Radioprotection 2019, 54(2), 103–109

https://doi.org/10.1051/radiopro/2019016

Available online at:
www.radioprotection.org

ARTICLE

The "As Low As Reasonably Achievable" (ALARA) principle: a brief historical overview and a bibliometric analysis of the most cited publications

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Received: 22 January 2019 / Accepted: 29 April 2019

Abstract – The "As Low As Reasonably Achievable" (ALARA) principle is largely followed in the radiology field. The current article provided a historical overview on the evolution and development of the ALARA principle and its related concepts. Meanwhile, the scientific impact of papers dealing with the ALARA principle was largely unknown. The current study aimed to identify the body of literature dealing with the ALARA principle, which of them were cited the most, and which of their references were cited the most. The Web of Science database hosted by Clarivate Analytics was accessed. Relevant papers were identified and analyzed. The search identified 979 relevant publications. Six journals (*Health Physics*, *Pediatric Radiology*, *Radiation Protection Dosimetry*, *Transactions of the American Nuclear Society*, *Fusion Engineering and Design*, and *American Journal of Roentgenology*) have accounted for nearly one-fifth of these publications. The most cited publications and references mainly related to two patient groups, children and pregnant women. It is important to adhere to the ALARA principle whenever a decision is made to irradiate a patient, because the exact effect of radiation on the patient health is not yet totally understood and predictable.

Keywords: as low as reasonably achievable (ALARA) / computed tomography / dose assessment / radiation protection / historical profile

1 Introduction

1.1 Historical overview

Ionizing radiation has a versatile role for diagnostic imaging. From plain radiographs, three-dimensional imaging by computed tomography (CT) or cone beam computed tomography (CBCT), to real-time videos by fluoroscopy, the discovery of X-rays by Wilhelm Röntgen has benefited countless patients and healthcare practitioners and is being utilized on everyday basis. Very soon after its discovery, concerns about its safety were raised, and there has been a need to address and continuously elaborate on radiation protection, to keep it in line with the development of knowledge of the biological effects of radiation. To balance the risks and benefits of using radiation for diagnostics, the International Commission on Radiologic Protection (ICRP) has introduced the "As Low As Reasonably Achievable" (ALARA) principle in 1977 (ICRP, 1977; Hendee and Edwards, 1986). In brief, the radiation exposures should be justified, optimized and below the allowable limits. The ALARA principle is coming from preceding philosophy and has been emphasized as our understanding towards medical physics progresses in the 21st century. The International X-ray and Radium Protection Committee (IXRPC) was founded in 1928 in Stockholm, Sweden to address the dangers of over-exposure to X-rays (and radium) and to establish an international standard of radiation protection. At that time, recommendations on working hours, shielding thickness and apparatus specifications were published. The ALARA principle was not officially born yet. It was worded as "screening examinations should be conducted as rapidly as possible with minimum intensities and apertures" and with "the use of protective shielding and safety rules" (IXRPC, 1929). This wording was continued to be used in 1934 and 1937 recommendations issued by IXRPC (IXRPC, 1934, 1938).

In 1950, IXRPC was renamed as International Commission on Radiological Protection (ICRP) and they "strongly recommended that every effort be made to reduce exposures to all types of ionizing radiations to the lowest possible level" (ICRP, 1951). This recommendation applied to not only X-rays and radium, but also beta and gamma radiations newly covered by ICRP at that time. Since then, ICRP introduced the notion that the radiation exposure should be kept "at the lowest

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practicable level/limit" or "as low as practicable" in its publications in the 1950s and emphasized this practicability since 1959 and early 1960s (ICRP, 1955, 1958, 1959, 1960, 1964). In 1966, ICRP further tuned the concept to be "as low as is readily achievable" (ICRP, 1966), which was finally shortened to become the renowned phrase of "as low as reasonably achievable" (ALARA) in 1977 (ICRP, 1977). At that time, however, ALARA did not stand alone: "social and economical consideration being taken into account" followed the phrase (ICRP, 1977). The principle has evolved so much during the century, as the usage of radiation has increased globally for research activities and daily clinical examinations, whereas the understanding of the radiation physics and its biological effects also improved over the years.

1.2 Bibliometric analysis

Though the ALARA principle has been introduced many years ago, and many publications have since mentioned it, the scientific impact of papers dealing with the ALARA principle was largely unknown. Unlike systematic reviews and meta-analyses that summarized and analyzed the study outcomes, a bibliometric analysis can evaluate the semantic content of the publications (usually the title, abstract, and keywords) to unveil the recurring words, as well as the identity of the contributors in terms of authorship, country, journal, journal category, and so on. Such an analysis can enable scientists to quickly identify the major research themes, heavyweight contributing factions, and journals in which they can look for relevant publications. Highly cited publications can also be identified for further reading and referencing. Therefore, the current study aimed to identify the body of literature dealing with the ALARA principle, which of them were cited the most, and which of their references were cited the most.

2 Methods

The Web of Science database hosted by Clarivate Analytics was accessed on 15 March 2018. A searched was performed with the following strategy: TOPIC = ("as low as reasonably achievable") OR TOPIC = (ALARA). The search would identify publications with either of the phrases within their titles, abstracts or keywords. The publication year, Web of Science category and document type of these publications were recorded. The top ten most cited publications were identified. Moreover, the cited references of the publications were analyzed with CRExplorer to construct a reference publication year spectroscopy (RPYS) (Marx and Bornmann, 2014; Marx *et al.*, 2014; Yeung, 2017; Yeung and Wong, 2019). RPYS could identify in which years important references were published so that the total citation count made to the references published in those years would be much higher than the preceding and succeeding years. By default, the magnitudes of the peaks of RPYS were the extent of deviation from the 5-year median. The most cited reference from each of the large positive peak was identified.

3 Results

The search yielded 979 publications (Fig. 1), in which 683 were original articles, 99 were meeting abstracts, 69 were reviews, 59 were proceedings papers, 48 were editorial materials, 17 were letters, three were reprints and one was a news item. Most of them were published in the journal categories of "Radiology, nuclear medicine/medical imaging" (476; 48.6%), "Nuclear science/technology" (358; 36.6%), "Public/environmental/occupational health" (210; 21.5%), "Environmental sciences" (204; 20.8%) and "Pediatrics" (99; 10.1%). It should be noted that these Web of Science categories were not mutually exclusive, so a publication could be classified into multiple categories.

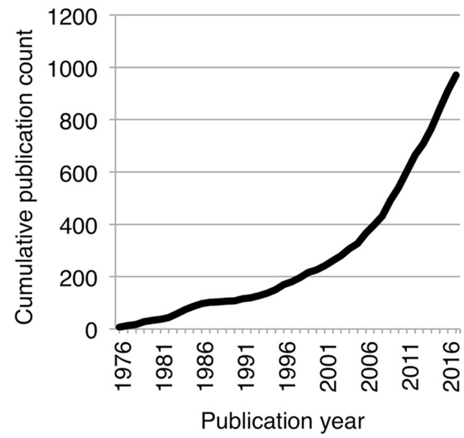

Fig. 1. The cumulative publication count of publications concerning the "As Low As Reasonably Achievable (ALARA)" principle. It could be observed that the annual publication count has increased since around 2005.

Journals that contributed at least 20 publications were *Health Physics* (125 papers; 2.2 citations per paper), *Pediatric Radiology* (66 papers; 22.4 citations per paper), *Radiation Protection Dosimetry* (40 papers; 4.7 citations per paper), *Transactions of the American Nuclear Society* (36 papers; 0.1 citations per paper), *Fusion Engineering and Design* (23 papers; 3.7 citations per paper) and *American Journal of Roentgenology* (20 papers; 15.4 citations per paper). Together, they have accounted for 18.9% of the 979 publications. Moreover, clinical journals among these had higher average citations per paper than their non-clinical counterparts.

The top ten most cited publications mentioning the ALARA principle are listed in Table 1. Half of them were dealing with radiation risks or management issues for pediatric ($n = 3$) or pregnant ($n = 2$) patients. The other half were concerning dosage reduction or raising the awareness of radiation safety.

Most of the cited references were published since the 1970s. The RPYS starting from 1950 is displayed in Figure 2. The five most prominent positive peaks were located in 1977, 1990, 1994, 1997 and 2002. The most cited references from each of the peaks are listed in Table 2. Two of them were ICRP Publications that gave recommendations on radiation protection. The other three were all concerning radiation risk and dose of pediatric patients.

No positive peak has a magnitude of over +10 before 1977. Those largest peaks with a magnitude of +5 or above were in 1954, 1959, 1968–1969. References published in these years with multiple citations from the 979 publications included the "Recommendations of the International

Table 1. The ten most cited publications concerning the "As Low As Reasonably Achievable (ALARA)" principle.

Rank	Publication	Citation count
1	Miglioretti DL *et al.* 2013. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatr.* 167(8): 700–707.	347
2	McCollough CH, Primak AN, Braun N, Kofler J, Yu L, Christner J. 2009. Strategies for reducing radiation dose in CT. *Radiol. Clin.* 47(1): 27–40.	346
3	Frush DP, Donnelly LF, Rosen NS. 2003. Computed tomography and radiation risks: What pediatric health care providers should know. *Pediatrics* 112(4): 951–957.	317
4	Brody AS, Frush DP, Huda W, Brent RL. 2007. Radiation risk to children from computed tomography. *Pediatrics* 120(3): 677–682.	298
5	Murphy MJ *et al.* 2007. The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75. *Med. Phys.* 34(10): 4041–4063.	266
6	McCollough CH, Schueler BA, Atwell TD, Braun NN, Regner DM, Brown DL, LeRoy AJ. 2007. Radiation exposure and pregnancy: When should we be concerned?. *Radiographics* 27(4): 909–917.	201
7	Patel SJ, Reede DL, Katz DS, Subramaniam R, Amorosa JK. 2007. Imaging the pregnant patient for nonobstetric conditions: Algorithms and radiation dose considerations. *Radiographics* 27(6): 1705–1722.	159
8	Hausleiter J *et al.* 2010. Image quality and radiation exposure with a low tube voltage protocol for coronary CT angiography: Results of the PROTECTION II Trial. *JACC: Cardiovasc. Imaging* 3 (11): 1113–1123.	145
9	Goske MJ *et al.* 2008. The 'Image Gently' campaign: Increasing CT radiation dose awareness through a national education and awareness program. *Pediatr. Radiol.* 38(3): 265–269.	135
10	Semelka RC, Armao DM, Elias J, Huda W. 2007. Imaging strategies to reduce the risk of radiation in CT studies, including selective substitution with MRI. *J. Magn. Res. Imaging* 25(5): 900–909.	115

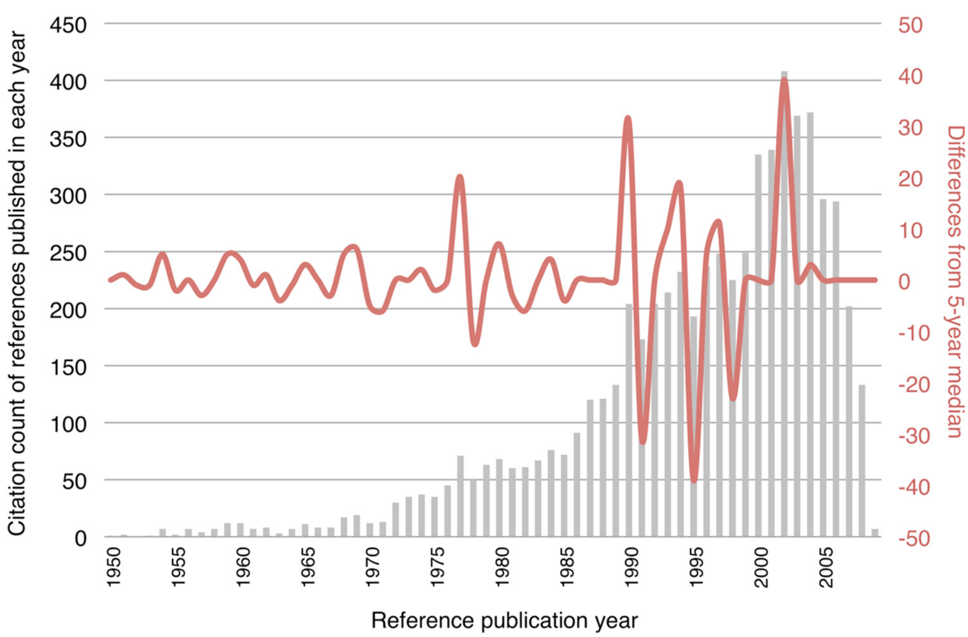

Fig. 2. The reference publication year spectroscopy (RPYS). It could be observed that years 1977, 1990, 1994, 1997 and 2002 have large positive peaks, meaning that the total citation count for references published each of these years was much larger than their preceding two and succeeding two years.

Commission on Radiological Protection. ICRP Publication 1" (1959; 3 citations), "Limits for qualitative detection and quantitative determination. Application to radiochemistry" by Lloyd A. Currie (1968; 2 citations; 2830 total citations), and "The question of radiation exposure to the hand from handling ^{99m}Tc" by C. M. Neil (1969; 2 citations; 13 total citations). The citation counts of the latter two papers were retrieved from another literature database, Scopus, because

Table 2. The most cited reference from each of the five largest positive peaks in the reference publication year spectroscopy (RPYS).

Year	Publication	Citation count (by the 979 ALARA publications)
1977	ICRP. 1977. Recommendations of the ICRP. ICRP Publication 26. *Ann. ICRP* 1(3).	8
1990	ICRP. 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. *Ann. ICRP* 21(1–3).	8
1994	Shu XO, Jin F, Linet MS, Zheng W, Clemens J, Mills J Gao YT. 1994. Diagnostic X-ray and ultrasound exposure and risk of childhood cancer. *Br. J. Cancer* 70(3): 531.	4
1997	Huda W, Atherton JV, Ware DE, Cumming, WA. 1997. An approach for the estimation of effective radiation dose at CT in pediatric patients. *Radiology* 203(2): 417–422.	6
2002	Brenner DJ. 2002. Estimating cancer risks from pediatric CT: Going from the qualitative to the quantitative. *Pediatr. Radiol.* 32(4): 228–231.	12

ALARA, "As Low As Reasonably Achievable".

Table 3. The ten most cited references of the 979 publications.

Year	Publication	Citation count (by the 979 ALARA publications)	Total citation count
2001	Brenner DJ, Elliston CD, Hall EJ, Berdon WE. 2001. Estimated risks of radiation-induced fatal cancer from pediatric CT. *Am. J. Roentgenol.* 176(2), 289–296.	32	1724
2001	Paterson A, Frush DP, Donnelly LF. 2001. Helical CT of the body: Are settings adjusted for pediatric patients?. *Am. J. Roentgenol.* 176(2): 297–301.	16	300
2000	Pierce DA, Preston DL. 2000. Radiation-related cancer risks at low doses among atomic bomb survivors. *Radiat. Res.* 154(2): 178–186.	15	442
2001	Donnelly LF *et al.* 2001. Minimizing radiation dose for pediatric body applications of single-detector helical CT: Strategies at a large children's hospital. *Am. J. Roentgenol.* 176(2): 303–306.	15	334
2007	Brenner DJ, Hall EJ. 2007. Current concepts – Computed tomography – an increasing source of radiation exposure. *N. Engl. J. Med.* 357(22): 2277–2284.	15	4175
2003	Frush DP, Donnelly LF, Rosen NS. 2003. Computed tomography and radiation risks: What pediatric health care providers should know. *Pediatrics* 112(4): 951–957.	14	319
2002	Brenner DJ. 2002. Estimating cancer risks from pediatric CT: Going from the qualitative to the quantitative. *Pediatr. Radiol.* 32(4): 228–231.	12	321
2003	Linton OW, Mettler FA Jr. 2003. National conference on dose reduction in CT, with an emphasis on pediatric patients. *Am. J. Roentgenol.* 181(2): 321–329.	11	248
1996	Pierce DA, Shimizu Y, Preston DL, Vaeth M, Mabuchi K. 1996. Studies of the mortality of atomic bomb survivors. Report 12, Part I. Cancer: 1950–1990. *Radiat. Res.* 146(1): 1–27.	10	607
2004	Lee CI, Haims AH, Monico EP, Brink J. A, Forman HP. 2004. Diagnostic CT scans: Assessment of patient, physician, and radiologist awareness of radiation dose and possible risks. *Radiology* 231(2): 393–398.	10	382

ALARA, "As Low As Reasonably Achievable".

they are not indexed in Web of Science. These papers are related to the quantitative measurement of radioactivity and hence related to the subsequently published ALARA papers.

Regardless of publication year, the ten most cited references of the 979 publications are listed in Table 3. All but one of them was published since the 2000s. Table 3 differs from Table 1, as the publications listed in Table 1 were the most cited ones by all publications (not confined to citations by ALARA publications only).

In addition, the keywords used by the authors of the 979 publications were analyzed. There were 292 keywords that appeared in more than 1 publication. The 25 commonest keywords are listed in Table 4. Several radiation concepts were found: radiation protection, radiation safety, operational

Table 4. The 25 commonest author keywords listed in the publications.

Keyword	Frequency
ALARA	110
Radiation protection	51
Radiation	50
Computed tomography	46
Radiation dose	45
Radiation exposure	38
Fluoroscopy	24
Children	21
Effective dose	18
Radiation safety	18
Operational topics	16
Dosimetry	15
Image quality	15
Risk assessment	15
Dose reduction	14
Optimization	14
Pediatric	14
Dose	13
Ionizing radiation	10
Ultrasound	10
Nuclear medicine	9
Cancer	8
Digital radiography	8
Nephrolithiasis	8
Quality assurance	8

topics, dosimetry, image quality, risk assessment, dose reduction, optimization, and quality assurance. Frequently mentioned imaging modalities were computed tomography, fluoroscopy, ultrasound, and digital radiography. While children were mentioned in 21 publications as keywords, pregnancy and fetus were mentioned as keywords in 5 and 4 publications respectively.

4 Discussion

The current study has revealed that most of the publications dealing with the "ALARA" principle were original articles. Half of them were from radiology, nuclear medicine/medical imaging journals and one-tenth were from pediatrics journals.

From the keyword analysis, radiation protection was the most popular topic. The awareness of radiation protection among various stakeholders varied. For instance, a survey on pediatricians reported that 15% of respondents were familiar with the ALARA principle, and 14% recalled relevant formal teaching from their former training (Thomas *et al.*, 2006). Another survey on non-radiologist clinicians reported that 37% of respondents attended a radiation protection course, and the majority was unsure of the relative radiosensitivity of different organs (Quinn *et al.*, 1997).

Relevant to radiation protection, dosimetry was another topic identified from keyword analysis. Publications have investigated the dosimetry in many aspects, such as concerning the eye lens, during neuroradiology procedures, and for pulmonary embolism (Alexander *et al.*, 2010; Schembri *et al.*, 2010; Carinou *et al.*, 2014). Because of the lack of the awareness of radiation protection by stakeholders who may involve in patient management, the "take home" message of these dosimetry studies should be made more assessible and visible to them.

Dose reduction and image quality were two other topics listed in Table 4 that were often related to each other. Scientists have investigated in various scenarios on how to reduce radiation dose while maintaining adequate image quality for diagnostics, such as the reduction of tube voltage or tube current-time product for CT scans (Hausleiter *et al.*, 2010; Tamm *et al.*, 2011), and a switch from analogue to digital radiography with the use of flat panel detectors (FPD) (Seibert, 2006; Schaefer-Prokop *et al.*, 2008).

The mostly concerned patient groups of the highly cited ALARA publications were pediatric and pregnant patients. This is reasonable as children are still growing up with rapid mitosis and thus a higher risk of cancer over the lifetime (Frush *et al.*, 2003; Miglioretti *et al.*, 2013). These messages were brought by papers ranked 1st and 3rd in Table 1. Meanwhile, the 6th ranked paper in Table 1 reported that various radiologic and nuclear medicine examinations produced small radiation doses to the embryo or fetus in general, which should produce minimal to negligible absolute risks of fetal effects (McCollough *et al.*, 2007).

The current results showed that the second-largest journal category of the ALARA publications was "Nuclear science/technology" (36.6%). A further examination found that actually half of them were published in journals categorized into both "Radiology, nuclear medicine/medical imaging", and "Nuclear science/technology". Only 175 publications were published in journals solely belonged to the latter. These publications covered a wide range of themes, with some of the more cited papers concerning topics such as a measurement of neutron dose distribution outside the treatment field of a passive scattering nozzle (Tayama *et al.*, 2006), a review on the physical aspects of X-ray detectors (Hoheisel, 2006), and a computational study that evaluated the best quantum energies for optimizing the image quality for digital breast tomosynthesis (Baptista *et al.*, 2014). Indeed, when the author keywords of this subset of 175 publications were examined, there were few keywords with multiple appearances, with the top ones being ALARA ($n = 13$), ITER (International Thermonuclear Experimental Reactor, $n = 10$), decommissioning ($n = 6$), Monte Carlo simulation ($n = 4$), and radiation protection ($n = 4$). The decommissioning papers dealt with the assessment and estimation of radiation exposure dose during decommissioning of nuclear facilities (Jeong *et al.*, 2014; Jeong *et al.*, 2016; Kim *et al.*, 2018).

Author keywords have indicated that radiation safety and effective dose have been important topics. The knowledge or guidelines of radiation biology and safety are changing from time to time. For instance, are the gonads highly radiosensitive? The tissue specific weighting factor for gonads have reduced from 0.25 in 1977 ICRP Publication 26, down to 0.20 in 1991 ICRP Publication 60, and further down to 0.08 in 2007

ICRP Publication 103. It remains to be elucidated if that means the gonads are actually exposed to a lower radiation risk than estimated in the past. Another aspect with rapid evolution is the computational phantoms used for radiation dosimetry or radiological science. It was observed that the phantoms had evolved from stylized phantoms based on quadratic equations since the 1960s, to voxel phantoms based on tomographic images since the 1980s, and to boundary representation (BREP) phantoms that are deformable and based on advanced primitives since the 2000s (Xu, 2014). The advanced technology applied to computational phantoms undoubtedly has allowed scientists to assess radiation dose more realistically and potentially in a more individualized way.

The adherence to the ALARA principle is coherent with the technology advancement that reduces medical radiation exposure to patients. In dentistry, the D-speed intra-oral X-ray films, which required a relatively high radiation dose, were popular in the 1970s, but were superseded by E-speed films in early 1980s and further by F-speed films in late 1990s (Farman, 2005). The use of newer generation intra-oral films has reduced radiation dose given to the patients. Moreover, the replacement of films by digital detectors made of phosphor plates or solid state devices further reduced the dose by at least 50% (Farman, 2005). The use of low dose protocols of dental CT is also relevant (Yeung *et al.*, 2019). These are some examples related to some of the frequently mentioned author keywords, such as dose reduction, and digital radiography.

One advantage of using the RPYS method was the ability to identify important references that were much more cited than references published in preceding and succeeding years. This is not possible by using the conventional citation count method, as readers may notice by comparing Tables 2 and 3. Table 2 actually gives the details from the peaks identified in Figure 2. All the information would be lost and unidentified by simply counting the citation number received by each publication, without accounting for the citation number of related publications in adjacent years.

This study has several limitations. First, publications not indexed by the Web of Science literature database were not included and analyzed in the current study. Second, the search strategy might have missed relevant publications that did not mention ALARA, but synonymous phrases with a regional popularity, such as "as low as reasonably practicable" (ALARP) used in the United Kingdom, and "so far as is reasonably practicable) (SFAIRP) used in the United Kingdom and New Zealand. Moreover, only the ALARA principle was considered, whereas there existed other principles or campaigns that promoted radiation awareness among specific target groups, such as the Image Gently campaign for minimizing radiation exposure in children that started in 2007 (Goske *et al.*, 2008) and similarly the Image Wisely campaign for adults that started in 2010 (Brink and Amis, 2010). In Europe, there is also the EuroSAFE Imaging campaign, as an initiative introduced in 2014 by the European Radiology Association (www.eurosafeimaging.org). Publications related to these campaigns might be missed from the analysis if they did not mention ALARA. Third, bibliometric analysis relies on the literature database to provide data labels or tags to code the publications, such as publication type, country of origin, and journal category. However, such labels are lacking to assess the study model, that is, if the publications were based on human, animal, phantom, or computations.

In overall, the above examples of conceptual and technological changes have illustrated the importance of continual adherence to the ALARA principle whenever a decision is made to irradiate a patient, because the exact effect of radiation on the patient health is not totally understood and predictable. Readers should also be aware of the fact that though ICRP historically first addressed the risks and health detriment associated to the medical use of radiation, the ALARA principle can have a much broader perspective for the protection of people as well as ecosystems.

5 Conclusion

Nearly 1000 publications about the ALARA principle were identified in this study. Those published in clinical journals had more citations per paper than those published in non-clinical journals. Several recurring radiation concepts were identified from author keywords, such as radiation protection, radiation safety, operational topics, dosimetry, image quality, risk assessment, dose reduction, optimization, and quality assurance. Frequently mentioned imaging modalities were computed tomography, fluoroscopy, ultrasound, and digital radiography. For papers concerning nuclear science and technology, a recurring theme was the monitoring of exposure dose of workers decommissioning nuclear facilities. Since some surveys indicated the lack of radiation protection awareness of various groups of healthcare workers, relevant campaigns such as the EuroSAFE Imaging should continue to be promoted.

IRB Statement

No IRB approval was required.

Acknowledgements. This work received no funding.

Conflicts of interest. The author declares that he has no conflicts of interest in relation to this article.

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Cite this article as: Yeung AWK. 2019. The “As Low As Reasonably Achievable” (ALARA) principle: a brief historical overview and a bibliometric analysis of the most cited publications. *Radioprotection* 54(2): 103–109