation of overall RESIDUAL RISK acceptability, and preparation of a RISK MANAGEMENT report for the whole system as defined in ISO 14971.

When a part of the AEBRS is not ME EQUIPMENT, and that part is not integrated into another ME EQUIPMENT as part of the AEBRS, the non-ME EQUIPMENT may not be covered by other existing safety standards. In this case, the RISK MANAGEMENT of the AEBRS should address the entire system, including non-ME EQUIPMENT that are part of the AEBRS.

4.3.2 RISK ANALYSIS of an AEBRS

The aim of RISK ANALYSIS of an AEBRS is to identify HAZARDs and estimate RISK arising from combining MDE, MCF, and EBE.

In line with 3.2 and 3.4 of ISO 14971:2007, and ISO TR 24971:2013, the MANUFACTURER should maintain criteria for RISK acceptability, those criteria being part of its RISK MANAGEMENT policy.

NOTE 1 Reference models in 4.2 can be extended to describe the configuration of AEBRS in the RISK ANALYSIS and can help to prevent essential elements from being overlooked in the RISK ANALYSIS.

The MANUFACTURER who integrates the AEBRS should identify and document the intended use and reasonably foreseeable misuse of the AEBRS as well as those qualitative and quantitative characteristics that could affect the safety of the AEBRS and their limitations.

The MANUFACTURER who integrates the AEBRS should identify the HAZARDs of an AEBRS. Only HAZARDs arising from combining MDE, MCF, and EBE to constitute the AEBRS should be considered.

Since there are various combination patterns of MDE, MCF, and EBE among different AEBRSs, identification of HAZARDs or HAZARDOUS SITUATIONS for each should be performed for each AEBRS. The RISK(s) of the HAZARDs or HAZARDOUS SITUATIONS, including the probability and the severity of the resulting HARM should be estimated for each AEBRS.

NOTE 2 Even when the same MDE and EBE are used, the MCF can be different among AEBRSs. For example, the gating window can be respiratory phase-oriented in one AEBRS and respiratory amplitude-oriented in another AEBRS.

4.3.3 RISK EVALUATION

For each identified HAZARD or HAZARDOUS SITUATION, the MANUFACTURER who integrates the AEBRS should decide, using the criteria defined in the RISK MANAGEMENT plan, if RISK reduction is required. This PROCESS should be carried out independent from RISK EVALUATION of each EQUIPMENT.

4.3.4 RISK control

The MANUFACTURER who integrates the AEBRS should be aware that RISK CONTROL of the AEBRS should be performed when RISK reduction is required. If the RISK CONTROL is practical, the AEBRS should be designed by the MANUFACTURER to be inherently safe. If this is not practical, then protective measures such as barriers or alarms somewhere in the AEBRS are appropriate. The least preferred protective measure is a written warning or contra-indication of the AEBRS.

4.3.5 Evaluation of overall RESIDUAL RISK acceptability

An iterative procedure should be continued until the RISK is reduced to acceptable levels established in the RISK MANAGEMENT plan of the AEBRS with or without consideration for the medical benefits.

4.3.6 RISK MANAGEMENT report

The MANUFACTURER who integrates the AEBRS should carry out a review of the RISK MANAGEMENT PROCESS of the AEBRS and the results of this review should be recorded as the RISK MANAGEMENT report before commercial distribution and before clinical application.

The responsibility for review should be assigned in the RISK MANAGEMENT plan to persons having the appropriate authority for the AEBRS.

4.3.7 Examples of RISK MANAGEMENT of an AEBRS

The following are typical types of HAZARDs which are often identified in the RISK ANALYSIS for an AEBRS: IRRADIATION HAZARD, electromagnetic HAZARD, mechanical HAZARD, and electrical HAZARD.

IRRADIATION HAZARDs specific for an AEBRS are connected to the functionality of this system, which is an adaptation of the external-beam RADIOTHERAPY to the changes in PATIENT anatomy or physiology.

The most common RISKs resulting from the major HAZARDs for an AEBRS for intra-fractionally moving TARGET VOLUMES are underdose or overdose of the TARGET VOLUME or overdose of the OARS and surrounding normal tissues.

NOTE 1 Annexes B and C show examples of RISK MANAGEMENT of an AEBRSs.

NOTE 2 A fishbone diagram (Ishikawa diagram) is an effective method to create a list of failure modes and identify HAZARDs or HAZARDOUS SITUATIONS arising from combining MDE, MCF, and EBE as the source of HARM. An example of a fishbone diagram of an AEBRS is provided in Annex B.

The following phases are likely phases during which HAZARDS can be found for an AEBRS:

1) design phase;
2) construction phase;
3) use phase;
4) maintenance phase.

During the design phase and construction phase, if some part of the IT network of the RESPONSIBLE ORGANIZATION is used for communication, the RESPONSIBLE ORGANIZATION as well as MANUFACTURER should participate in the RISK MANAGEMENT PROCESS. Since OPERATORs of AEBRS in a RESPONSIBLE ORGANIZATION are often involved in the use phase and the maintenance phase of the AEBRS, the RESPONSIBLE ORGANIZATION should be aware of the RISKs and control them. Further guidance for this system integration may be found in ASTM F-2761.

5 Guidance for design elements that should be considered for safe integration of an AEBRS for intra-fractionally moving TARGET VOLUMES

5.1 General

Specific safety guidelines for the AEBRS for intra-fractionally moving rigid TARGET VOLUMES are described in the following subclauses. These guidelines are to be addressed by the MANUFACTURER who integrates the AEBRS to assure safe integration and operation of the AEBRS for rigid TARGET VOLUMES exhibiting intra-fractional movements.

5.2 Specific guidelines for an AEBRS

5.2.1 Configuration of the AEBRS

The MANUFACTURER who integrates the AEBRS should define the required performance.

The MANUFACTURER who integrates the AEBRS should select equipment and design the AEBRS so that the system performs IRRADIATION as intended.

Criteria for selection and design of EQUIPMENT should be based on:

a) the specification of data acquisition for MDE;
b) the specification of the input and output data interfaces of all the AEBRS components;
c) the compatibility of MDE hardware with IRRADIATION (both for MDE functionality and translucency);
d) the compatibility of MDE hardware with magnetic fields and RF RADIATION, where appropriate;
e) the requirement that the MDE field of view is adequate under all TREATMENT delivery conditions.

The correct configuration and performance of the AEBRS should be confirmed by testing the basic performance of the system.

The MANUFACTURER should state the required performance, as well as the tests and conditions to verify correct function in the ACCOMPANYING DOCUMENTATION.

A description of the intended configuration, confirmation of the correctness of the configuration and the results of checking the function of each piece of equipment should be described in the ACCOMPANYING DOCUMENTATION.

NOTE For example, the ACCOMPANYING DOCUMENTATION can include a statement that the MDE performance can be compromised due to the EBE configuration, e.g. obstruction of an optical path.

5.2.2 INTERLOCKS

The MANUFACTURER should consider implementation of an INTERLOCK, if uncontrolled continuation of a function would pose an unacceptable RISK.

INTERLOCKs included as part of the AEBRS should be checked by a method to be determined by the MANUFACTURER.

The method should be documented in the ACCOMPANYING DOCUMENTATION.

NOTE 1 An INTERLOCK can be checked by artificial or dummy data, failure signals, shut down of a healthy signal or a watchdog signal.

A description of all INTERLOCKs should be included in the ACCOMPANYING DOCUMENTATION.

The levels of failure and the INTERRUPTION or TERMINATION PROCESS for each level of failure should be defined and described in the ACCOMPANYING DOCUMENTATION.

In the cases described below, INTERLOCK signals should be required if continued operation would pose an unacceptable RISK, if

– inconsistency of time stamps or position data from multiple MDE is detected,
– any signals between functions in MCF are outside the acceptable range, or
– the feedback signals are outside the acceptable range.

NOTE 2 Signals passed between functions in the MCF are signals from the PREDICTION MODEL and those from the ADAPTATION INSTRUCTION generator.

5.2.3 Coordinate system

The coordinate system used for all input or output data of all AEBRS EQUIPMENT should be consistent, so as to ensure that IRRADIATION by the EBE is performed correctly.

The MANUFACTURER of the AEBRS should use the coordinate system definition provided by IEC 61217 and state it accordingly in the ACCOMPANYING DOCUMENTATION.

The coordinate systems of the MDE(s) and the MCF should be the same as that of the EBE. Otherwise, the MANUFACTURER should define and validate the transformations between the coordinate systems of the EBE, MCF and MDE. Any coordinate system which is accessible by the USER should be described in the ACCOMPANYING DOCUMENTATION.

If the USER can configure or select between two or more MDEs, then the MANUFACTURER should consider any possible HAZARDs associated with the configuration or the selection.

5.2.4 Communication between pieces of equipment

5.2.4.1 Connection

If the RISK MANAGEMENT of the AEBRS requires the RESPONSIBLE ORGANIZATION to safeguard the communication between the MDE, MCF, and EBE, then such provisions should be described in the ACCOMPANYING DOCUMENTATION.

All connections should be uniquely identified and labelled. Where confusion between OPERATOR- or PATIENT-accessible connections could lead to an unacceptable RISK, appropriate keying (mechanical or software) should be provided.

5.2.4.2 MDE data acquisition

Where data describing the position of the rigid TARGET VOLUME is calculated, the algorithm should be described in the ACCOMPANYING DOCUMENTATION.

The frequency and the conditions of data acquisition by the MDE and of the calculation of the target position before and during a TREATMENT should be determined by the MANUFACTURER, and described in the ACCOMPANYING DOCUMENTATION.

NOTE The calculation of the target position can be carried out by using one or multiple image data sets of either the target itself or fiducial markers. For example, the 3D position of a fiducial marker can be calculated from 2 kV X-ray images taken from different angles.

5.2.4.3 Synchronization of data

An AEBRS should use a common timer for each MDE, MCF and EBE. The method of data synchronization should be defined in the ACCOMPANYING DOCUMENTATION.

NOTE The timer can be relative or absolute, i.e. a real world clock.

Data acquired by any MDEs in the AEBRS should be sent to the MCF together with a time stamp.

5.2.4.4 Data transfer

Data transferred to or from EQUIPMENT in the AEBRS should use a communication protocol that verifies error-free transmission. Consistency, correctness, and completeness of the data transferred between MDE and MCF should be checked, and data transferred between MCF and EBE should be checked.

The criteria defining consistency, correctness, and completeness should be stated by the MANUFACTURER. The measures to check consistency, correctness, and completeness should be stated by the MANUFACTURER in the ACCOMPANYING DOCUMENTATION.

The input data from the MDE into the PREDICTION MODEL in the MCF should be checked against pre-established limits defined by the MANUFACTURER. The output data sent from the PREDICTION MODEL to the ADAPTATION INSTRUCTION generator in the MCF should be checked against pre-established limits defined by the MANUFACTURER. The output data sent from the ADAPTATION INSTRUCTION generator to the evaluation/selection function in the MCF should be checked against pre-established limits defined by the MANUFACTURER. Signal(s) sent from the MCF to the EBE should be within the acceptable range defined by the MANUFACTURER. At least one of the components of the AEBRS should provide information when the signal is out of the acceptable range.

5.2.4.5 Redundancy

The redundancy of communication between equipment comprising an AEBRS can be implemented through the use of multiple pathways of either wired or wireless communication lines, where the main line and alternative lines should be designed to support equivalent communication requirements.

If a redundant communication method between equipment comprising an AEBRS is implemented, then it should be described in the ACCOMPANYING DOCUMENTATION.

If a redundant communication method is not implemented, then a justification for this decision should be described in the ACCOMPANYING DOCUMENTATION.

5.2.4.6 Protocol of data transfer

The MANUFACTURER should define the communication protocols used for each signal transmitted through each interface, including command signals for system control, status checks and INTERLOCK signals. These protocols should be described in the ACCOMPANYING DOCUMENTATION.

5.2.5 Interactions between MDE, MCF and EBE

The electric, magnetic and electromagnetic emissions and their interactions between MDE, MCF and EBE should be identified to ensure the safety of an AEBRS. The interactions are categorised as follows:

a) electric, magnetic, or electromagnetic interference from one part of MDE, MCF, or EBE to another;

b) ionizing radiation from the MDE interacting with the MCF or the EBE, or ionizing radiation from the EBE interacting with the MCF or the MDE;

c) mechanical interactions including acoustic noise from MDE to MCF or EBE, or EBE to MCF or MDE.

For a), IEC 60601-1, and IEC 60601-1-2 (EMC) can be applied to AEBRS for safety and related testing. For b), IEC 60601-2-68 and either IEC 60601-2-1 or IEC 60601-2-64 can be applied. For c), IEC 60601-1 can be applied.

Test methods to evaluate the influence of the static magnetic field, pulsed magnetic fields, and RF radiation on other equipment are available in IEC 60601-2-33, which provides guidance on EM compatibility testing. Further guidance for testing the performance of medical devices in the presence of MRI fields can be found in ISO TS 10974.

Equipment labelled as MR conditional or MR safe per IEC 62570 may need additional RISK ANALYSIS for use in AEBRS.

5.2.6 Status check of each piece of equipment

The specification of status check signals for each piece of equipment including the required frequency should be described in the ACCOMPANYING DOCUMENTATION.

The status of each piece of EQUIPMENT and communication line comprising the AEBRS should be checked immediately before each time the MCF allows the EBE to start IRRADIATION. The status of each piece of EQUIPMENT and communication line comprising the AEBRS should be checked periodically with a frequency determined by the MANUFACTURER.

NOTE The frequency for checking the status of INTERLOCKs can be different as determined for each piece of EQUIPMENT.

5.2.7 Failure state judgement

The criteria defining failure, the number of repeat attempts, and the requirements for failure notification should be described in the ACCOMPANYING DOCUMENTATION.

If a failure of any piece of EQUIPMENT comprising the AEBRS is detected, by receiving a failure signal from the EQUIPMENT, by not receiving a healthy signal when expected, or by detecting no response from the EQUIPMENT, a failure or warning message should be displayed to the OPERATOR and an alert signal should be sent to the EBE to TERMINATE or INTERRUPT the IRRADIATION as described in IEC 60601-1-8.

NOTE For example, the reason can be the disconnection of a communication line, the failure of a watchdog, the failure of MDE or MCF, or the malfunction of software of INTERLOCKs in the AEBRS.

5.2.8 LATENCY related to an AEBRS

5.2.8.1 General

There are at least two situations whereby LATENCY associated with the AEBRS can influence the safe operation of the AEBRS for PATIENTS showing intra-fractionally changing anatomy or physiology. These situations can occur both in gating systems and tracking systems (Figure 9 and Figure 10, respectively).

Situation A: During IRRADIATION:

1) The rigid TARGET VOLUME moves intra-fractionally.
2) MDE detects the motion of the rigid TARGET VOLUME.
3) MCF predicts the location of the TARGET VOLUME, verifies the displacement between the actual and predicted locations, and determines that the difference is larger than the threshold.
4) MCF sends a signal to the EBE to stop the IRRADIATION.
5) EBE receives the signal to stop the IRRADIATION.
6) IRRADIATION is stopped or paused.

Situation B: While IRRADIATION is paused:

1) The rigid TARGET VOLUME moves intra-fractionally.
2) MDE detects the motion of the rigid TARGET VOLUME.
3) MCF predicts the location of the TARGET VOLUME, verifies the displacement between the actual and predicted locations, and determines that the difference is smaller than the threshold.
4) MCF sends a signal to the EBE to re-start the IRRADIATION.
5) EBE receives the signal to re-start the IRRADIATION.
6) IRRADIATION is re-started.

The time spent during each event and the time between two events can change with the combination of MDE, EBE, and MCF, and the type of operating system and network. The dose distribution in a PATIENT showing intra-fractional changes will change accordingly.

NOTE 1 LATENCY is a possible source of error. Examples of the error are as follows: For gating, the beam on/off signal might be sent at the wrong phase of respiration. For tracking, the signal to instruct the beam direction might direct the beam to a position that is shifted from the TARGET VOLUME.

The MANUFACTURER should estimate changes in dose distribution resulting from intra-fractional changes of anatomy or physiology in the two situations, A and B. Results of the estimation should be documented in the ACCOMPANYING DOCUMENTATION.

The degree of change in the dose distribution in the PATIENT is also affected by the amplitude and period of the intra-fractional changes during both situation A and situation B.

Further, it may not be possible for the MANUFACTURER to determine the LATENCY related to the AEBRS for some combinations of MDES, EBES and MCFS. Contributions to the LATENCY of the AEBRS may vary from one installation to another due to differences in the networks supplied by the USER or RESPONSIBLE ORGANIZATION.

For safe integration and operation of the AEBRS for PATIENTS showing intra-fractionally changing anatomy or physiology, a method to estimate the effect of LATENCY related to the AEBRS as a whole should be used to solve these issues.

An example of tools used for such method, a dynamic phantom, is described in Annex D.

The method to estimate the effect of LATENCY should be documented in the ACCOMPANYING DOCUMENTATION.

NOTE 2 For example, the effect of the LATENCY includes interplay between a moving TARGET VOLUME and a moving beam (e.g., IMRT, VMAT, LIGHT ION SPOT SCANNING).

The MANUFACTURER should check whether LATENCY can change as described in AA.13 of A.3.

5.2.8.2 Determination of LATENCY effects

A dynamic phantom, which can simulate a PATIENT showing intra-fractionally changing anatomy or physiology, is recommended as a tool to evaluate the effects of LATENCY in the AEBRS. However, if there are other ways to evaluate the effect of LATENCY related to the AEBRS without using a dynamic phantom, these can be substituted. A simple dynamic phantom is described in Annex D.

In principle, the effect of LATENCY related to the AEBRS should be measured on site.

However, if there are other ways to estimate the effect of LATENCY related to the AEBRS, these can substitute for measurement on site. The acceptable range of the effect of LATENCY related to the AEBRS and its evaluation should be defined by the MANUFACTURER and described in the ACCOMPANYING DOCUMENTATION. The estimated effect of LATENCY related to the AEBRS should be within the acceptable range defined by the MANUFACTURER.

The MANUFACTURER should consider possible effects of LATENCY degradation during the treatment in RISK MANAGEMENT.

Often the effect of the time between step 2 and step 4 or between step 2 and step 5 in situations A and B described in 5.2.8.1 can only be measured without the effect of the time between step 1 and step 2 or the time between step 5 and step 6 even when a dynamic phantom is used. In that case, it should be clearly stated in the ACCOMPANYING DOCUMENTATION which parts of LATENCY related to the AEBRS from step 1 to step 6 have been

evaluated. A statement should be included regarding the residual uncertainty due to the residual components of LATENCY related to the AEBRS.

The type of measurement, whether by dynamic phantom or other methods, and its specifications should also be stated in the ACCOMPANYING DOCUMENTATION.

The effect of interplay between a moving target and a moving beam (e.g., IMRT, VMAT, LIGHT ION SPOT SCANNING) should be evaluated.

5.2.9 Typical verification items of the AEBRS

Appropriate integrated verification tests of the AEBRS should be performed. For these tests, a dynamic phantom, which can simulate PATIENTs showing intra-fractionally changing anatomy or physiology, should be used. See Annex D for an example of a simple dynamic phantom. Typical verification items are listed below:

a) Comparison between planned dose distributions and delivered dose distributions for PATIENTs showing intra-fractionally changing anatomy or physiology, when gating or tracking is used.

b) Accuracy of the PREDICTION MODEL in estimating the motion of PATIENTs showing intra-fractionally changing anatomy or physiology.

c) Performance of the MCF.

d) End-to-end tests including motion detection, TREATMENT PARAMETER ADAPTATION, TREATMENT PLANNING and TREATMENT delivery.

5.2.10 Validation of AEBRS

The contents of the tests should be determined by an independent clinical USER.

5.3 Specific guidelines for the MOTION COORDINATION FUNCTION

5.3.1 PREDICTION MODEL

A PREDICTION MODEL should be implemented in the MCF by the MANUFACTURER, if

– the motion of the TARGET VOLUME is related to the motion of a surrogate, or

– the LATENCY in the communication between equipment comprising the AEBRS combined with the internal delay of the equipment requires compensation to produce the correct IRRADIATION of the PATIENT.

The PREDICTION MODEL should be described in the ACCOMPANYING DOCUMENTATION as far as that is not proprietary. The deviation between the PREDICTION MODEL and acquired position data should be displayed to compare with pre-established limits defined by the MANUFACTURER.

The total delay of the communication between equipment and the internal delay of equipment comprising the AEBRS should be taken into account when determining the PREDICTION MODEL.

NOTE Surrogates can be used for the detection of the motion by MDE.

5.3.2 Gating and tracking

5.3.2.1 Gating

When a BEAM GATING SIGNAL is provided by the ADAPTATION INSTRUCTION generator of an MCF, IRRADIATION by the EBE should be controlled by the BEAM GATING SIGNALS. These SIGNALS can constitute a BEAM resume signal or a BEAM HOLD signal. The BEAM GATING SIGNAL should conform to the requirements of the EBE. The BEAM GATING SIGNAL should be transmitted at the timing determined by the MCF.

The IRRADIATION by the EBE should be TERMINATED

– if the time elapsed following receipt of a BEAM HOLD signal exceeds the criteria of allowable elapsed time defined by the MANUFACTURER;

– if the position of the rigid TARGET VOLUME as estimated from the data provided by the MDE fails to agree within the acceptable range with its predicted position at the IRRADIATION timing instructed by the ADAPTATION INSTRUCTION generator.

NOTE 1 The MDE monitors the intra-fractional movement of the rigid TARGET VOLUME or an appropriate surrogate. For information regarding the estimated position of the rigid TARGET VOLUME based on the data from an MDE, see the description in 5.2.1.

Information describing the BEAM GATING SIGNALS for BEAM resume and BEAM HOLD should be described in the ACCOMPANYING DOCUMENTATION.

NOTE 2 A BEAM stop signal or a BEAM restart signal constitutes the BEAM GATING SIGNAL for LIGHT ION BEAM therapy.

5.3.2.2 Tracking

The following information should be provided to the OPERATOR or software for verification:

– The acceptable range, before and during IRRADIATION, of the discrepancy between the predicted rigid TARGET VOLUME position based on the ADAPTATION INSTRUCTION in the MCF and the position estimated from data acquired by the MDE, or

– The acceptable range, before and during IRRADIATION, of the discrepancy between the predicted rigid TARGET VOLUME position based on the DATA provided prior to the TREATMENT and the position estimated from data acquired by the MDE.

The IRRADIATION should be terminated either manually by the OPERATOR or automatically by pre-programmed software, when the position of the TARGET VOLUME as estimated from data acquired by the MDE is out of the acceptable range.

Annex A
(informative)

A minimum set of HAZARDs to consider for adaptive TREATMENT functions

A.1 Overview

HARM related to the use of AEBRS consists of HAZARDs associated with the individual equipment, and those related to integration into the system. The HAZARD categories to consider by the MANUFACTURER of an AEBRS are identified in ISO 14971, IEC 60601-1:2005 and IEC 60601-1:2005/AMD1:2012. The AEBRS adds functionality to include and integrate intra-fraction monitoring of the TARGET VOLUME position and shape. This annex focuses on HAZARDs associated with the following HARM categories of general radiation therapy:

a) proliferation of the tumour,

b) loss of function of normal tissue,

c) oncogenic events.

These HARM categories are associated with the following HAZARDS:

1) therapeutic IRRADIATION is delivered outside clinical intent (including margins),

2) TREATMENT plan does not match anatomy at time of TREATMENT,

3) therapeutic IRRADIATION cannot be delivered.

This annex identifies associated HAZARDOUS SITUATIONS based on a reference design for the adaptive TREATMENT functionality of the AEBRS. For these HAZARDOUS SITUATIONS, guiding questions are provided to be considered by the MANUFACTURER when identifying failure modes in actual design instances.

In this annex references to “absorbed dose” can be interpreted as prescribed monitor units that represent the planned clinical intent, and not the actual absorbed dose inside the PATIENT. This relationship is normally calculated in advance and approved by a physician in advance of the adaptive TREATMENTs (e.g. during TREATMENT PLANNING).

HAZARDs and HAZARDOUS SITUATIONS related to mechanical and electrical effects are not considered in this annex. Refer to Table E.1 in ISO 14971:2007 for further guidance. Also excluded are the individual EQUIPMENT’S HAZARDs and the potential increase of its RISK level in view of a changed intended use. The MANUFACTURER of the AEBRS is responsible to consider these aspects in view of the specific design of the AEBRS under development.

A.2 Reference design for adaptive TREATMENT functionality

Clause 4 provides examples of AEBRS configurations, consisting of three types of EQUIPMENT, MDE, MCF and EBE, and deployment of adaptive TREATMENT control sub-functions for gating and tracking. This annex further details the reference design from a functional decomposition perspective, see Figure A.1. The MANUFACTURER of the AEBRS should provide a rationale for the final design and deployment of functions to MDE, EBE and/or additional hardware for MCF.

Not shown are the necessary preconditions for adaptive therapy, such as the availability and validity of 4D prior data and state-dependent TREATMENT plans.

RISK assessment for AEBRS should consider at least the HAZARDOUS SITUATIONS related to the adaptive TREATMENT control functionality and reference design, as listed below. Further guiding questions for each HAZARDOUS SITUATION are provided in subsequent subclauses for each HAZARDOUS SITUATION.

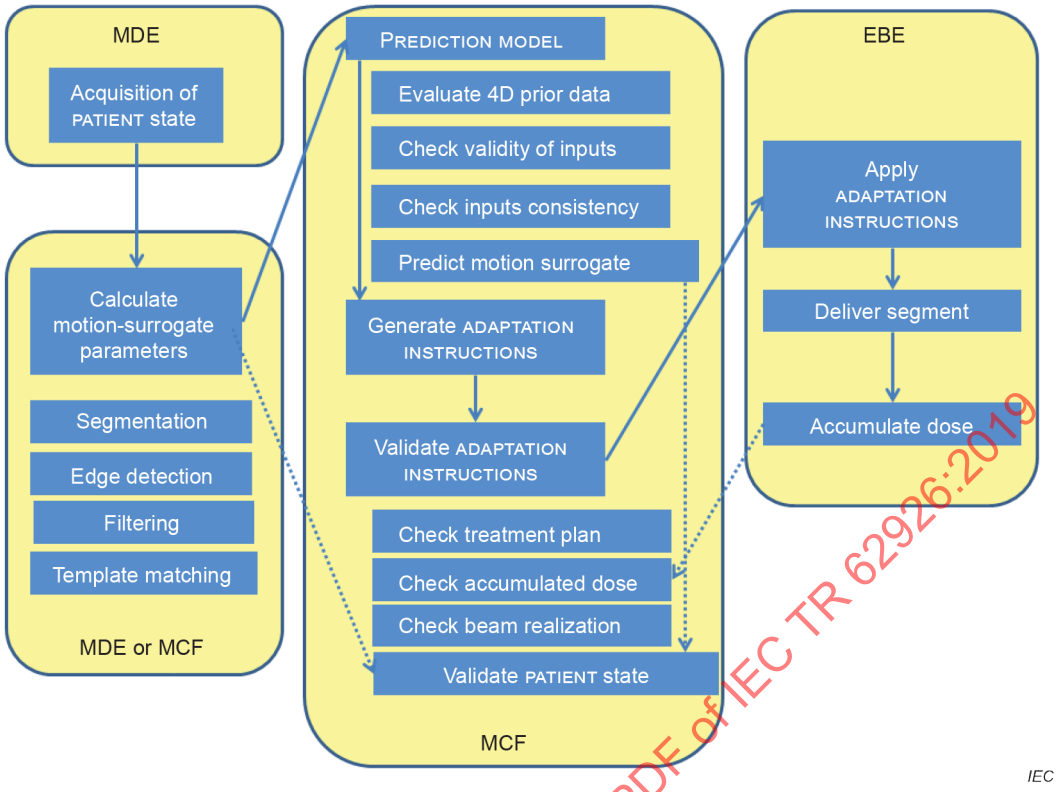

Figure A.1 – Functional decomposition of adaptive TREATMENT control for gating and tracking functionality in the AEBRS

In Figure A.1, deployment is tentatively indicated for the three identified equipment categories MDE, MCF and EBE. Actual assignment of functions to hardware or equipment depends on quality of service and processing capabilities available at selected MDE(s). In an actual design, a subset of sub-functions may be present.

A.3 Overview of HAZARDOUS SITUATIONS

The HAZARDOUS SITUATIONS of the following AA.1 to AA.16 should be considered, and the following sub-sections provide additional guidance when assessing possible causes of HARM and its RISK, and identifying mitigations for HAZARDOUS SITUATIONS significantly contributing to RISK as identified by the MANUFACTURER. The normative text of this document provides further guidance for implementation of several mitigations, when required.

AA.1 The TREATMENT plan does not match the selected PATIENT

Consider at least the following situations:

(a) PATIENT data on TREATMENT plan incompletely or erroneously entered into MCF

(b) PATIENT data associated with the (4D) TREATMENT plan in the MCF does not match (or is not checked against) PATIENT data registered at the EBE for PATIENT currently undergoing TREATMENT

(c) Absorbed dose accumulated in previous episodes (fractions) not administered correctly with PATIENT data

(d) MCF selects TREATMENT plan for earlier or later episode (fraction)

AA.2 The PREDICTION MODEL does not match the selected PATIENT

Consider at least the following situations:

(a) PATIENT data on prior 4D motion data and TREATMENT plan are inconsistent

(b) PATIENT data from MDE (if available) does not match PATIENT data on MCF

(c) Motion detection data or motion surrogates cannot be identified uniquely

AA.3 The coordinate systems do not match between functions

Consider at least the following situations:

(a) Current and prior 4D motion data and motion surrogates do not match due to difference in system setup

(b) Data between MDE acquisition and motion-surrogate parameter calculation and/or PREDICTION MODEL lacks unique descriptive orientation data

(c) Not all software components use the agreed RT coordinate systems

(d) Inconsistent coordinate transformations between MDE and EBE, and MCF sub-functions, for any of the relevant PATIENT orientations (head-first/feet-first, prone/supine/decubitus)

AA.4 The segment absorbed dose is not being accumulated correctly

Consider at least the following situations:

(a) Failing connection from absorbed dose accumulation device to MCF

(b) Requested delivery by MCF is not being realized by EBE

(c) Inaccurate or inadequate bookkeeping of delivered absorbed dose (spatial distribution) versus gate/track instructions

AA.5 The cumulated segment absorbed dose indicates that fraction absorbed dose will be exceeded

Consider the following situation:

(a) Overshoot in a (daily) fraction should allow for fraction termination and re-planning

AA.6 The fraction absorbed dose cannot be realized with remaining segments for current PATIENT state and EBE configuration (position/MLC capabilities)

Consider at least the following situations:

(a) ADAPTATION INSTRUCTIONs generation and/or validation fails to simulate and evaluate the complete set of segment plans required to deliver the absorbed dose for the current fraction (episode)

(b) Logged information from already delivered adaptive fraction is insufficient to allow a calculation of the remaining fraction absorbed dose to complete TREATMENT.

AA.7 The PATIENT state monitoring data stream is broken, the fraction cannot be completed or is completed based on the wrong data

Consider how the MCF is resilient against at least the following situations:
(a) MCF acts on available motion surrogate parameters without evaluating its time stamp

(b) Motion-surrogate parameter module provides time-stamped data based on outdated or invalid data

(c) Lack of MDE data due to hardware or software failure. Typical reconfiguration times can be minutes (software reboot) up to days (broken hardware)

AA.8 The MDE field of view is obstructed or compromised by other equipment

Consider at least the following situation:

(a) Evaluate all field-of-view obstructing or compromising situations, such as masks, MDE data reception equipment (e.g. MRI RF coils) for all prescribed beam directions (especially for tracking).

AA.9 The motion-surrogate parameter calculation fails

Consider how the MCF is resilient against at least the following situations:

(a) MDE data quality is compromised, for example due to EMC, ESD (Electro-Static Discharge) or unexpected contrasts or artifacts in images, background illumination differences (for cameras), leaking belt, data buffer overflow or missing frames

(b) Algorithm is not deterministic with respect to LATENCY

(c) MDE data stream varies in frame rate or spatial resolution

(d) MDE signal polarity opposite from required polarity (e.g. due to connectivity issue with 'free-style connectors')

AA.10 There is a poor match between the 4D motion model metadata and the motion-surrogate parameter(s)

Consider at least the following situations:

(a) 4D motion model data in calibration experiment based on relative (differentiating) sensor, compared with data from absolute sensor during TREATMENT, or vice versa

(b) Wrong motion state selected (e.g. inhale versus exhale edge detection)

(c) Difference in primary motion direction sensitivity for model and motion-surrogate during TREATMENT (e.g. anterior-posterior displacement versus feet-head displacement)

(d) Time stamp on motion surrogate parameter may not reflect time of acquisition, especially if MDE does not have a clock (e.g. belt with analog filters)

AA.11 Incorrect prediction: The 4D motion model and the TREATMENT plan (segment) do not match (geometrical)

Consider at least the following situations:

(a) Mismatch between planning and motion detection data, e.g. due to 'private' (non-DICOM) geometrical image attributes

(b) Different 'field of view' for prior and actual motion data, which compromises the PREDICTION MODEL

(c) Image distortion across field of view not identical between prior and actual data

(d) Actual motion pattern, or TARGET VOLUME position, not part of PREDICTION MODEL or TREATMENT plan(s)

(e) Incorrect selection of (subset of) implanted internal markers

(f) Incorrect 3D model calculation from implanted marker or detected anatomical edges

AA.12 The motion pattern or TARGET VOLUME deviates from (segment) plan

Consider at least the following situations:

(a) Difference in breathing characteristic between calibration setting and TREATMENT, or variable during fraction (chestwall versus diaphragm; shallow versus deep; regular versus irregular)

(b) Tumour regression or edema, or internal organ shift, as detected by MDE reveals differences between current PATIENT state and TREATMENT plan

(c) Prevent IRRADIATION in case of (undetected) sudden motion (coughing, mediastinal hiccups), much faster than overall system LATENCY for MCF / EBE

AA.13 The phase delay / LATENCY is too long between motion detection and availability of validated TREATMENT instructions

Consider at least the following situations:

(a) Calculated motion surrogate parameters time-stamped with post-calculation timing, not with MDE acquisition timing

(b) Lack of a shared clock between MDE, MCF, and EBE.

NOTE MDE does not have a real world clock, or clock syncing functionality.

(c) Timing for MDE and 4D model, and ADAPTATION INSTRUCTION generation is non-deterministic

(d) Motion surrogate parameter calculation, as used to validate PATIENT state immediately prior to segment delivery, introduces a phase delay where it is not noticed that anatomical location is (structurally) offset relative to plan

AA.14 The connection between MCF and EBE is not functioning

Consider at least the following situations:

(a) Gating function polarity inverted between MCF and EBE (logical or wiring error)

(b) Tracking instructions leading to wrong TREATMENT beam geometry.

(c) Communication to EBE does not fail in a safe way. (e.g. rather than just stopping TREATMENT, some data is corrupted which results in a clinical significant error)

AA.15 The EBE did not start/stop IRRADIATION in response to an MCF request

Consider at least the following situations:

(a) MCF relies for ADAPTATION INSTRUCTIONS and for 'plan completion criteria' on requested beam delivery, not on realized (measured) beam delivery (i.e. there maybe confusion between adapting from original plan or from the current state of the delivery following previous adaptations)

(b) MCF does not output a stop gating signal in relation to the expected duration of the modeled and detected PATIENT state

AA.16 There are differences in units of measure

Consider at least the following situations:

(a) Difference in units of measure for geometry, especially metric versus US system

(b) Difference in the origin of coordinate system

(c) Difference in the order of application adaptive movements (especially for 6D transformation which are not commutative)

(d) Loss of traceability between the prescribed MU and the intended absorbed dose in the original plan

Annex B
(informative)

An example of RISK ANALYSIS for an AEBRS with gating function using X-RAY FLUOROSCOPE as an MDE

B.1 Configuration of the example AEBRS

In the example described in this annex, the AEBRS comprises an MDE, a gating function provided by an MCF, and a proton beam therapy system as the EBE. The MDE consists of two sets of diagnostic x-ray fluoroscopes mounted on the gantry of the proton beam therapy system. The MCF of the AEBRS provides a gating function and the software for the function is installed on a workstation. The MDE, MCF, and EBE should be interconnected correctly for automated gating to occur. The AEBRS operates independently of the TREATMENT PLANNING SYSTEM and record and verify system during IRRADIATION.

The MCF uses data describing the motion of an internal fiducial marker as the surrogate of motion of a rigid TARGET VOLUME. The MCF uses the data to provide SIGNALS to INTERRUPT the proton beam delivery or continue the radiation delivery (BEAM HOLD or beam restart) to the workstation. The workstation communicates with EBE and sends the instructions to the EBE. The workstation displays the mode of the system to the OPERATOR at all times.

To enable or disable automated gating, the OPERATOR presses the 'gating enable button' on the workstation. The OPERATOR monitors the display of the workstation and can judge whether to interrupt, continue, or terminate any time during the therapeutic IRRADIATION.

B.2 PROCESS overview

Several fiducial markers are implanted around the rigid TARGET VOLUME beforehand. Based on TREATMENT PLANNING using computed tomography images after the implantation of the markers, the relationship between the location of the markers and the rigid TARGET VOLUME at each respiratory phase is loaded into the workstation as "marker information" in the configuration parameters before each TREATMENT. TREATMENT PARAMETERS such as PATIENT information, field information, gantry angle, and couch angle for the TREATMENT also are loaded before the therapeutic IRRADIATION.

The MDE sends two sets of diagnostic x-ray fluoroscopic image 30 times a second to the workstation.

In the PREDICTION MODEL of the MCF, using a template image and real-time pattern matching algorithm, the projection of one or more of the fiducial markers in the 2D images are automatically detected. Three-dimensional location of the internal surrogate marker at the expiration phase is calculated within 0,1 s.

In the instruction generation function of the MCF, when the coordinate of the marker is more than 2 mm from its planned location along the x, y, or z axes, an instruction to INTERRUPT the therapeutic IRRADIATION is generated. When the coordinate of the marker is within 2 mm of its planned location along the x, y, and z axes, instruction not to INTERRUPT the therapeutic IRRADIATION is generated.

In the instruction evaluation/selection function of MCF, if the recognition score of the pattern matching or the certainty score of 3D calculation of the marker is evaluated to be lower than the threshold, the instruction to INTERRUPT the therapeutic IRRADIATION is generated.

B.3 HAZARDOUS SITUATIONS and RISK fishbone diagram

HAZARDOUS SITUATIONS relating to the AEBRS are listed in Annex A. The RISK ANALYSIS for an AEBRS can also be guided by the RISK fishbone diagram to visualize the relationship between the incident, the failure mode, the HAZARD, and the HARM. In this Annex B, a RISK fishbone diagram for one specific HARM of the AEBRS was made as an example. The fishbone diagram for the HAZARD of proton IRRADIATION to an unintended position using an AEBRS for intra-fractionally moving rigid TARGET VOLUME is shown in Figure B.1. HAZARDOUS SITUATIONS and HAZARDs were visualized with respect to the AEBRS reference model in 4.2.3 and also HAZARDOUS SITUATIONS listed in Annex A. See C.2 for each corresponding category and failure mode

Fishbone diagrams for other HAZARDs such as inability to deliver proton IRRADIATION, which may cause proliferation of the tumour as a HARM, prolongation of time of fluoroscope, which may cause oncogenic events as a HARM, or mechanical HAZARDs can be made separately.

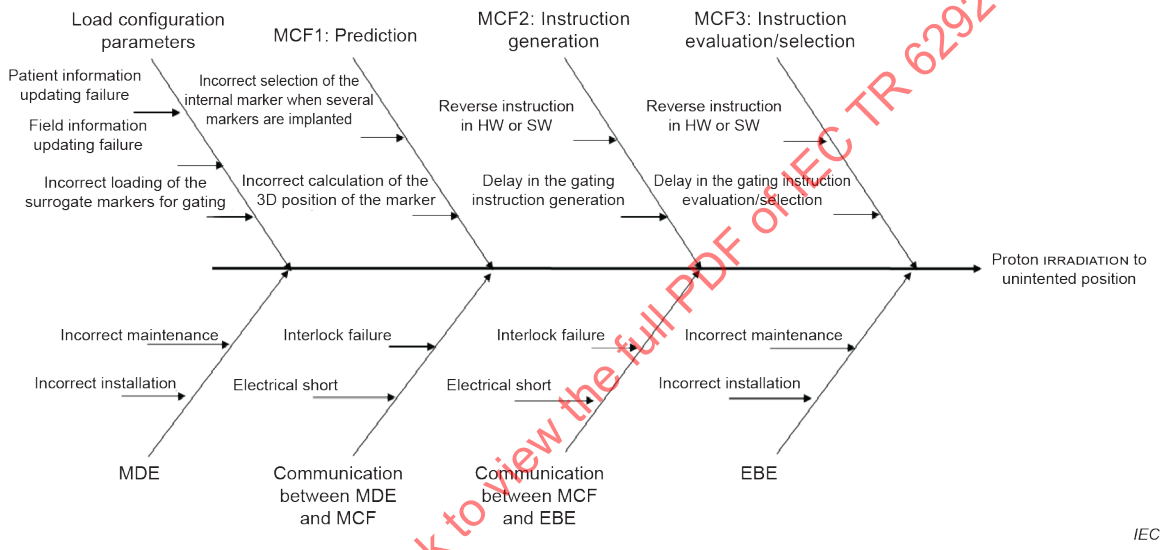

Figure B.1 – Risk fishbone diagram for an AEBRS

Severity and probability of the HAZARDs and HARM should be evaluated in RISK ANALYSIS following identification of the failure modes described above.

B.4 Failure Mode and Effect Analysis (FMEA)

The following is an example of Failure Mode and Effect Analysis (FMEA) for an AEBRS with a gating function as an MCF and two sets of X-RAY FLUOROSCOPES as MDE. Only some parts of FMEA which are specific to the AEBRS are shown as examples. RISK EVALUATION and RISK CONTROL are out of scope of this Annex B.

Table B.1 – Failure Mode and Effect Analysis (FMEA) for an AEBRS using fluoroscope as a MDE, gating function as an MCF, and proton beam therapy machine as an EBE

Equipment and software	Function	Failure mode	Failure influence		Before mitigation			Design requirement	RISK CONTROL method		Measure details (Method for RISK reduction)		After mitigation			Remarks
			Phenomenon	HAZARD (Influence)	Severity of harm	Frequency of harm	Risk level		Design	Labelling	No.	Requirement	Severity of harm	Frequency of harm	Risk level	
Communication between MDE and MCF	Data transfer	Cable disconnection	Unable to communicate	No image												
		Data sending failure	Unable to send data from MDE to MCF	Unnecessary X-ray exposure												
		INTERLOCK failure	Unable to notify the failures of MDE by alarm	Unnecessary X-ray exposure												
Load configuration parameters	Load configuration parameters specific for the PATIENT	Failure in updating TREATMENT PARAMETERS	PATIENT information updated failure	Proton IRRADIATION to unintended location												
			Field information updating failure													
			Planned gantry angle updating failure	Unnecessary X-ray exposure												
			Planned couch angle updating failure													
		Failure in loading marker information	No loading of the markers for gating	Unnecessary X-ray exposure												
			Incorrect surrogate markers for gating	Proton IRRADIATION to unintended location												

Equipment and software	Function	Failure mode	Failure influence		Before mitigation			Design requirement	RISK CONTROL method		Measure details (Method for RISK reduction)		After mitigation			Remarks
			Phenomenon	HAZARD (Influence)	Severity of harm	Frequency of harm	Risk level		Design	Labelling	No.	Requirement	Severity of harm	Frequency of harm	Risk level	
MCF1: Prediction	Oder to MDE: start X-ray fluoroscope	Unable to output X-ray ON signal to relay (X-ray control panel)	Unable to start fluoroscopy	No images												
	Oder to MDE: stop X-ray fluoroscope	Unable to output X-ray OFF signal to relay (X-ray control Panel)	Unable to stop fluoroscopy	Unnecessary X-ray exposure												
	Image processing using the data from MDE (X-ray fluoroscope)	Data processing failure	Degradation on image	Unnecessary X-ray exposure												
		Delay in data processing	Unable to make image within limited time	Unnecessary X-ray exposure												
	Cumulative timer	Timer checking failure	Unable to stop X-ray system automatically	Unnecessary X-ray exposure												
	Pattern matching	Failure in recognition of the internal fiducial markers	Unable to find the internal marker	Unnecessary X-ray exposure												
		Failure in differentiation of the internal fiducial markers	Incorrect selection of the internal marker when several markers are implanted	Proton IRRADIATION to unintended location												
	Calculate 3D location of the internal surrogate marker	Failure in using two 2D images to calculate 3D location of the marker	Incorrect calculation of the 3D location of the marker	Unnecessary X-ray exposure												
	Indicate the expiration location	Expiration location indication failure	Unable to detect the baseline shift	Proton IRRADIATION to unintended location												

Equipment and software	Function	Failure mode	Failure influence		Before mitigation			Design requirement	RISK CONTROL method		Measure details (Method for RISK reduction)		After mitigation			Remarks
			Phenomenon	HAZARD (Influence)	Severity of harm	Frequency of harm	Risk level		Design	Labelling	No.	Requirement	Severity of harm	Frequency of harm	Risk level	
MCF2: Instruction generation	Reverse	Reverse instruction in HW or SW	IRRADIATION when not to IRRADIATE and not IRRADIATE when to IRRADIATE	Proton IRRADIATION to unintended location												
	Delay	Delay in the gating instruction generation	IRRADIATION when not to IRRADIATE and not IRRADIATE when to IRRADIATE	Proton IRRADIATION to unintended location												
MCF3: Instruction evaluation /selection	Reverse	Reverse HW or SW failure in the MCF	IRRADIATION when not to IRRADIATE and not IRRADIATE when to IRRADIATE	Proton IRRADIATION to unintended location												
	Delay	Delay in the gating instruction evaluation /selection	IRRADIATION when not to IRRADIATE and not IRRADIATE when to IRRADIATE	Proton IRRADIATION to unintended location												
Communication between MCF and EBE	Data transfer	Cable disconnection	Unable to send gating signal	Unable to provide therapy (possibly unnecessary X-ray exposure)												
		Electrical short	Unable to send gating off signal	Proton IRRADIATION to unintended location												
		INTERLOCK failure	Unable to terminate or interrupt the IRRADIATION	Proton IRRADIATION to unintended location												

B.5 RISK ANALYSIS

Figure B.2 shows the RISK ANALYSIS and how the HAZARDOUS situation might be analyzed in order to attribute a probability of HARM as defined in ISO 14971.

It is used for identifying the severity and frequency of the harm and characterizing the grade of RISK and acceptance of RISK level before and after the mitigation for the HAZARDS.

It is used for the examples in Table B.1 and Table C.1.

Severity of Harm		
Category	Severity	Definition
Ⅰ	Catastrophic	Death
Ⅱ	Critical	Heavy Injury
Ⅲ	Serious	Light Injury
Ⅳ	Minor	Lighter Injury
-	Negligible	

Grade of Risk					
Severity / Frequency	Ⅰ	Ⅱ	Ⅲ	Ⅳ	-
A	1	3	7	13	-
B	2	5	9	16	-
C	4	6	11	18	-
D	8	10	14	19	-
E	12	15	17	20	-
-		-	-	-	-

Frequency of Harm		
Level	Frequency	Reference
A	Frequent	$\geqq 10^{0}$/Yr
B	Probable	$\geqq 10^{-1}$/Yr
C	Occasional	$\geqq 10^{-3}$/Yr
D	Remote	$\geqq 10^{-5}$/Yr
E	Improbable	$< 10^{-5}$/Yr
-	Not Applicable	

Acceptance of Risk Level			
Level	Risk	Acceptance	Risk Mitigation
H	1-9	Unacceptable	Necessary
M	10-17	Conditional	ALARP
L	18-20	Acceptable	Not necessary

IEC

Figure B.2 – Tables for RISK ANALYSIS

Annex C
(informative)

An example of RISK ANALYSIS for an AEBRS with tracking function using two different MDEs

C.1 Configuration of the example AEBRS

An example AEBRS comprises an infrared surface imaging equipment identified as MDE 1, a diagnostic x-ray fluoroscope identified as MDE 2, a tracking function as an MCF, and a MEDICAL ELECTRON ACCELERATOR as an EBE. The MCF of the AEBRS provides a tracking function and the software for the function is installed on a workstation. The MDEs, MCF, and EBE should be organized properly for automated tracking to occur. The AEBRS operates independently of the TREATMENT PLANNING SYSTEM and the record and verify system during IRRADIATION.

The MDE 1 acquires data for monitoring the motion of the abdominal surface using infrared equipment as a surrogate to estimate the motion of the rigid TARGET VOLUME. The MDE 2 uses diagnostic x-ray fluoroscopy to monitor the motion of an internal fiducial marker as a surrogate to estimate the motion of the rigid TARGET VOLUME. The two MDEs send information to the MCF, the tracking function, in the work station. The workstation communicates with the EBE and sends the instructions to INTERRUPT or continue to deliver therapeutic RADIATION (BEAM HOLD or BEAM resume) to the EBE. The workstation displays the mode of the system to the OPERATOR at all times.

To enable or disable automated tracking, the OPERATOR presses the 'tracking enable button' on the workstation. The OPERATOR monitors the display on the workstation and can judge whether to interrupt, continue, or terminate any time during the therapeutic IRRADIATION.

C.2 Failure Mode and Effect Analysis (FMEA)

HAZARDOUS SITUATIONs should be listed as shown in Annex A and the relationship between the incident, the failure mode, the HAZARD, and the HARM should be visualized as shown in Annex B. These are out of scope in this Annex C.

Table C.1 shows a Failure Mode and Effect Analysis (FMEA) for the AEBRS described above in C.1. Only some parts of FMEA which are specific to the AEBRS are shown as examples. RISK EVALUATION and RISK CONTROL are out of scope of this Annex C.

Table C.1 – Failure Mode and Effect Analysis (FMEA) for an AEBRS with tracking function as an MCF, and Infrared (IR) camera as MDE 1, x-ray fluoroscope as MDE 2, and MEDICAL ELECTRON ACCELERATOR as EBE

Equipment and software	Function	Failure mode	Failure influence		Before mitigation			Design requirement	RISK CONTROL method		Measure details (Method for RISK reduction)		After mitigation			Remarks
			Phenomenon	HAZARD (Influence)	Severity of harm	Frequency of harm	RISK level		Design	Labelling	No.	Requirement	Severity of harm	Frequency of harm	RISK level	
Infrared(IR) camera as a MDE1	Monitoring	Failure in automatic monitoring of Surface motion	IR body markers move out of IR camera view	Under dose –TARGET VOLUME and overdose to OAR and normal tissues												
			IR camera's view is changed after model-production													
X-ray fluoroscopy as a MDE2	Monitoring	Failure in automatic monitoring of internal motion of the TARGET VOLUME	Internal motion of the TARGET VOLUME or its surrogate cannot be detected sufficiently	Under dose –TARGET VOLUME and overdose to OAR and normal tissues												
MDE1 connection to MCF	Data transfer	Failure in the communication between MDE1 and MCF	Predicted location of the TARGET VOLUME is different from its real location	Under dose –TARGET VOLUME and overdose to OAR and normal tissues												
MDE2 connection to MCF	Data transfer	Failure in the communication between MDE2 and MCF	Dislocation from the predicted location of TARGET VOLUME cannot be informed to MCF correctly	Under dose –TARGET VOLUME and overdose to OAR and normal tissues												
Synchronization of data	Data comparison	Failure in synchronization of data between MDE1 and MDE2	Dislocation from the predicted location of TARGET VOLUME cannot be informed to MCF correctly	Under dose –TARGET VOLUME and overdose to OAR and normal tissues												