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Some Critical Remarks on the Radiological Protection System: An epistemological analysis of radiation quantities and units*

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Abstract: After decades of research and improvements, ICRU recognizes that the system of quantities and units, designed to measure ionizing radiation, "fallen short of perfection due to compromises among the unavoidable ambiguities inherent in the real natural world and the need nonetheless for a basic set of useful quantities". The difficulties stem from the complexity of the phenomena that occur in the interaction of ionizing radiation with matter. Due to these problems, difficulties for definition and dissemination of quantities and units used in radiation protection are evident and some criticism has been presented. In the radiological protection system currently recommended for situations of the radiation exposure, it must be calculated, taking into account the available data, the equivalent dose and effective dose values - immeasurable quantities used only for the purpose of limitation. On the other hand, measurements must be performed by dosimeters calibrated in operational quantities (dose equivalents). This duality of quantities encompasses a number of scientific and philosophical problems, which we discuss in our paper. We argue that excessive quantities and units proposed over time causes confusion in their applications. The commitment between scientific rigor and the need for convenience of concepts and procedures to be implemented makes the metrology of ionizing radiation (in particular, radiological protection) a suitable domain for questioning some very deep epistemological beliefs.

Keywords: Radiological Protection, Measurement, Quantity, Concept, Philosophy of Science.

Resumo: O objetivo deste artigo consiste em apontar problemas conceituais existentes proteção radiológica. Para a realização desta meta, lançamos mão da análise minuciosa de vários documentos oficiais publicados pelos órgãos internacionais e nacionais envolvidos nesta área. Também investigamos os (poucos) debates promovidos pelos especialistas em proteção radiológica. Como se trata de uma análise conceitual, incidindo sobre algumas das definições mais relevantes na área de proteção radiológica, descrevemos as deficiências que as envolvem. Finalmente, defendemos a importância da análise conceitual para a formulação de eventuais soluções para a superação de tais problemas.

Palavras Chave: Proteção Radiológica, Medida, Grandeza, Conceito, Filosofia da Ciência.

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Introduction

Ionizing radiation is inherent to a wide range of technologies, from electricity generation to the diagnosis and treatment of cancer, making it an integral part of the daily lives of most citizens. In view of its inherent risks, if ionizing radiation is to be used safely, radiation exposure must be quantified and the damage it could cause to human health and the environment must be assessed. This requires the *standardization* of procedures and measurements. According to the International Atomic Energy Agency (IAEA), "[t]he radiation risks to people and the environment that may arise from the use of radiation and radioactive material must be assessed and must be controlled by means of the application of standards of safety" (IAEA, 2014, p. 1).

Generally speaking, measurements constitute fundamental quantification operations in the empirical sciences, and have been studied from a variety of historical and epistemological perspectives (e.g., Tal, 2017; Mari, 2003). One of the key concepts for metrology (the science of measurement and its application) is that of *quantity* – the "property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference," which means that magnitudes can be quantified. In general the reference is a *measurement unit*: a quantity adopted "by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number" (JCGM, 2012, p. 2, 6). The choice of quantity to be measured[1] and unit of measurement, plus their respective definitions, are basic steps in any measurement process.

While for some of the natural sciences, the quantities of interest are consensual and defined very simply (areas in which research and metrological developments focus on measurement methodologies), in others the definition of quantities has prompted much effort and discussion on the part of the scientific community – with ionizing radiation being a case in point. The complexity inherent to the interaction between radiation and matter also makes the task of defining quantities a complex one. When it comes to defining quantities in the field of radiological protection, which considers safety in the use of radiation, the difficulties are even greater.[2]

The field known as *radiation protection* or *radiological protection* (RP) concerns the "protection of people from harmful effects of exposure to ionizing radiation, and the means for achieving this," as well as "the means for preventing accidents and for mitigating the consequences of accidents if they do occur" (IAEA, 2014, p. 408). RP aims to introduce procedures and monitor dose levels to ensure the safe use of radiation in all activities that involve the use of radiation. *Quantifying* the potential damage of radiation and setting permissible dose levels are the major challenges for RP.

The current system of RP is based on three principles: *justification* (all decisions that imply exposure to radiation must be justified), *optimization* (the dose received by people involved in any kind of operation that involves radiation must be As Low As Reasonably Achievable [ALARA]), and the *limitation* of dose (ICRP, 2007, p. 14, 43, 88-101; IAEA, 2014, p. 4). These principles, especially the last two, depend on the quantification of the dose received and knowledge about the relationship between the dose received and the potential harm to the health of the people exposed to radiation. In other words, the principles of RP rely on radiation *quantification* methods and procedures, which are in turn closely related to the system of quantities and units adopted.

The doses of radiation received by medical patients in radiotherapy treatments and in diagnostic radiology are justified by the goals of the procedure to which they are exposed. While the doses should be as low as possible, it is also understood that they must be weighed against the potential benefits of the procedure to the patient. Meanwhile, occupational doses of radiation, such as the radiation to which workers are exposed at facilities where radiation is used, and by people who circulate around such facilities (the public), are the main concern of RP, and should not be higher than the limits set for them.

According to the International Bureau of Weights and Measures (BIPM), the impact of "ionizing radiations on medical (diagnostics and therapy), environmental (natural and in emergencies) and nuclear industry activities, shows the need for a world-wide harmonized system of quantities and units to assure the accuracy and comparability of their measurement" (BIPM, 2017). To illustrate this impact, the BIPM site features some statistics on exposure to ionizing radiation every year: 35 million medical examinations using radionuclides; four billion x-ray examinations; eight million radiotherapy treatments; and 11 million workers professionally exposed to ionizing radiation. It also shows just how many facilities use radiation around the world: around 11,000 clinical accelerators and 2,300 ^{60}Co sources for external beam therapy; 2,500 High Dose Rate (HDR)/Low Dose Rate (LDR) brachytherapy facilities; over 200 industrial gamma irradiators; and 1,300 industrial electron accelerators (BIPM, 2017). These figures go some way to demonstrating the importance of calculations and measurements of potential or actual exposure by workers at radioactive facilities, patients, and the general public in the use of ionizing radiation.

Since the early 1900s, the quantities and units adopted in RP have gone through successive alterations and refinements (Clarke and Valentin, 2009). Today, these quantities constitute a complex system that is not easily applicable in practical terms and which, despite having been fairly well assimilated by the RP community, still sparks controversies

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[1] In metrology, a "measurand" is defined as the quantity to be measured (JCGM, 2012, p. 17). The terms employed in metrology can be found in the International Vocabulary of Metrology (VIM) – Basic and general concepts and associated terms (JCGM, 2012).

[2] In the scope of this work, the term "radiation" is used to refer to ionizing radiation.

amongst scientists from the area.

In this paper, we describe and analyze some controversial questions concerning the set of *quantities* and *units* employed in RP, especially the system's structure, the characteristics of quantities defined for this domain, and the standardization procedure. These quantities are employed for calculating dose limits and for measuring doses received or to be received by the public and workers. The focus here will be on the quantities and units used for expressing dose values, but not on the dose limits values which are recommended. The peculiarities of this set of quantities, including its nomenclature and unorthodox nature, which produces a lot of conceptual confusion (besides the international scientific community's difficulty in reaching a consensus), are the aspects of the radiological protection system that this paper addresses. Our goal is to describe and understand the most controversial topics of the RP system that deal with its quantities and units. To do so, we conduct a review of the literature that addresses controversial aspects of the system, albeit without covering all the publications on the subject. What interests us here is to grasp why the system is how it is and to point out to some epistemological consequences of its characteristics.

Ultimately, we want to home in on the discussion of the scientific problems involved in the creation and recommendation of quantities for RP and their consequences for the community involved with these quantities, without failing to consider the public at large. Some of these scientific problems – e.g., the need to make approximations and the normative nature of the concepts – are epistemological in nature (González et al., 2016, p. 74). The controversial issues discussed here essentially involve: (1) the duplication of types of quantities; (2) the methodologies for calculating and measuring quantities; (3) the metrological status of some of the quantities; and (4) the functionality of the system of quantities and units. These issues primarily concern the *values* involved in the decisions that the scientific community has taken, which we will also discuss here. Values such as scientific rigor, the ease of introducing and using the system, the possibility of translating names into different languages, and the stability of the system also fall within the scope of this paper.

The science and practice of measurements have to be the object of concern and care because they are the most important elements in the standardization of measurements in RP. To those who are initiated in radiological protection, the system may appear rather less complex, not so much because they already know it, but because over the years they have got used to working with these quantities and dealing with their idiosyncrasies on a daily basis. Even so, we do not believe any professional would fail to recognize that the system is not simple. In fact, it is not made just for the initiated, but has important interfaces with society as a whole, such as when a patient is notified about the dose received in a computed tomography scan or when the general public has to be informed about the seriousness of a nuclear accident. In order to understand the decision-making processes of the expert commissions of the international agencies, we would have to carry out a comprehensive study of their structures and dynamics, and read the minutes of the meetings that led to recommendations concerning the quantities that are controversial. The research for this article did not involve such activities, but we were nonetheless able to identify some political trends in the documents published by the official RP organizations, such as the International Commission on Radiological Protection.

Despite the tacit knowledge embodied in the expert community, we hold that it is very important to point out the epistemological flaws that can be assigned to the RP system. A presentation of the controversial system of quantities and units of radiological protection would therefore seem fitting for the purposes of demonstrating the epistemological ambiguity of the system. The first section, "Basic Concepts of the RP System," contains this analysis, which is divided into three subsections on the fundamental quantities of radiation, concepts concerning the damage caused by radiation, and the RP quantities system. Only a summary of the RP system is given, concentrating on the conceptual building blocks and meaning of each quantity. It is not the aim of this paper to propose new scientific concepts which could be employed in RP. Mathematical formulations and subtleties are overlooked. In the second section ("Criticisms and Epistemological Problems"), the main controversial aspects of the system are presented and discussed, focusing on the criticisms and defenses made by experts from the area. There are four sub-sections, each one addressing a specific group of related questions. Finally, the last section presents some brief comments designed to sum up the epistemological (or conceptual) ambiguities of the system of quantities in radiological protection.

1. Basic concepts of the RP system

The International Commission on Radiation Units and Measurements (ICRU) is a non-profit and non-governmental organization whose goal is "to develop and promulgate internationally accepted recommendations on radiation related quantities and units, terminology, measurement procedures, and reference data for the safe and efficient application of ionizing radiation [. . .]." In the field of RP there is a specific, independent organization, the International Commission on Radiological Protection (ICRP), which releases recommendations on the prevention of diseases associated with exposure to radiation and environmental protection. ICRP also defines the quantities and units to be employed exclusively in the field of RP, for which it receives the support and recommendations of ICRU. IAEA plays a very important role in discussing and promoting the concepts and values adopted by ICRU and ICRP.

The system of quantities and units for RP recommended nowadays by the international entities (ICRU, ICRP, and IAEA) is anything but simple or intuitive and it is not consensus in the scientific community. In order to set the groundwork for our presentation, we first must review some key concepts of RP, starting with its fundamental physical quantities. Following this brief review, we discuss some concepts related to the damage induced by radiation and the means of quantifying it. Finally we present the RP quantities and units system. The focus will be on exposure due to external beams, since we are addressing the quantities created for this kind of exposure.

1.1 The physical quantities of radiation and their units

The main characteristic of high-energy radiation is its capacity to ionize the atoms of the matter with which it interacts. Early on, this property was used to quantify radiation, and the first quantity proposed by the ICRU, exposure[3] (*X*), was based on air ionization. At the second International Congress of Radiology (ICR), held in Stockholm in 1928, exposure was defined as the charge generated by photon beams (x-rays and gamma rays) in air per unit mass of air, and its original unit of measurement was the *roentgen* (R). Although this quantity is still used in practice, it is today not recommended for RP and is gradually being replaced by other quantities, which we will discuss in due course (Jennings, 2007, p. 11). By measuring the charge of ions produced by radiation in air, the pioneers affirmed the existence and the relevance of the phenomenon: the effects of radiation exist physically because we are capable of measuring them. Thus did the pioneers of ionizing radiation take an important step in the challenging task of quantifying it.

The fundamental and most important physical quantity used in this field is the absorbed dose (*D*): the mean energy *imparted* by radiation to matter per unit mass. It was introduced by the ICRP in 1954 because "the Commission realized that it would no longer be sufficient to express all exposure restrictions in roentgen units" (Clarke and Valentin, 2009, p. 90). Its current unit in the International System of Units (SI) is the *gray* (Gy), a special name for joule per kilogram (J/kg), but its original unit was the *rad* (radiation absorbed dose), which corresponds to 0.01 Gy.

While exposure can only be used for photon beams in air, absorbed dose can be used for any kind of radiation beam in any medium (including, most importantly, water and the different tissues in the human body). There are many quantities that have derived from absorbed dose, including the ones defined for RP. The term "dose" is often employed rather generally and imprecisely because it can refer to the amount of radiation, no matter what quantity is involved.

Two other fundamental quantities representing the intensity of a radiation beam are kerma (kinetic energy released per unit mass, *K*), which has the same dimension as absorbed dose and is expressed in the same unit (Gy), and particle fluence (Φ) – the number of incident particles on the cross-section of a sphere, expressed in m^{-2} in SI units. While kerma takes into account all the kinetic energy released by the radiation in the medium through ionization, absorbed dose takes into account just the energy imparted to the medium, not accounting for the radiation energy that escapes from the volume of interest. In laboratories, radiation beams are quantified using one of these three physical quantities,[4] summarized in Table 1. The dissemination of these quantities through the metrological chain provides the *standardization* for radiation measurements.

Table 1. The physical quantities of radiation and their units

Physical quantities		
Symbol	Name	Unit
D	absorbed dose	gray (Gy), special name for J/kg
K	kerma	gray (Gy), special name for J/kg
Φ	particle fluence	m^{-2}

However, in 2011, after decades of research and improvements, ICRU recognized that the system designed to measure radiation had "fallen short of perfection due to compromises among the unavoidable ambiguities inherent in the real natural world and the need nonetheless for a basic set of useful quantities" (ICRU Report 85: ICRU, 2011, p 5). ICRU Report 85 only covers fundamental quantities, like the three mentioned above. The difficulties clearly stem from the complexity of the phenomena that occur in the interactions of radiation with matter. These phenomena have statistical (non-deterministic) behavior and depend on the kind and energy of the radiation involved and the properties of the natural medium.[5] Any scientific endeavor to represent natural and artificially induced processes mathematically will inevitably be idealized and imperfect.

Although less accurate and precise than many quantities in others domains of metrology, measurements of fundamental physical quantities in radiation are being obtained, with a relatively low uncertainty, in different metrological laboratories around the world. The definition of these quantities enables them to be determined by "primary reference measurements"[6] with less than one percent of uncertainty.[7] Taking into account all the difficulties that arise in radiation measurements, one percent uncertainty is regarded as low. Levels of precision vary greatly in the measurement of different kinds of quantities. "In time metrology, we can measure with a precision of a few parts in hundreds of billion, yet when it comes to measurement of the radiation needed in hospitals and upon which our lives may depend, the precision is a few percent (a few parts in a hundred)" (Willians, 2014, p. 10-21).

[4] Of the three physical quantities mentioned here, particle fluence is classified by the ICRU as a radiometric quantity, with the purpose of characterizing a radiation field, while absorbed dose and kerma are classified as dosimetric quantities, which supply "a physical measure to correlate with actual and potential effects" of the radiation.

[5] The stochastic nature of the interaction of radiation with matter, with often complex statistical distributions, imposes the use of approximations even for the fundamental quantities in ionizing radiation. (ICRU, 2011 – 2. General considerations)

[6] Primary reference measurements are metrological procedures used to obtain a measurement result without relation to a measurement standard for a quantity of the same kind, as set forth in VIM (JCGM, 2012, p.18).

[7] All the uncertainties expressed in this paper are expanded uncertainties with an approximately 95% confidence level (coverage factor k =2). This means that there is a 95% chance that the "true" value of the measurand lies in the interval around the measured value ± the uncertainty value.

1.2 Quantifying the risks for health

The lack of "perfection" in the system of quantities in radiation goes far beyond those recognized in the fundamental quantities presented in ICRU Report 85. If the physical phenomena involved in radiation interactions are characterized by complexity, then the complexity, uncertainty, and unpredictability of the biophysical and biochemical phenomena implicated in the harm caused by radiation to living beings is far greater (Tubiana et al., 1990, p. 1-21; ICRU, 1993, p. 1). The problem of "the need for simplification" is probably more visible in the RP domain:

> When the scientific method is used to describe and model the reality associated with radiation exposure and its health effects, inevitably some qualities are lost, including subtle, specific anomalies and phenomena associated with such complicated problem. [...] Of course it is remarked that this happens in all areas of science and technology but it seems to be particularly sensitive in the sciences of quantifying radiation exposure [...] (González et al., 2016, p. 72-73)

What biological damage is caused by a radiation beam? This is the question that RP research addresses with the aim of setting limits for human exposure, as people are continuously exposed to radiation. Biological damage can arise from *deterministic* effects (tissue lesions) and *stochastic* effects (of a probabilistic nature, such as inducing cancer and hereditary effects). In most occupational exposure, doses and dose-rates are low; in these situations, stochastic effects are prevalent. The concept of *detriment* is designed to sum up the potential damage caused by exposure to radiation; in other words, it is related to the hazard of an exposure. The ICRP defines detriment as follows:

> The total harm to health experienced by an exposed group and its descendants as a result of the group's exposure to a radiation source. Detriment is a multidimensional concept. Its principal components are the stochastic quantities: probability of attributable fatal cancer, weighted probability of attributable non-fatal cancer, weighted probability of severe heritable effects, and length of life lost if the harm occurs. (ICRP, 2007, p. 20)

It is well known that the detriment caused by radiation depends on the energy absorbed by human body tissues, but not just this: different radiation qualities (radiation type and energy) will produce different effects. For instance, the detriment to the human body from the same doses of photon and neutron radiation varies considerably: depending on its energy, a neutron beam can be up to 20 times more harmful. Here, it is important to highlight another feature of a radiation beam: the density of ionization it brings about. The higher the density, the more energy is transferred along the track of the radiation through the medium[8] and the more likely this radiation will be to produce damage.

As early as 1951, the ICRP introduced the concept of *relative biological effectiveness* (*RBE*) in a bid to establish a relationship between the damage caused by different radiation beams (Clarke and Valentin, 2009, p. 88). *RBE* data obtained in recent research are employed to evaluate the detriment of radiation and calculate the factors to be employed in determining the quantities of RP. Despite the considerable volume of scientific research undertaken in recent decades – the 2005 French Sciences Academy's report alone highlights over 300 publications as references – the results are still insufficient to build a reliable and consensual model for RP, where doses and dose rates tend to be low (Tubiana et al., 2005). The information sketched out thus far gives a basic idea of the challenge that standardization in the area of RP represents.

1.3 Quantities, units, and measurements in RP

The current system of RP is made up of two groups of quantities with different purposes and calculation methodologies, whose aim is to set dose levels that take into account the risk associated with different kinds of radiation and which are *equivalent* to one another. This explains why the term "equivalent" is used as a kind of wildcard to mean equivalence of damage caused by radiation.

The first group is that of *protection* (or primary[9]) quantities, whose calculation supplies the values of the permissible dose limits for human beings, but which were not conceived to be experimentally measured. As they were conceived for calculating dose limits, they are also called *limiting* quantities. The second group is that of *operational* quantities, which are defined for measurements and which, through the calibration of the equipment employed in making the measurements, provide conservative equivalent values to quantities from the first group. In both groups of quantities, experimental data and computer calculations (simulations using the Monte Carlo method) supply the factors used in their calculation and calibration methodologies.

The first group of quantities includes: the *equivalent dose* in an organ or tissue (H_T) and the *effective dose* (E), which, respectively, represent the dose limits that each organ and the whole body can receive over a given period of time with a low risk to health, including any potential stochastic effects.

[8] The term used to describe the density of ionization of a radiation quality is linear energy transfer (LET or L), which expresses the amount of energy transferred to the medium per unit length of the track of the beam, generally expressed in $keV/\mu\text{up}m$. LET depends on the type of particle, its kinetic energy, and the radiation interaction cross-section for the medium in question (interaction probabilities or coefficients). For this reason, LET is not determined only by the characteristics of the beam, but also by those of the medium.

[9] "Primary" is the term used in the context of RP to highlight the limiting feature of the protection quantity. It is used in a completely different sense from the term which is used in metrology when one says that the value of a quantity was determined by a primary reference measurement. See note 6.

Equivalent doses are calculated considering the types of radiation occurring in the exposure investigated, using factors designed to represent the estimated detriment of the different kinds of radiation involved (w_R).

Damage caused to tissues in the human body has different effects on human health. In order to estimate the detriment of exposure on the human body as a whole, the damage to each radiosensitive organ or tissue has to be weighted by specific factors. As such, *effective dose* is calculated by summing the *equivalent doses* weighted by the relative detriment attributed to the organs or tissue of the human body, using weighting factors w_T (ICRP, 2007, p. 63-68). Since w_T values depend on the effects of the radiation in question and the research data upon which they are based, setting these values "requires a great degree of judgment" and is open to review (Shapiro, 2002, p. 68).

As indicated, protection quantities are used in national regulations, generally based on ICRP and IAEA recommendations, to set the dose limits for the workplace and for individuals from the public. For example, the dose limits of *effective dose* (whole-body exposure) in one year recommended by ICRP and IAEA for workers are 20 times higher than they are for the lay public (respectively, 20 mSv and 1 mSv) (ICRP, 2007, p. 99; IAEA, 2014, p. 132-133).

The operational quantities (second group) are *ambient dose equivalent* – $H^*(d)$, *personal dose equivalent* – $H_p(d)$, and *directional dose equivalent* – $H'(d,\Phi)$, which are defined to be used in measurements in workplaces and areas surrounding facilities and in specific parts of individuals' bodies exposed to radiation. The measured values of those quantities represent the deposited dose at the depth d of the human body, in a specific direction given for an angle Φ, in degrees. (ICRP, 2007, p. 70-71). Operational quantities "usually should provide an estimate of or upper limit for the value of the limiting quantities due to an exposed, or potentially exposed, person [. . .]" (Dietze, 2001, p. 1). Table 2 summarizes the ICRP and IAEA recommended RP quantities in the updated system, all of which have the same unit, the sievert (Sv).

Table 2. RP quantities

Symbol	Name	Used for calculating the dose limit
	Protection, or primary, or limiting quantities	
H_T	equivalent dose	in an organ or tissue
E	effective dose	in the whole body
	Operational quantities	
Symbol	Name	Used for measurement in
$H_p(d)$	personal dose equivalent	individual monitoring
$H^*(d)$	ambient dose equivalent	area monitoring
$H'(d,\Omega)$	directional dose equivalent	area monitoring

Protection quantities (*equivalent dose* and *effective dose*) and operational quantities (*dose-equivalents*) are all derived from and have the same dimensions as *absorbed dose*. They are also expressed as joules per kilogram (J/kg), but when J/kg is used in RP, it is termed *sievert* (Sv). Operational quantities are defined and determined in such a way that their values are conservative relative to the protection quantities.

In calibration laboratories, the beams emitted by sources of radionuclides or x-ray tubes (reference radiation fields) are characterized in terms of physical quantities (*air kerma rate* or *particle fluence*) using standards calibrated in primary or secondary laboratories (Dietze, 2001, p. 9). This is the key step for the standardization of radiation measurements. Values of physical quantities are converted into values of operational quantities using conversion coefficients previously calculated and tabulated for the conditions described in standards and documents published by international organizations (ISO, 1996; ICRU, 1998; IAEA, 2000). By these means the operational RP quantities are traced to the primary standards of the physical quantities.

Radiation monitors like Geiger-Müller meters, ionization chambers, etc., which are used in radiometric surveys at workplaces or to determine the dose received by the human being using them, are calibrated in radiation beams of a known intensity to give reliable indications of the operational quantities in *sievert* (Dietze, 2001, p. 9-11). The uncertainties in the calibration of a dosimeter in operational quantities are at least three times greater than in the calibration values of an *air kerma* reference instrument, owing to the factors that express the detriment of radiation (PTB, 2017). Measurements with a calibrated dosimeter using operational quantities in the workplace involve much higher uncertainties, around ten percent, considering all the geometric and stability problems existing in such settings.

If the description of the two groups of quantities for RP seems confusing or unintelligible, it is not just because of the authors' inability to present the RP system. Despite the fact that most scientists recognize that the quantities system is successful in RP, some specialists in the area have noted that the current structure is "too complicated and difficult to be readily used in practice" (Sabol et al., 2011, p. 119; Mattsson and Söderberg, 2013, p. 7), while others have commented that the nomenclature could cause confusion (Gonzalez, 2012, p. 2; Tauhata et al., 2013, p. 148), and still others go to the point of claiming that the concepts and quantities in RP "have drifted into what may be regarded as chaos"[10] (Rossi, 1996).

In RP, the bases for the international system of quantities and units, and the set of concepts, procedures, and dose levels all derive from publications released by ICRP and ICRU. ICRP publishes documents, named *ICRP Recommendations*, which present general conceptual guidelines for RP. There have been three major historical landmarks in the ICRP recommendations: ICRP Publication 26 (1977), ICRP Publication 60 (1991), and ICRP Publication 103 (2007). To some extent, the foundations of the current system date back to the 1977 publication, where *dose equivalent* (H) was first used with the aim of quantifying the risk of radiation to human tissue by using the quality factor of the radiation, $Q(L)$. This publication introduced *effective dose equivalent* (H_E) (first for internal exposure and then, in 1980, also for external exposure), a quantity that represents the *dose equivalent* for the whole body.

[10] Although it is cited by different authors (Kellerer, Thomas, Sabol), Prof. Herald Rossi's letter to the editor of Health Physics published in 1996 (volume 70, issue 3) does not appear in the online version of the journal: the pages on which the letter was printed are missing.

In ICRP Publication 60, the *equivalent dose* in a tissue or an organ (H_T) was created, and H_E was replaced by *effective dose* (E). The method for calculating H_T is slightly different from the method for calculating H, because it uses a radiation weighting factor (w_R) that does not depend on the tissue. This alteration, designed to simplify the calculation of *equivalent doses* (and consequently *effective doses*), sparked criticism because it impaired the scientific rigor of the calculation (Kellerer, 1990; BCRU, 1993; Pelliccioni and Silari, 1993; Thomas 2004). Furthermore, the concept of *effective dose* enables doses received from external beams (measured in *H*(10)* or $H_p(10)$)) to be added to the doses received from intakes of radionuclides. The conceptual framework set forth in the 2007 publication with regard to quantities differs little from that of the 1991 publication; only a few weighting factors were altered.

The operational quantities were proposed by ICRU in the 1980s (ICRU, 1985; ICRU, 1988), but their current names and definitions were given in *ICRU Report 51* (ICRU, 1993; Jennings, 2007, p. 11-12). As they are intended to give a conservative value of the limiting quantities, the conversion coefficients used to calculate their values from the physical quantities (*air kerma rate* or *particle fluence*) have to be recalculated and republished when the protection quantities change.

2. Criticisms and epistemological problems

In the scientific literature, there are both staunch champions and severe critics of the system of quantities, as well as those who defend it in general terms, but make certain pointed criticisms. As we highlighted in the introduction, many difficulties and complaints have been voiced by professionals involved in RP. In 1998, Ralph H. Thomas, from the University of California, wrote an article pointing out the "seven deadly sins" of RP quantities: "lack of fundamental guidance, ambiguity, immeasurability, duality, instability, inconsistency and lack of rigour" (Thomas, 1998, p. 87-89). These problems are still present in the updated quantities system and they are still a matter of discussion among experts in RP for their controversial nature. We will discuss some of them here, focusing on *four* kinds of issues that include most of the "sins" present on the Thomas's list:

(*i*) Lack of rigor, inconsistency, and tension between academic scientific rigor and radiation in the workplace;

(*ii*) The duality of types of quantities and the non-measurability of limiting quantities;

(*iii*) Deficiency of communicability, surplus quantities, and impracticability;

(*iv*) Instability: the need of change versus too many changes in the system.

Below, we address each of these groups separately, bearing in mind that they are all interlinked in one way or another and sometimes overlap. Further, the first three types of questions are always in tension with the fourth, instability, since the criticisms targeted towards the first three presuppose the need for the system to be changed.

2.1 Lack of rigor, inconsistency and tension between academic scientific rigor and radiation in the workplaces

Evaluating the detriment of low doses of radiation, where stochastic effects predominate, depends on extrapolating relative biological effectiveness (RBE) data for higher doses – i.e., the damage caused by radiation where the doses are higher. The estimation of the factors employed to obtain the limiting quantities is based on a model that assumes that the damage caused by low doses of radiation increases in proportion to the dose received and that this can be calculated by summing the doses received – which is known as the linear non-threshold (LNT) model. However, alongside the dearth of empirical data to corroborate this model, it also ignores the existence of effects that could have a strong influence on the dose-effect relationship. "Owing to the high uncertainty of experimental and epidemiological data obtained at low doses, if at all available, the shape of the dose-effect relationship in this dose range remains an open question" (Dietze and Menzel, 2004, p. 460). Besides this, ICRP uses LNT as a model for creating quantities and setting dose limits.

Thomas points out that ICRP's treatment of the LNT model is not consistent with its philosophical qualification of model, since LNT is sometimes treated hypothetically. But for Thomas, LNT is not a hypothesis, hence it cannot be tested. He brings to discussion some philosophical concepts in these words: "Not being a viable or legitimate hypothesis LNT is not susceptible to testing against falsification." As such, it should not be described by ICRP as the "best" tool for predicting the risk of low doses of radiation (Thomas, 2004, p. 279). More recent references simultaneously contradict and support Thomas's arguments. The 2005 report by the French Academy of Sciences features some experimental studies that do not corroborate the hypothesis that underpins the LNT model. In other words, this hypothesis has indeed been tested, but has failed to pass the test. The difficulty of testing the LNT model is well known, and results should be handled with corresponding care. Nonetheless, the report's conclusions are similar to the position held by Thomas:

> In conclusion, this reports raises doubts on the validity of using LNT for evaluating the carcinogenic risk of low doses (<100 mSv) and even more for very low doses (<10 mSv). The LNT concept can be a useful pragmatic tool for assessing rules in radioprotection for doses above 10 mSv; however since it is not based on biological concepts of our current knowledge, it should not be used without precaution for assessing by extrapolation the risks associated with low and even more so, with very low doses (< 10 mSv) [. . .] . (Tubiana et al., 2005, p. 4)

The possibility of reviewing the limits of the permissible dose and the reasons why they should be reviewed underlie the discussion concerning the validity of the LNT model (Tubiana et al., 2006). It is worth mentioning the different interpretations of the reports, both of them based on the same sources: the French Academy of Sciences and the Biological Effects of Ionizing Radiation (BEIR), from the American Academy of Sciences (Tubiana and Aurengo, 2005; BEIR

VII, 2005). The different conclusions of these reports and the arguments for and against reviewing dose limits are undoubtedly interesting questions from a philosophical point of view. These conceptual problems have been addressed in two recent publications (Ferreira, 2013a; Ferreira, 2013b), but they are not discussed here because they are related to the values of dose limits, not the quantities and units in which they are expressed.

If LNT is a model or a hypothesis, these philosophical concepts should be brought into scientific discussions; in other words, it is impossible for the expert community to effectively avoid this kind of discussion. The problem of lack of rigor goes far beyond the employment of the LNT model. Experts from this domain recognize that the uncertainties involved in determining the values of the quantities employed in RP are high because of the estimates involved, especially when it comes to the risks of biological damage. According to ICRP:

> The determination of quantities relevant to radiation protection often involves significant uncertainty. In addition, a variety of approximations must be used for relating physical measurements to biological effects caused by radiation. Although a comparatively wide margin may be admissible in radiation protection, it is essential that quantities employed be unambiguously defined and that approximations be clearly identified. (ICRU, 1993, p. 1)

However, some experts argue that high levels of uncertainty do not preclude scientific rigor in the definition of quantities. A. M. Kellerer affirms that the use of radiation weighting factors (w_R) – that are "receptor free" or do not depend on how the radiation interacts with the tissue – is a flaw in the scientific rigor of the calculation, thus, in the definition of H_T (Kellerer, 1990). Kellerer advocates that in an actual radiation field with a range of energy (that means, a radiation field with an energy spectrum, not a single energy), w_R cannot be regarded as tissue-independent. He states that the "simplicity of the approach is thus lost whenever one deals with mixed radiations" because "there is no radiation weighting factor for a mixed field" (Kellerer, 1990, p. 5). Even more important than the technical problem in the ICRP and ICRU's weighting factor approach are the conclusions that Kellerer extracts from the situation, which explicate some of the problems RP faces:

> The practice of radiation protection can usually be based on simplifications and approximations. The present discussion may, therefore, appear as a fancy way to make plain things complicated. Conceptual clarity is, on the other hand, an essential ingredient of simplicity, and simplicity must not be confused with looseness or with the approximations that are admissible under many circumstances. The rigour of the underlying definitions may not become apparent in many applications of radiation protection quantities, but it is the necessary skeleton that supports the system of radiation-protection measurements, computations and calibrations and that avoids conflicts of interpretation and needless discussions.
>
> Confusion in the basic definitions can never be fair price for simplicity. But rigorous definitions do not exclude the use of approximations, if they are recognized as such. (Kellerer, 1990, p. 6)

Thomas reiterates Kellerer's call for rigor (Thomas, 2005, p. 5). He states that in the 40 years preceding ICRP Publication 60, "steady progress towards the establishment of a rigorous, stable and integrated system of dosimetry had been achieved" before the introduction of E. This quantity "was hastily conceived and its introduction seriously disrupted that previous progress" and "subsequent evaluation of E has found it to be flawed in several respects" (Thomas, 2004, p. 277). Accepting the criticisms that call for scientific rigor, Thomas qualifies ICRP's approach to the calculation of *mean absorbed dose* in an organ (D_T) that avoids the mathematical operation of integration as "mathematikophobia" (Thomas, 2005, p. 11).

Also, for Brenner, *effective dose* is a flawed concept that should be replaced by a new quantity. He points out three problematic issues concerning *effective dose*: the different stochastic endpoints of cancer induction employed, the independence of age at exposure, and the confusion and misuse that the concept allows (Brenner, 2008, p. 521-522). He also proposes to replace E with a new quantity, named "effective risk," which would be "less prone to misuse, [...] more directly understandable, and [...] based on more defensible science" (Brenner, 2008, p. 522-523). But the replacement of E by "effective risk" has been criticized by members of the ICRP Task Group that investigates the use of *effective dose* as a risk-related protection quantity (Harrison et al., 2016, p216).

The criticisms of Kellerer, Thomas, and Brenner were made from technical points of view over the simplifications and approximations employed in RP quantities calculations, despite their recognition of the need for approximations and simplifications. These criticisms raise an epistemological question regarding what kind or level of simplification would be acceptable. Is there an epistemological threshold for the simplifications that quantities like H_T, E, and the operational *dose-equivalent* could employ? What kind of epistemological criteria would be defensible? Built between science and practical regulations, RP must always deal with these epistemological questions and would profit from deep, ongoing conceptual discussion on this groundwork.

Abel Julio González, the representative of Argentina at the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), consistently points out the epistemological weakness exhibited by RP quantities and units. He also discusses issues arising from practical situations. On the normative nature of protection quantities, González, the Brazilian Carlos Eduardo de Almeida, and the Argentinean Francisco Spano describe the status of these quantities thus:

> Few human endeavors have achieved this level of sophisticated simplification to characterize and regulate exposure to a detriment

> agent. However, the protection quantities are unique and universal, but 'by definition' and not in the mathematical sense of 'existence and uniqueness'. Because if they were in that sense, they should be able to solve all problems covering the entire field of interest without further clarification [...] (González et al., 2016, p. 72)

This means that protection quantities depend on their definitions, which include the normative values of the weighting factors, and that they are also defined for normative purposes (to express dose limits). As to some extent these quantities are artificially defined to represent the risk of radiation exposure, they are not really physical quantities, as we will discuss in the next subsection. Because of the practical purposes of the system, the need for rigor has to be balanced against the need for quantities that can be employed in the workplace. But if protection quantities were physical quantities, like absorbed dose, they still would not fulfill the conditions of uniqueness and universality.

Thomas targets his criticisms of the decision-making process at the way the quantities were conceived. He states that "the scientific input to the standard-setting process is necessarily a delicate balance between the ivory tower of academia and the practical concerns of the workplace" and he argues that "the concerns of the workplace should take primacy over the ivory tower in the development of radiation protection standards policy" (Thomas, 2004, p. 277-278). Workplaces are generally concerned about evaluating radiation levels and the doses workers and the lay public receive. Evaluations of this kind involve measurements, meaning the use of calibrated instruments or personal dosimeters to measure operational quantities. What about Thomas's criticism of lack of rigor? Wouldn't more rigorous concepts or mathematics make the system harder to be used in practice? It seems that there is a contradiction in Thomas's requirements: If the concerns of the workplace should be attended first, we should look for a simpler system and be less concerned with the academic rigor of the calculations.

The "ivory towers" *seem* to be the international organisms responsible for defining the quantities, ICRU and ICRP, in Thomas's view. He calls for a decision-making process that is open to the community.[11] This is a serious suggestion, but would such an open process help address the concerns of workplaces? In order to be able to answer this question, we should investigate the procedures and decision-making processes of responsible commissions and not just scientific publications, as has been the case thus far.

An interesting view has been presented by Sabol and collaborators (Sabol et al., 2011), who emphasize many shortfalls of the present system of RP quantities that hamper their implementation. They argue that the present system "is excellent for the scientific approach" and research, but it needs to be simplified to be fit for practical and regulatory purposes. This article clearly distinguishes rigor and sophistication of scientific approaches from the need for simplification to design a system for use in the workplace. Sabol's article mentions some problems concerning the suitability of the system that we will bring up in section 3.3, as this is a matter that is closely related to the issues discussed there.

2.2 The duality of types of quantities and the non-measurability of limiting quantities

First, we will address the question of the duality of types of quantities and then we will discuss the characteristics of limiting quantities. Is RP committed to employing two types of quantities: limiting quantities, used only for calculating permissible dose limits, and operational quantities, used for measurements? Thomas holds that RP is a branch of the field of toxicology and that in all other branches of this field, permissible dose limits are supplied in terms of the same quantity in which the dose is measured. They could be obtained by simply distinguishing the physical quantity to be measured and the risk coefficient (estimated by experts), just as in other areas of toxicology. He believes that the system should be reformed so that the dose limits of radiation can be expressed using the same quantities by which radiation itself is measured (Thomas, 2004, p. 279-280). Would such a change be feasible or welcome?

In this proposal, Thomas does not only envisage greater rigor and clarity in the process of measuring doses, but he also wants to separate values obtained by *objective* means (physical quantities) from those obtained by *subjective* approaches (risks estimated by experts). One may agree with Thomas's proposals and his aim of clarifying what is being measured, but still point out the philosophical weakness of the distinction between objectivity and subjectivity upon which it is based. Not least because he claims that the judgments of experts based on available data are "non-scientific" (Thomas, 2004, p. 279). This perspective can only be understood as deriving from a simplistic division between the objectivity and scientific criteria of physical quantities and the subjectivity, and therefore non-scientific nature, of values based on data that cannot be formalized but which are proposed and agreed upon by experts. These remarks do not invalidate Thomas's proposal that we believe it is worth discussing.

In a debate with B. Lindell, from the Swedish Radiation Protection Institute, in the "Topics Under Debate" section of the journal Radiation Protection Dosimetry, Thomas reiterates his arguments in favor of measurable quantities, while Lindell rebuts, remembering the problems that came about in the past which led to the establishment of duplicate types of quantities: "In order to understand the meaning and intended use of the primary limits recommended by ICRP, we have to look back at the historical development of these limits" (Thomas, Lindell, and McDonald, 2001, p. 290).

For Lindell, when stochastic effects are taken into account in calculations of limits, the creation of non-measurable quantities is necessary because "probabilities are not measurable." Furthermore, when also considering the exposure

[11] In fact, this was addressed in the 2007 recommendations, for which there were two phases of international public consultation, two drafts (2004 and 2006) and presentations to international entities (Clarke and Valentin, 2009).

of individuals to internal sources of radiation, limits cannot be expressed only in reference to external radiation beams. Thus, ICRP defines the principal limiting quantity as the effective dose, which is prospective and "is one step closer to the operational protection quantities." The duality of types of quantities, argues Lindell, has not made the system hard to use at all (Thomas, Lindell, and McDonald, 2001, p. 291). In fact, most of the critics of the system do not see the two types of quantities as a problem; they generally point out problems in some aspects of the quantities, but not in the existence of two different types (e. g., Dietze and Menzel, 2004; Gonzalez et al., 2016; Sabol et al., 2011).

Embedded in the determination of both protection quantities and operational quantities are factors designed to estimate the detriment from exposure. By including these estimates in the values to be determined, we are now talking about quantifying not physical or biological phenomena, but a dose related to the risk arising from the phenomena that occur at the interaction of radiation and biological tissue. The quantities do not represent natural phenomena, but the risk[12] of causing damage (detriment) associated with radiation. The problems that arise from a system like this cannot be resolved by studying nature and its phenomena. As Lindell mentions in his defense of the duality of the system, one must be aware of the reasons that led to the definitions of the quantities (Thomas, Lindell, and McDonald, 2001, p. 290). No knowledge of the phenomena involved and the estimates of biological damage is sufficient for us to understand the "reasons" behind the system of quantities in RP.

In routine RP procedures in facilities that deal with penetrating radiation, it is normal to employ *H*(10)* for the monitoring of environments in radiometric surveys and $H_p(10)$ for individual monitoring of workers. Both are compared with the limiting values of *E* (effective dose). Table 3, based on a table from the *Safety Report Series N^o 16* (IAEA, 2000), sums up the operational quantities employed and the corresponding protection quantities. Given that *H'(3)* and $H_p(3)$ are rarely employed, the four quantities used to measure external beams constitute a relatively simple set of quantities.

According to G. Dietze, from PTB (Germany), operational quantities "are often used in place of those [protection] quantities in practical regulations" (Dietze, 2001, p. 1). This use would seem to indicate that we are able to express limits in terms of the very quantities used to measure them. But this use of operational quantities demands some consideration. As far as we are aware, there is no other reference to this way of employing RP quantities. Besides, the concept of effective dose allows the addition of $H_p(10)$ values to values of doses received internally. If dose limits are expressed in operational quantities for external fields, the doses received by ingestion or inhalation of radionuclides must be considered separately. The use of operational quantities for limiting purposes is mentioned here not as a suggestion of change, but just as an example of the misuse of the system owing to its complexity and as an indication of a possible path forward for change.

Table 3. Operational quantities employed in routine practice (after IAEA, 2000)

External radiation	Limiting quantity	Operational quantity for	
		Area monitoring	Individual monitoring
Strongly penetrating radiation	effective dose	*H*(10)*	$H_p(10)$
Weakly penetrating radiation	dose equivalent to the local skin	*H'(0.07,Ω)*	$H_p(0.07)$
	dose equivalent to the lens of the eyes	*H'(3,Ω)*	$H_p(3)$

Conversely, one of Thomas's proposals for the *2005 Draft for Consultation Proposal*s is that "only protection quantities" be defined, while the means to measure them should be left to the "the ingenuity of dosimetrists" (Thomas, 2005, p. 25). This is a proposal that could leave dosimetry experts and all those involved in safety in the workplace in dire straits. Paradoxically, it seems a proposal proffered from the heights of the ivory tower of academia. Probably, Thomas hopes that the new definitions of protection quantities would make them easy to measure. But the science and practice of measurements have to be the object of carefully concerns, for they are the relevant elements in the standardization of measurements in RP.

If we had just one type of measurable quantity, the system of RP would be easier to understand and more user-friendly. In particular, it would be more defensible for science and metrology. The history of quantities and units in RP has led to the current state of affairs, with two groups of quantities and one unit. And although many would seem to still dream of returning to a time when one measured the very quantity in which the dose limit was expressed (e.g., Pelliccione and Silari, 1993, p. 70), there is nothing to indicate that this could happen.

As we stated before, while the duality of the system is not frequently criticized, some aspects of the quantities it uses have been targeted by experts. Now, let us move on to address the characteristics of limiting quantities, especially the fact that they are not designed for measurements. Despite wide use of the system almost all over the world, protection (limiting) quantities are unorthodox in the science of metrology:

> The protection quantities are strange quantities because they do not meet the more elementary requirements for a quantity: they are neither measurable nor traceable; accuracy or precision in their amount cannot be formally defined. (González et al., 2016, p. 71)

Do we need quantities like that? As they are not experimentally measurable, can they even be referred to as quantities? According to the metrological definition reproduced

[12] The RP quanttities are "risk-adjusted" dosimetric quantities for use in the control of radiation exposures (Harrison, 2016, p. 222). Calculating or measuring these dose-quantities, in Sv, is different from estimating the risk. "This risk is a function of the probability of an unintended event causing a dose, and the probability of detriment due to that dose" (ICRP, 2007, p. 32). For risk estimation see Annex A of ICRP Publication 103 (ICRP, 2007).

in the introduction to this article, a quantity is a quantifiable property of a phenomenon, body, or substance. Quantities E and H_T are absorbed doses weighted by the detriment associated with a given radiation type and energy. According to the ICRP, these quantities are doses "that allow quantification of the extent of exposure of the human body to ionising radiation from both whole and partial body external irradiation and from intakes of radionuclides" (ICRP, 2007, p. 29). They were only conceived to calculate permissible dose limits. As such, can they be considered the properties of a phenomenon or body?

In their analysis of limiting quantities, Dietze and Menzel raise some questions: "Is the effective dose a physical quantity? Is it a single-valued or multi-valued quantity?" (Dietze and Menzel, 2004, p. 458). In the ensuing discussion, they state that since E is calculated by an equation that gives one value for a given external radiation and exposure condition, it can be used like a single-valued quantity. But they also remark:

> This does, however, not mean that in a given external radiation field and exposure conditions all persons receive exactly the same effective dose, independent of sex or body size, but the value of E obtained by this procedure is used as an adequate approximation for use in practical radiological protection. (Dietze and Menzel, 2004, p. 462)

Based upon this observation, Dietze and Menzel add that E is not designed for individual risk estimates but "can be applied only for risk management and limitation in operational situations" (Dietze and Menzel, 2004, p. 458). *Absorbed dose* is really a physical quantity, but the stochastic effects considered in RP require "additional empirical assumptions based on radiobiological and physical data." As we remarked before, limiting quantities do not represent natural phenomena, but the detriment associated with exposure to radiation. Hence, E is not strictly a physical quantity. Experts like Dietze and Menzel highlight the features and limitations of these quantities:

> In spite of limited knowledge and the underlying simplifying assumptions, the use of effective dose and tissue and radiation weighting factors has proven to be an approach that is adequate for operational radiation protection in many exposure situations of practical relevance. However, it is important to recognize and respect the limits of its applicability. (Dietze and Menzel, 2004, p. 462)

In other words, this is the epistemological feature of E as a quantity: it is based on normative values (weighting factors), it is not defined for to be used in experimental measurements, and it is not really a physical quantity, but it is adequate and useful for the purposes it was created for. Although E may be considered metrologically flawed, any plans to change the system would surely have to be substantiated by much stronger reasons than simply the inadequate use of metrology concepts. As the most important RP quantity, *effective dose* could also be regarded as an emblematic example of a systemic approach that attracts praise for is usability, but also draws criticism for its basic conception. For Harrison and other members of the ICRP Task Group, "effective dose is accepted and applied internationally as the central radiological protection quantity, and has proven to be a *valuable* and *robust*[13] quantity for use in the optimization of protection and setting of control criteria: limits, constraints, and reference levels" (Harrison et al., 2016, p. 216). Further, the ICRP Task Group states that E is also "a useful tool in controlling exposures received by patients undergoing medical diagnosis and interventional procedures." However, like the abovementioned article by Dietze and Menzel, other works have drawn attention to the inappropriate use of E for individual risk assessment (Menzel and Harrison, 2012, p. 45; Harrison et al., 2016, p. 216).

In virtue of the unorthodox conception of quantities in RP, whose definitions and calculation and measurement procedures employ very diverse concepts, recent studies in the epistemology of measurement can help us but little in comprehending their nature. In "Epistemology of measurement," Lucca Mari argues that in measurement systems, "measurements are intersubjective and objective evaluations" (Mari, 2003, p. 28). The subjective part refers to the communication of a measurement result, which should be "inter-subjectively communicable," and the objective part implies that the measurement result should be related only to the measurand or the object of measurement, whatever the environment or the observer. Given the complex set of procedures at play in RP, which involve using physical and radiobiological data, approximations, computer simulation calculations, and experimental measurements and calibrations, such a procedure encompasses evaluations that seek objectivity in the results, but its procedures envisage, above all, results that are "intersubjectively communicable" through comparisons with values supplied in regulations (dose limits).

From the realization of fundamental quantities in primary laboratories to their dissemination to the calibration laboratories used in area and individual monitoring, the chain of ionizing radiation metrology follows the ordinary requirements of objectivity of measurements. However, while the methods for calculating limiting quantities and measurements in operational quantities, used in RP, may be based on methods that seek objectivity, they employ factors and approximations that make the results suitable for the purposes of setting dose limits and verifying the observance of such limits, but they do not represent natural phenomena objectively.

It could be that intersubjective aspects predominate in RP measurement systems, but they are an ingenious set of measurements that are also designed for objectivity. Nonetheless, theories about the epistemology of measurement have little to contribute to our understanding of the epistemological problems raised by measurement systems in RP due to their unorthodox conception, with the non-exclusive use of physical quantities. The duality of the types of quantities in RP and the features of the limiting quantities are a challenge

[13] Terms italicized by the authors of the present text. These terms are examples of the values used to evaluate the quantities.

for studies of the means employed to ensure the safe use of radiation.

2.3 Communicability, surplus quantities, and impracticability

Summing up the debate on measurable quantities between Thomas and Lindell that we discussed in the previous subsection, the moderator, J. C. McDonald, considers that the improved understanding of the problems related to RP has made the system increasingly sophisticated and there is no way to go back to a time when everything was easier. He adds that considerable rigor is called for in definitions of quantities for RP:

> They need to satisfy many conditions, perhaps too many. When they are examined from the point of view of a metrologist, they may be considered to be deficient in many respects. When they are viewed by a radiobiologist, they may appear to be naïve or overly simplistic. A radiation protection technologist at a nuclear power plant may have difficulty understanding their sometimes-subtle implications. (Thomas, Lindell, and McDonald, 2001, p. 292)

The community which interacts with these quantities is indeed very diverse: physicists, engineers, technicians, technologists, chemists, biologists, doctors, nurses, and other professionals that work in the areas of medicine, industry, research, and services (Grupen, 2010, p. XIII; Tauhata et al., 2013, p. 72). It is undeniably a hard task to create a system that meets the requirements of all these stakeholders. For non-experts in RP, the system could bring more problems; but it is also true that the system's weaknesses are a problem for everybody.

In their article on limiting quantities, Dietze and Menzel recognize the existence of problems, but conclude that ICRP's approach is adequate for many of the relevant practical situations (Dietze and Menzel, 2004, p 462). In other words, the limiting quantities are themselves clearly limited, and it would be worth explicating their limits, as, indeed, was advocated by ICRU itself when it defined these quantities (ICRU, 1993).

While recognizing, like the most of the professionals of the area, that the system of RP is "successful," González and colleagues summarize the difficulties of the system of quantities and units in these words:

> In general terms, it seems that the system includes a myriad of quantities and there has been substantial confusion among professionals and the general public on their distinction, use and even need. There has also been misunderstanding on the perception of units used to express the values of such quantities. It should be recognized that some of these problems are simple linguistic and grammatical, including difficulties in translation. These are issues of concern to the metrological community responsible for the physical realization of the quantities and its worldwide dissemination and meaningful traceability. (González et al., 2016, p. 80-81)

Taking a different stance than Thomas, Sabol and colleagues recognize that assessments of exposure and detriment caused by radiation based on the current system are "much better developed that the protection in any other area dealing with hazardous or dangerous materials and phenomena" (Sabol et al., 2010, p. 121). However, they add, "such an 'almost perfect' system is almost impossible to introduce because of many obstacles." The non-measurability of some quantities, the large number of quantities that makes the system too complicated, the frequent changes made, and the ambition to satisfy the requirements of different stakeholders are the four obstacles mentioned by these authors. They also point out that the tendency to complexify the system has led to the misuse of the basic concepts:

> The tangible evidence about the quite frequent incorrect use of the current system of quantities and units can be found in all kinds of publications related to radiation protection. There are always some mistakes or misunderstandings, which can be found in monographs [. . .], scientific papers and other documents, including national regulations. (Sabol et al., 2010, p. 121-122)

We agree with these authors: mistakes are to be found in several of the publications consulted for our research.[14] On the other hand, Sabol, Navrátil, and Rosina opine that "it would not be wise to abandon the current system, which is excellent for scientific approach." But if the system is not adequate for practical purposes, it should surely be modified and simplified for use in regulatory and practical settings. For this reason, the authors propose that the present system of quantities in RP should be maintained or further developed for scientific studies, while a simplified system should be introduced for "controlling radiation exposure in practices" (Sabol et al., 2010, p. 122). The creation of a parallel system for regulatory use could bring up other problems, and would certainly be criticized by the experts who already express concern at the lack of scientific rigor of the current system. However, the proposal is worth considering and discussing in the related forums.

One of the problems highlighted by many of the system's critics has to do with the names of some quantities. The inversion of the words in two of the terms, *equivalent dose* and *dose equivalent*, does nothing to further the acceptance of the system, and indeed is more a cause of confusion. Brazil serves as a good example of the care needed when it comes to understanding and disseminating

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[14] We have chosen do not to mention the publications where we found subtle mistakes that certainly stem from the complexity of the system. However, the first section, on RP units, of a publication on RP (Grupen, Claus. Introduction to Radiation Protection. 2010) for undergraduate students does not distinguish clearly the purposes and genesis of the quantities, presents some incorrect names and symbols, and even frequently confuses the basic concepts of quantity and unit (Grupen, 2010, p. 7-16).

the system. "*Dose equivalent*," the term from ICRP Publication 26 (1977), was translated incorrectly into Portuguese as "*dose equivalente*" (literally "equivalent dose") and published in these terms in 1988 in a national standard (CNEN, 1988). "The correct translation would be *equivalente de dose*, because the concept defined was of equivalence between doses of different types of radiation to produce the same biological effect" (Tauhata et al., 2013). The creation of the quantity *equivalent dose* in 1991 (ICRP Publication 60) left persons responsible for the nomenclature adopted in Brazil in the uncomfortable position of using the name of a quantity that already existed to refer to a new quantity in a bid to make the translations more coherent. In the 2011 Brazilian standard (CNEN, 2011), which incorporates the quantities from ICRP 60, *equivalent dose* is translated correctly as "*dose equivalente*" and *effective dose* is also correctly translated as "*dose efetiva*." Meanwhile, the operational quantities also appear with the correct inversion of the word order, such that *dose equivalents* became "*equivalentes de dose*" in Brazil. The experts responsible for adopting misleading nomenclature in the 1988 standards could easily be blamed, but the fact is that the original names for the quantities and their inconstancy are ultimately the main reason for the confusion.

In the same way, González and coworkers point out that *dose equivalent* has led to multiple translation problems, since it is "untranslatable to many languages that shall use the expression 'equivalent of dose' rather than 'dose equivalent,"' which corresponds exactly to the Brazilian situation. González also took part in a Task Group to study the issues arising from the Fukushima nuclear accident. In one if its reports, the authors point out that "the translation of equivalent dose *vis-à-vis* dose equivalent has been problematic in languages using ideograms such as Japanese." They also observe that the use of *dose equivalent* "is grammatically questionable in English" because "dose is a noun (or a verb) and its forced use as an adjective should be done with care" (González et al., 2013, p.516). Considering that the system of quantities and units is designed for use in all countries of the world, its nomenclature deserves special attention.

González and colleagues have analyzed the adequacy of the system in practice and have shown several difficulties (2016, p. 80-96). They highlight the difficulty of using the system when communicating radiological information to the public, because it is "less suited for use in the public domain where communication with non-experts is required" (p. 97). There are also pedagogic problems, like the difficulty in explaining and understanding the difference between quantities and between kinds of quantities (limiting and operational). When values of measurements or calculations are communicated, it is uncommon to give the name of the quantity, just the values and their unit of measurement. The fact that the unit for all radiological quantities is the same (sievert) can result in "confusion and misunderstanding" (González et al., 2016, p. 97). González's (2016) paper seems to agree with Sabol's (2010) work with respect to the problems encountered around the world in the use of the current system of quantities and units in RP. Likewise, both articles point out that there are too many quantities in the system.

The key issue to improve the system and its use is the *pedagogical* role of IAEA. Loosely speaking, its documents are easier to understand and more user-friendly. IAEA's *Safety Standard Series* stand out as helpful guides for the different institutions involved in applying the international recommendations in RP (IAEA, 2000; IAEA, 2014). Similarly, the *memorandum* on Fukushima comments that "ways to improve and foster information exchange and education and to develop 'easy-to-read' material on the system of radiological protection quantities and units are sorely needed" (González et al., 2013, p. 518).

Another question that scarcely receives attention in technical documents and scientific papers is the *practice of measurement*. One of the most important jobs of any national calibration laboratory is to ensure that instruments used in the field supply reliable measurements. Calibration is the key procedure for providing standardization for radiation measurements, including those made for RP purposes. Often, calibration laboratories end up also providing their clients with guidance on the best way to make their measurements,[15] showing that they also have a pedagogical role. Meanwhile, IAEA's decisions are designed to clarify and standardize practices, proving extremely valuable in the rocky terrain of RP. In this sense, its declarations and assistance in spreading standards even serve to strengthen calibration laboratories. In view of the complexity and the problems of the system recognized by some experts (Dietze and Menzel, 2004; Thomas, 2004; Sabol et al., 2011; González et al., 2016), the good functioning of the calibration network, supported by metrology institutions and IAEA, is fundamental for quantities to be used appropriately.

2.4 Instability: the need for change versus too many changes in the system

So far in this section we have presented the views of radiological protection experts, describing some arguments in favor of changing the system (either specific alterations or a complete overhaul) and some in favor of maintaining the system as it is. As such, there is no need to repeat these points here. The problem of the instability of the system lies in tension with the problems presented earlier by the critics keen to see either a partial or complete overhaul of the system. We would argue that one of the most serious "sins" of the system is its instability: it suffers from constant alterations and the creation of new quantities. Mastery of the protection system is crucial for the professionals that use it to do so confidently. Every time it is changed, RP professionals have to learn the new concepts and change the way they conduct their controls, which could imply changing their documents and the spreadsheets used for calculations. Also, when al-

[15] Whether on the phone, face-to-face with clients, on websites, or even through information included in calibration certificates, one of the goals of calibration laboratories is to provide guidance for the owners and users of radiation monitors on their use to ensure the most accurate measurements.

terations are made, queries may emerge when dose values obtained using the previous methodology are compared with dose values obtained using the new one. Thus, the system's stability is important for providing a sense of security for professionals in the actions and decisions they make in the area.

In several papers, Thomas repeats the same sentence: "It seems that to every problem in health physics there is a solution that requires the invention of a new quantity" (Thomas, 2004, p. 278). He attributes it to an anonymous author, but it could be also heard in any medical physics classroom or laboratory. When we consider all the branches of medical physics, the number of quantities and measurement procedures is far greater than in the system of quantities in RP. The frequent creation of quantities in medical physics is due to developments in the techniques employed in diagnostic procedures and treatments using radiation and the quest for quantities that better represent patients' exposure to radiation. The constant "invention of new quantities" is a concern for the professionals who work with radiation, and in RP it heightens the perceived instability of the system. Warren Sinclair reports that initially, workplace professionals did not like the changes when ICRP Publication 60 (1991) was released, because they had only just adapted to the previous recommendations:

> The 'field' which was still becoming accustomed to handling the ICRP quantities in the context of ICRP 26, suddenly had a new set of problems and issues with ICRP 60. It reacted rather negatively at first but soon, very soon to their credit, began evaluating these issues and problems. (Sinclair, 1996, p. 783)

At that time, there seems to have been a more critical awareness of the instability of the system. Pelliccioni and Silari voiced several criticisms of ICRP Publication 60 and stressed that the choices made by ICRP (and ICRU) and the constant updates of the system created a confusing situation that introduced instability to the system. In the conclusion of the paper, they even said that the frequent alterations made by ICRP were a cause for criticism against the peaceful use of nuclear energy (Pelliccioni and Silari, 1993). Since the system has remained unchanged for over 20 years now, criticism of its instability is less frequent, but it is still voiced. Sabol and colleagues draw attention to the difficulties brought about by alterations to the system in developing countries: "The often changed or modified quantities and associated conversion coefficients may not always be correctly interpreted by those supplying the data [for UNSCEAR] reflecting the exposure situation in developing countries" (Sabol et al., 2011, p. 119).

Interestingly, a rare consensus in the field of radiation seems to have emerged precisely around the idea that any alteration to the system of quantities should be the fruit of broad-based discussion and be consistent to the point of not prompting new plans for alterations in the short term. For example, Thomas has argued that "[r]adiation protection cannot continue to change its vocabulary every decade or so. Any change to be recommended by ICRP must be based on adequate database to permit wise decisions" (Thomas, 2004, p. 287).

As we have seen, while many specialists and even some didactic texts on RP state that the current system of quantities and units for this area is rife with problems, some investigations about the development of the system do not report on any such difficulties or criticisms (NEA, 2011; Clarke and Valentin, 2009; Jennings, 2007). Although the quantities have developed "away" from the phenomena of nature, they are somehow being naturalized. It is as if they had "evolved" by natural selection. Some of the quantities survive the criticisms of the community; their continued existence in our "environment" over the recent decades is a sign of their "robustness."

Generally speaking, the system is treated as a given; perhaps not completely consolidated, but with a set structure. Above all, it seems as if everyone is tired of change. Only small alterations would be welcome, since more radical overhauls of the system would be very costly in every sense. Every effort should be made to *clarify* the concepts involved and to understand their limitations and, wherever necessary, to correct any imprecisions. Indeed, this is the inclination of the ICRP's 2007 recommendations, which contain more continuity than change with regard to the 1991 recommendations. In a review of the ICRP recommendations, the differences between ICRP Publication 103 (2007) and previous ICRP recommendations (Publication 60, from 1991) are described in the following terms: "Some recommendations remain because they work and are clear, others have been updated because understanding has evolved, some items have been added because there has been a void, and some concepts are better explained because more guidance is needed" (Clarke and Valentin, 2009; p.98).

Using Kuhn's terminology (while understanding that the differences with regard to the context of basic research to which he refers should be borne in mind), the RP scientific community, with the exception of a few reform-minded individuals, seems keen only to have research of the kind done in normal science so as to improve the system (Kuhn, 1970). For most scientists, there are not enough anomalies to justify a paradigm shift.

Even so, there is the prospect that soon ICRP will propose a new approach to operational quantities according to the latest definition of protection quantities (ICRP, 2007). In 2010, ICRP set up Report Committee 26 (RP 26) to discuss the problematic aspects of the current operational quantities for external beams and propose an alternative system for these quantities. A set of operational quantities that differs in some respects from those used today was presented at the 2015 ICRP International Symposium on the System of Radiological Protection. The reformulation simultaneously aims to overcome the existing problems and to simplify the system of quantities (Endo, 2016).

In order to control the values of *effective dose* (whole body doses), two operational quantities are proposed: *ambient dose equivalent* (H^*), for area monitoring, and *personal dose equivalent* (H_p), for individual monitoring. The values of these operational quantities will be obtained by applying the "effective dose conversion coefficients" (h_{Emax} and h_E) to the physical quantity. The main physical quantity will be *particle fluence* ($\Phi(E)$), which depends on the energy spectrum of the radiation beam. The new operational quantities proposed for individual and area monitoring are the absorbed dose to the lens of the eye and absorbed dose to local skin, while the limiting quantities will be stated in terms of *absorbed dose* to the same body parts. On this change, the Task Group in charge of investigating the uses of *effective dose* advanced:

> It is proposed that consideration should be given to discontinuation of the use of equivalent dose as a distinct protection quantity, leaving effective dose as the primary protection quantity relating to stochastic effects, and dose equivalent as the operational quantity used in measurements. Deterministic limits would be set in terms of absorbed dose. (Harrison, 2016, p. 218)

Skin doses (at extremities) and lens doses, where the deterministic effects are most important, will be controlled in terms of absorbed dose in the respective tissue. The operational quantities proposed by RP 26 for measuring these doses are *directional absorbed doses* ($D'_{lens}(\Omega)$ and $D'_{local\ skin}(\Omega)$) for area monitoring, and *personal absorbed doses* ($D_{p,\ lens}$ and $D_{p,\ local\ skin}$) for individual monitoring. These quantities will also be determined by applying conversion coefficients that relate the *particle fluence* to the respective *absorbed dose* in the tissue.

The suggested changes will simplify the system and resolve some of its issues, such as the obtainment of underestimated *dose-equivalent* values in relation to *effective dose* values in certain situations and the confusing inversion of "dose" and "equivalent" in the names of the quantities, since *equivalent dose* will no longer be part of the system. However, other problems, like the duality of quantities, the presence of quantities that cannot be measured experimentally, the complexity of the system and resulting difficulty of its operationality, and the use of factors that do not take important features of the radiations into account are some of the issues that will remain if these changes are introduced.

As for the fact that the system will probably be changed again, accentuating the stakeholders' perception of its instability, this could be seen from two different, albeit consistent, viewpoints. It could, for instance, be sustained that the current system has remained practically unaltered for a long while. The foundations of the system were laid 40 years ago in ICRP 26, while the operational quantities were set in the 1980s and the limiting quantities, under their current formulation, were proposed 26 years ago, in ICRP 60. As such, from this perspective, to say the system is unstable would be unfounded, and therefore change would be welcome. On the other hand, as many experts have stressed (Ditze, 2001, p. 1; Sabol, 2011, p 119), the time some countries, especially developing countries, take to assimilate and implement any change is very long, often over ten years. For instance, in Brazil the quantity *personal dose equivalent* is still at its introductory phase for individual measurements, while in other cases different quantities than the recommended operational quantities are still used (e.g., *exposure*, and *photon dose equivalent* – a transitory quantity) at many radioactive facilities. In the countries where the transition to the most recent quantities recommended by ICRP and IAEA is still not complete, it is understandable for the suggested alterations to the quantities to be seen as making the system unstable.

3. Conclusions

In the previous sections we discussed technical, scientific, and conceptual problems pointed out by scientists and professionals of RP. It became clear in discussing these problems that the decision-making processes are as complex as the scientific matter involved and as important as them in the conception of ways to improve the system. When talking about the decision-making process in the RP system, it is important to bear in mind that decisions taken by ICRP have an impact on national and international policies designed to set maximum permissible dose values. The level at which they are taken means that the scientific studies that inform them must also be evaluated from a social and political perspective. The diagram in Figure 1, taken from ICRP Publication 109, illustrates the complex political and scientific process involved in the ICRP recommendations.

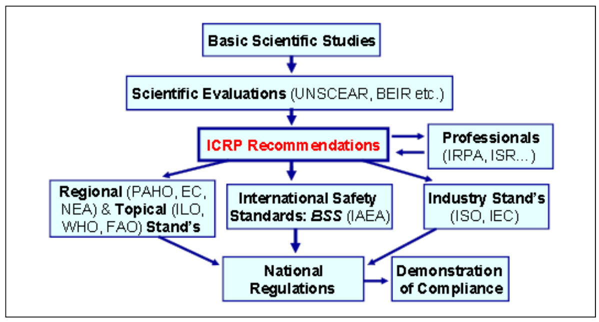

Figure 1: The basis for and use of ICRP recommendations on radiological protection policy (Clarke and Valentin, 2009, p. 102)

Extra-scientific concerns cannot be overlooked in the definition of quantities. For instance, defining a new quantity for ionizing radiation measurements in occupational settings means considering not only the scientific aspects of the definition, but also the human and technological resources available at the radioactive facilities around the world to undertake the measurements of the new quantity.

It should also be remembered that the economic issues associated with the cost/benefit ratio inherent to permissible dose limits underlie all discussions about the system and introduce biases to the institution of the system of quantities (Walker, 2000, p. 153-156). Even the cost/benefit of introducing the recommended system is a cause for concern on the part of countries that did not observe the previous recommendations (NEA, 2011, p. 3). The overlapping of several kinds of knowledge and of several different stakeholders makes the RP field complex in many respects and a big challenge for the scientific institutions involved. The dynamics of the process make the recommendations for RP an interesting theme for the philosophy of science, especially from the point of view of Science Studies.

Criticizing the ICRP's decision-making process, Ralph Thomas expresses concern that science is sidelined by political disputes over RP[16] (Thomas, 2005, p. 26). But is it really possible to clearly distinguish between science and politics in the resolutions and formulations of ICRU and ICRP documents? Do political actions and discussions weaken their rigor and precision or, considering the dynamics of RP, should we understand RP as being hybrid and complex, like all human enterprises? Are world views not always present in any proposal about what quantities to employ? In the quest for the improvement and stability of the system, other factors (usually considered external to nature, as they exist only due to human action) also come into play, such as scientific institutions, international organizations, and diplomatic conventions. These issues just make the RP quantities and units system more attractive for investigations focusing on its dynamics and on the values that underpin the words and actions of all its stakeholders.

Criticisms of the system oscillate between scientific (physical, mathematical, and even philosophical) rigor – typical of an academic perspective – and the priority due to the workplace, whose viewpoints are often overlooked by academia. It can be seen from the criticisms that the dissatisfactions expressed stem more from the scientists' different standpoints than their specific training/profession. Underlying these issues are epistemological problems that the community involved in RP, especially the international institutions responsible for the basic documents, would profit from recognizing and discussing. Is it possible to simultaneously address the concerns of the workplace and to improve the system's scientific rigor? There are also political issues in the decision-making processes of responsible institutions such as ICRP, ICRU and IAEA intertwined with epistemological issues. Finally, at the heart of these issues are the values that underlie all decision-making process.

The controversies discussed in the subsections of chapter 3 supply an overview of the problems (of a scientific or epistemological nature) raised by scientists about the system of quantities in units in RP and the problems (of a political nature relating to decision-making processes) in the dynamics of the establishment and review of this system. The roots of both types of problem can be traced to the *values* on which the different actors base their perspectives. The different levels of complexity involved in quantifying radiation and the risk of exposure could in part be responsible for the nagging presence of these problems and the somewhat unorthodox nature of the system. The problems raised by the current system make it clear that objective recourse to physical, chemical, and biological phenomena is not the way to overcome the disputes between the stakeholders. Some of the features of the current system are its normative aspect and the historical dynamics of its evolution. Some points of tension in the field of RP are clear: tensions between institutions responsible for defining the quantities, "regulatory" institutions, academia, and workplaces; tensions between scientific rigor and practical considerations; tensions between developed countries, with greater ease in introducing complex systems, and developing countries, where there are fewer material and human resources available for such an enterprise.

The idiosyncrasies of this system, with its two types of quantities, one of which is constituted of quantities that cannot be defined by experimental measurements, will surely continue to attract the criticism and admiration of the different actors involved in the field and remain an attractive yet challenging target of research for studies into the way this science should be operationalized.

Some of the postures and expositions of the scientists cited earlier in this article reveal pride at the refined construction of the system, which has been developed thanks to much hard work expended over several decades, for which reason the robustness of the system is stressed and all criticisms are assessed in the light of the qualities considered as intrinsic to the system. Finally, it is perceived that the problems call for conceptual discussions that the scientific community seems unwilling to engage in. Perhaps for this very reason, when it does so, in scientific articles, the treatment of some concepts generally exhibits very limited philosophical knowledge, which only goes to further complicate a situation that is already complex by nature.

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