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Systematic Review

Analyzing the Reliability and Cost of the Most Commonly Used Dosimeters for Personal Ultraviolet Radiation Monitoring—A Rapid Review

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Abstract: To identify the most used dosimeters for monitoring ultraviolet radiation (UVR) and analyze their reliability and cost for individual UV exposure monitoring, this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. An extensive search of the PubMed, Scopus, and Web of Science databases, covering 2005–2023, was conducted, including examining reference lists of retrieved studies. Of the 1202 records, 52 were eligible for analysis. Three types of dosimeters were identified: photosensitive, photochromic, and electronic dosimeters. Photosensitive dosimeters were utilized for 1236 samples across the studies, while photochromic dosimeters were employed for 360 samples. Electronic dosimeters, with a sample size of 3632, were the most extensively studied. This study highlights the variety of resources available for UVR assessment and the significance of specific dosimeter types in this field. Although few studies have explored the costs associated with dosimeter use, electronic dosimeters are the most cost-effective for radiation monitoring and provide the highest accuracy for measuring UVR exposure. Electronic dosimeters, known for real-time data and high precision, are reliable but costly, being approximately 16.5 times more expensive than photosensitive dosimeters and 160 times more expensive than photochromic dosimeters. Photosensitive dosimeters suit large-scale personal use, and photochromic sensors such as polysulphone dosimeters are also reliable. Additional costs for data analysis software, laboratory equipment, or external analysis services may be incurred, especially for advanced research-grade sensors.

Keywords: ultraviolet radiation exposure; UV dosimetry; electronic dosimeters; photosensitive film dosimeters; photochromic dosimeters

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1. Introduction

Skin cancer is one of the most common types of cancer worldwide. Ultraviolet (UV) radiation (UVR) is one of the main risk factors for skin cancer development [1,2]. In recent years, the incidence of melanoma and non-melanoma skin cancers has increased substantially, making them a public health concern. Cutaneous malignant melanoma is a particularly dangerous type of skin cancer because of its high mortality rate. Studies have shown that intermittent and intense exposure to the sun, often associated with leisure and sports activities, can increase the risk of melanoma [2]. As such, melanoma and other types of skin cancers have become significant public health issues [3–8]. In contrast to intense and intermittent exposure to solar UVR, chronic and cumulative exposure is more related to the development of basal-cell carcinoma (BCC) and squamous-cell carcinoma (SCC), both types of non-melanoma skin cancer [9]. Various skin cancer awareness campaigns have been conducted to address this issue. These campaigns aim to educate the public about the risks associated with sun exposure and promote sun-protection behaviors [4,10]. Alongside these awareness initiatives, several studies have been conducted over the years to monitor personal exposure to solar radiation [11,12].

The extent of exposure to solar UVR varies considerably depending on the circumstances, thereby influencing the potential risk of sun exposure. Leisure activities such as sunbathing or eating outdoors often result in prolonged periods of exposure to solar radiation. On the other hand, occasional exposure occurs during everyday activities, such as traveling to work or running errands. Notably, multiple brief exposures accumulate over time. Certain professions, including construction, agriculture, and lifeguards, involve substantial outdoor work, leading to high levels of exposure to solar radiation. Similarly, athletes who practice outdoor sports such as running, cycling, and swimming often face intense and prolonged exposure to solar radiation [6,8]. Portable solar dosimeters have been developed to measure this exposure. These devices allow for the measurement of the amount of UVR that an individual is exposed to, helping to identify risk behaviors and promote effective sun protection [10].

The industry has responded to research needs in this area by manufacturing various types of portable dosimeters. These include electronic dosimeters [13], which provide digital measures of UVR exposure; film-based dosimeters [14], which use photosensitive films to measure radiation exposure; and photochromic dosimeters [15], which change color in response to UVR doses. Electronic dosimeters utilize electronic circuits to convert radiation energy into electrical signals that can be stored, processed and displayed [16–18]. They can measure both UVA and UVB radiation with high precision and sensitivity [19–23]. However, they also have limitations such as high cost, calibration requirements, susceptibility to temperature and humidity, and potential electromagnetic interference [16–18]. Film-based dosimeters use photographic or polymeric films to record the UVR exposure. These films change their optical density based on the received radiation dose, which can be measured using an optical reader [24–26]. Film-based dosimeters are simple, cost-effective, and user-friendly; however, they have drawbacks including angle-of-incidence dependence, material degradation, and the need for chemical processing [16–18]. Photochromic dosimeters employ materials that reversibly change color when exposed to radiation. Common materials include organic dyes incorporated into substrates such as paper, plastic, or fabric. Photochromic dosimeters are sensitive, selective, and visual indicators of UVR. However, they also face challenges such as saturation, hysteresis, susceptibility to visible light, and quantification difficulties [15,18,27,28]. Considering the growing variety of available dosimeters, it is crucial to assess which types are most commonly used and how they perform in terms of reliability and cost-effectiveness when monitoring individual UVR exposure. This study aims to provide an analysis that addresses these gaps in the current literature by identifying the most used dosimeters for monitoring UVR and analyzing their reliability and cost for individual UV exposure monitoring.

This investigation primarily aimed to ascertain the most frequently employed dosimeters for solar UVR monitoring. This is of critical importance, as UVR exposure presents a significant public health risk associated with skin cancer and other health implications, thus necessitating precise measurement. Furthermore, the substantial variability in solar UV radiation owing to environmental factors underscores the importance of utilizing reliable dosimeters to accurately quantify individual exposure. A secondary objective was to assess the reliability and cost associated with measuring personal UVR doses.

2. Materials and Methods

This study was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic literature reviews [29]. The PRISMA methodology is an internationally recognized framework that enhances the quality and transparency of systematic reviews [30]. This study has been registered with the Open Science Framework (OSF) with the Identifier DOI https://doi.org/10.17605/OSF.IO/PK57B, accessed on 13 December 2024. The registration includes all details of the rapid review protocol, ensuring transparency and reproducibility.

A comprehensive search string of titles and abstracts was defined and conducted to identify relevant articles published between January 2005 and October 2023. Specific keywords were used in combination with AND or OR Boolean operators to refine the searches. The literature search for this study was carried out in November 2023, utilizing three distinct databases to ensure comprehensive coverage of relevant publications: PubMed, Scopus, and Web of Science. The search string (Table 1) was carefully adapted for each database to maximize the relevance and breadth of the results.

Table 1. Database search string.

Database	Search String
Pubmed	((“ultraviolet rays” [Title/Abstract] OR “ultraviolet” [Title/Abstract] OR “UV” [Title/Abstract] OR “UVA” [Title/Abstract] OR “UVB” [Title/Abstract] OR “UV-A” [Title/Abstract] OR “UV-B” [Title/Abstract] OR “ultraviolet radiation A” [Title/Abstract] OR “ultraviolet radiation B” [Title/Abstract] OR “sunlight” [Title/Abstract] OR “solar uv” [Title/Abstract] OR “solar radiation” [Title/Abstract]) AND (“dosimeter*” [Title/Abstract] OR “dosimetry” [Title/Abstract]) AND “exposure” [Title/Abstract]) AND ((humans [Filter]) AND (english [Filter]) AND (2005:2023 [pdat]))
Scopus	((TITLE-ABS-KEY (“ultraviolet rays”) OR TITLE-ABS-KEY (“ultraviolet”) OR TITLE-ABS-KEY (“UV”) OR TITLE-ABS-KEY (“UVA”) OR TITLE-ABS-KEY (“UVB”) OR TITLE-ABS-KEY (“UV-A”) OR TITLE-ABS-KEY (“UV-B”) OR TITLE-ABS-KEY (“ultraviolet radiation A”) OR TITLE-ABS-KEY (“ultraviolet radiation B”) OR TITLE-ABS-KEY (“sunlight”) OR TITLE-ABS-KEY (“solar uv”) OR TITLE-ABS-KEY (“solar radiation”))) AND ((TITLE-ABS-KEY (“dosimeter*”) OR TITLE-ABS-KEY (“dosimetry”))) AND (TITLE-ABS-KEY (“exposure”)) AND PUBYEAR > 2005 AND PUBYEAR < 2023 AND (LIMIT-TO (LANGUAGE, “English”))
Web of Science	“ultraviolet rays” (Topic) or “ultraviolet” (Topic) or “UV” (Topic) or “UVA” (Topic) or “UVB” (Topic) or “UV-A” (Topic) or “UV-B” (Topic) or “ultraviolet radiation A” (Topic) or “ultraviolet radiation B” (Topic) or “sunlight” (Topic) or “solar uv” (Topic) or “solar radiation” (Topic) AND “dosimeter*” (Topic) or “dosimetry” (Topic) AND “exposure” (Topic) AND English (Languages) AND 2005–2023

Eligible studies encompassed original research, observational studies, clinical trials, and systematic reviews or meta-analyses involving the utilization of UV dosimeters to monitor UV radiation exposure in human populations such as outdoor workers and athletes. Studies employing photosensitive, photochromic, or electronic dosimeters were included, provided they measured UV radiation exposure. The inclusion criteria also included studies that assessed the accuracy, reliability, and feasibility of UV dosimeters in real-world settings. The inclusion criteria were subjects aged > 18 years who were exposed to occasional sunlight, solar exposure measurement systems, portable devices, portable dosimeters, and skin changes. Exclusion criteria were applied to studies that focused solely on laboratory-based experiments or theoretical models, without practical application to human subjects. Additionally, research articles that did not provide sufficient details on the methodology of UV exposure measurement, or those that failed to report quantitative results, were not considered in this review. Only articles published between January 2005 and October 2023 were considered, focusing on recent advancements in dosimeter technology. Articles published in English, Spanish, or Portuguese with full-text availability were included. Studies that reported the reliability, accuracy, and cost-effectiveness of UV dosimeters were included. Moreover, we included studies reporting data on the human population. The exclusion criteria included studies on children, pets, use of satellite-based estimation of solar exposure, field dosimeters, and UV light. Studies on other populations, study designs, or the use of unrelated measurement tools such as spectrometers or environmental instruments were excluded.

The data obtained in this study were processed using Covidence, an online tool that facilitates systematic reviews. This tool enables efficient data management, including the removal of duplicates. Initially, 2873 potentially relevant studies were identified, and

522 duplicates were removed, resulting in the screening of 2351 records [31]. After eliminating duplicates, three authors reviewed the abstracts to select the relevant articles for review. This process was conducted independently to ensure impartiality. The inclusion criteria were as follows: original research, observational studies, clinical trials, and systematic reviews or meta-analyses involving the use of UV dosimeters for monitoring UVR exposure in human populations such as outdoor workers and athletes. We included studies that used photosensitive, photochromic, and electronic dosimeters to measure UVR exposure. Additionally, studies assessing the accuracy, reliability, and feasibility of UV dosimeters in real-world settings were included.

Exclusion criteria were applied to studies that focused solely on laboratory-based experiments or theoretical models without practical application to human subjects. Research articles that did not provide sufficient details on the methodology of the UV exposure measurement or those that failed to report quantitative results were also excluded. Only articles published between January 2005 and October 2023 in English, Spanish, or Portuguese, with full-text availability, were considered.

In cases of conflict or discrepancies in article selection, the three authors convened to reach consensus. This collaborative approach ensured that the final decision regarding the articles was to be included in the review.

3. Results

The selected articles (n = 125) were subjected to a thorough full-text review to assess their eligibility for inclusion in this study. During this phase, the authors carefully evaluated each article according to predetermined inclusion and exclusion criteria. After this detailed review, 73 articles were excluded, resulting in 52 articles being selected for the final analysis. Any disagreements that arose during this process were resolved through discussion and mutual agreement among the reviewers, ensuring a comprehensive and unbiased selection of studies for the final analysis. This process is illustrated in Figure 1, which provides a detailed flowchart of the study selection process in accordance with PRISMA guidelines.

The studies included in this review were published between 2008 and 2023 and spanned different countries and continents. The majority of the studies were cross-sectional (27) [8,15,19,24,26,28,32–52], followed by cohort studies (7) [22,23,53–57], experimental studies (6) [14,25,27,58–60], others (6) [13,20,21,61–63], systematic reviews (4) [16–18,64], case–control studies (1) [65], and case reports (1) [66]. Appendix A summarizes the study characteristics, including the year of publication, country of origin, study type, number of participants, type of measured UVR, and type of dosimeter used. Not all studies unequivocally reported the type of radiation measured (UVA/UVB) with a solar radiation dosimeter.

In this review, three types of dosimeters have been identified: photosensitive, photochromic, and electronic. Photosensitive dosimeters were used in a sample of 1236 participants across diverse study designs, such as “cross-sectional studies” (2) [24,26], “cohort study” (1) [56], and “experimental study” (3) [14,25,60]. Photochromic dosimeters were used in a sample of 360 participants, including in “cross-sectional studies” (7) [15,28,43,47–50], “experimental studies” (3) [27,58,59], and “case report” (1) [66]. The electronic dosimeter was the most utilized, with a sample size of 3632 participants, encompassing “cross-sectional studies” (18) [8,19,32–42,44–46,51,52], “cohort studies” (6) [22,23,53–55,57], and “other” study designs (6) [13,20,21,61–63]. Additionally, a sample of 41 was studied in “systematic reviews” (4) [16–18,64] and a “case report” (1) [66].

Among these dosimeters, electronic dosimeters are the most widely used, with six different commercial brands identified: GENESIS-UV (1559) [8,13,20–22,35–39,44,46,51,53,61,62], MarkII (146) [40,52], Scienterra (1204) [19,34,46,57,65], Shade (39) [31], SunSaver (672) [41,42,54,55], and University of Canterbury Department of Electrical and Computer Engineering, Canterbury, New Zealand (12) [23,33,63]. Film-based dosimeters are represented by two commercial brands: EBT3 UV (16) [14] and polysulphone dosimeters (1220) [24,25,56,60]. Finally, the photochromic dosimeters were associated with four commercial brands: colorimetric UV film dosimeter (NR) [27], UV Patch (11) [59], UV sensor JEC1-IDE (62) [58], and VioSpor

(Biosense) (287) [15,28,43,47–50,66]. These findings highlight the diversity of tools available for measuring UV radiation and the prevalence of specific brands within the field of study. The following table (Table 2) summarizes the studies by "commercial brand", number of studies, sample size, exposure type, measured UVR, sensitivity, and dosimeter type.

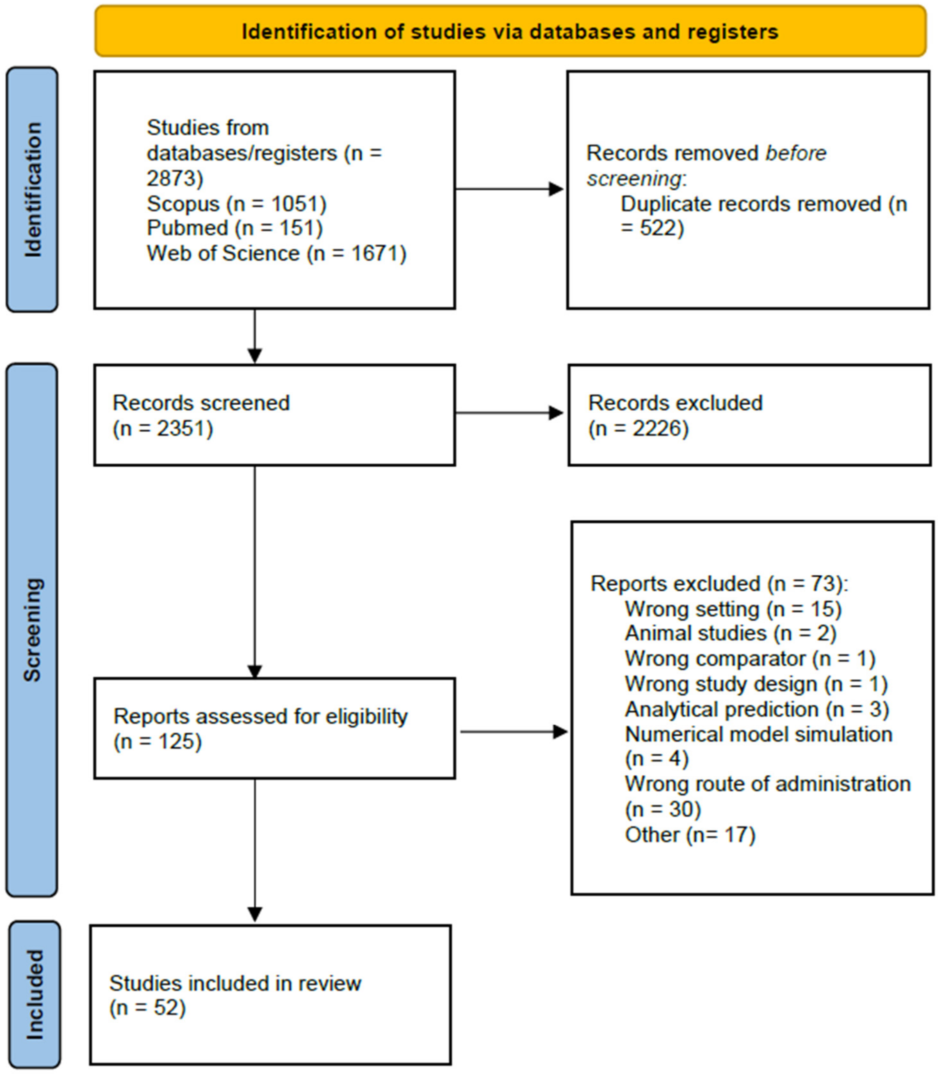

Figure 1. PRISMA flow diagram of the study selection process [29].

Table 2. Characteristics of studies according to dosimeter brand.

Brand	Studies	Sample	Exposure	UV Measured	Sensitivity	Dosimeter Type
GENESIS-UV	16	1559	Occupational (14) Leisure (1) Occasional (1)	UVA (2) NR (1) UVA/UVB (13)	200–800 nm (2) 280–320/320–400 nm (2) NR (12)	Electronic Dosimeter
Mark II	2	146	Occupational (2)	NR (1)	295–325 nm (1)	Electronic Dosimeter
Scienterra	5	1204	Occupational (3) Leisure (1) NR (1)	NR (2) UVB (2) UVA/UVB (1)	>320 nm (2) NR (3)	Electronic Dosimeter

Table 2. *Cont.*

Brand	Studies	Sample	Exposure	UV Measured	Sensitivity	Dosimeter Type
Shade	1	39	Leisure (1)	UVA/UVB (1)	NR (1)	Electronic Dosimeter
SunSaver	4	672	Occupational (2) Leisure (2)	UVA/UVB (1) NR (3)	NR (1)	Electronic Dosimeter
University of Canterbury Department of Electrical and Computer Engineering, Canterbury, New Zealand	3	12	Occupational (1) Sports (1) Occasional, Leisure, Occupational and Sports (1)	UVB (1) UVA/UVB (1) NR (1)	NR (1) 290–400 nm (2)	Electronic Dosimeter
Colorimetric UV film dosimeter	1		NR (1)	UVB (1)	NR (1)	Photochromic dosimeter
UV Patch	1	11	Leisure (1)	UVA/UVB (1)	NR (1)	Photochromic dosimeter
UV sensor JEC1-IDE	1	62	NA (1)	NA (1)	NR (1)	Photochromic dosimeter
VioSpor (Biosense)	8	287	Occupational (5) Sports (3)	UVB (6) NA (1) UVA/UVB (1)	NR (4) 280–400 nm (4)	Photochromic dosimeter
Polysulphone dosimeter	4	1220	Occupational (1) NR (4)	UVB (2) NR (3)	1–300 nm (1) 295–320 nm (1)	Film-based dosimeter
EBT3 UV	1	16	NR (1)	UVA/UVB (1)	280–400 nm (1)	Film-based dosimeter
Others	4	40	NA (4)	UVA/UVB (1) NR (3)	280–320/320–400 nm (1) NR (3)	

Key: NR—not reported in the study.

None of the experimental studies provided the associated costs of using these dosimeters. However, Henning et al. [16] indicated that the cost of each dosimeter varies. Electronic dosimeters range from USD 300 to 500, while photosensitive dosimeters vary from USD 0.5 (polysulphone film) to USD 48 (VioSpor). Photochromic dosimeters have a usage cost between USD 1 and USD 4 [17].

4. Discussion

Other reviews in this field of study have provided valuable insights into UV dosimeters and sensors. This review focused on identifying the most frequently used dosimeters for UVR monitoring. Additionally, it evaluated the reliability and cost of these dosimeters, addressing the substantial variability in UVR due to environmental factors, which are not comprehensively covered in existing reviews. This targeted approach aimed to offer practical recommendations for accurate and cost-effective UVR dose measurements, making it an essential resource for researchers and public health professionals.

In this study, 52 articles were analyzed to identify the most commonly used dosimeters for monitoring UVR. The analyzed articles employed three main types of dosimeters: electronic, photosensitive film, and photochromic. In five [16–18,64,65] studies, the dosimeter type was not specified.

Of the 52 studies, 30 utilized electronic dosimeters [8,13,19–23,32–42,44–46,51–55,57,61–63], 6 used photosensitive dosimeters [14,24–26,56,60], and 11 employed photochromic dosimeters [15,27,28,43,47–50,58,59,66]. These results indicate that photosensitive dosimeters are widely used in experimental studies, with a significant sample size of 1236. However, the number of cross-sectional [24,26] and cohort studies [56] conducted using this type of dosimeter is relatively low.

In contrast, photochromic dosimeters, despite having a smaller sample size of 360, have a higher number of cross-sectional study designs [15,28,43,47–50]. This suggests that photochromic dosimeters may be particularly useful in cross-sectional studies.

4.1. Electronic Dosimeters

The widespread use of electronic dosimeters in research underscores the importance of accurately measuring and monitoring the exposure to UVR. These instruments detect UVA and/or UVB radiation and provide real-time readings or data transfer for specific applications [23,52,55,63]. This functionality facilitates rapid analysis and monitoring, which is particularly advantageous in variable environments, where exposure to UVR can fluctuate rapidly. The utility and adaptability of these dosimeters are enhanced by their capacity to be worn as wristwatches or affixed to clothing or various anatomical sites, rendering them suitable for diverse research purposes [20–22]. However, electronic dosimeters have limitations that warrant further investigation. The dependence on electronic components renders these dosimeters susceptible to technical malfunctions or power failures, which may compromise the reliability of the data. Furthermore, although the capability to transfer data to applications is beneficial, it requires compatibility with specific software and devices, potentially limiting its applicability in certain research contexts [44–46]. In addition, deviations from the ideal erythema action spectrum can introduce errors, particularly when measuring solar spectra that differ from the calibration spectrum. Another consideration is the cosine response, as the dosimeter measures UVR less than anticipated owing to an imperfect cosine response [23,52,55,63]. This is partially compensated during calibration; however, discrepancies persist between the calibration setup and real-world applications. Furthermore, temperature dependency affects the dosimeter (sensor and electronics) because it is influenced by temperature fluctuations, which can affect measurements. Most electronic dosimeters do not continuously measure the UVR, thereby introducing uncertainty. Nevertheless, with a 5 s sampling interval, the maximum deviation was determined to be only 1.5% in short-term studies. Despite these uncertainties, when compared to a well-established Solar Light UV501 m over a 31-day period with varying weather conditions, the developed dosimeters demonstrated good reliability, with daily dose variations within approximately +3 to −4%. This suggests that electronic UVR dosimeters can provide reliable measurements for personal UV exposure studies, particularly when utilized over extended periods where fluctuations tend to average [58].

4.2. Photosensitive Dosimeters

Photochromic dosimeters, particularly those utilizing photosensitive films, were employed in six studies, totaling 1236 measurements. These dosimeters can measure both UVA and UVB radiation and provide comprehensive data on UVR exposure. This dual capability is essential for studies that require detailed information on different types of UVR, enhancing the depth and accuracy of the research findings [25,56,60].

One of the significant advantages of these dosimeters is the utilization of polysulphone films (PSF), which were employed in five studies with 1220 measurements. Polysulphone films are characterized by their stability and sensitivity to UVR, rendering them a reliable choice for dosimetry. Their efficacy in capturing UVR data has been demonstrated in several studies, indicating their suitability for various research applications [24,26].

PSF dosimeters are generally reliable for measuring UVR exposure; however, they have some notable limitations that warrant consideration. First, they only measure the cumulative UV exposure and lack temporal resolution. Additionally, PSF dosimeters are insensitive to radiation at wavelengths greater than 340 nm. They also have a limited angle of view when housed in a dosimeter badge, which can affect the measurements at larger angles of incidence. Furthermore, PSF dosimeters tend to overestimate exposure compared with electronic dosimeters, especially at near-perpendicular incidence. Their spectral response curve differs slightly from the CIE erythema function, necessitating diurnal and annual correction factors [25,56,60].

Moreover, these dosimeters require laboratory measurements to obtain UVR exposure data. This process is time-consuming and requires specialized equipment and expertise, potentially increasing the cost and complexity of studies. The requirement for laboratory analysis introduces the possibility of human error or equipment malfunction, which can affect the accuracy of data [24,26].

The calibration of PSF dosimeters involves several steps and considerations, each of which presents its own limitations. First, spectroradiometric control is essential because PSF dosimeters are typically calibrated against a homogeneously radiating half-space that remains constant over time. This ensures consistency but can be challenging to maintain. Additionally, because the PSF is insensitive to wavelengths above 340 nm, the UVA portion of the spectrum must be extrapolated during the calibration process, typically using the sun spectrum. This extrapolation can introduce errors [56,60].

The optical properties of the PSF were measured before and after exposure, and the difference between these values was used as a measure of exposure. This step requires precise optical absorbance measurements, which is technically demanding. Correction factors were then applied to yield the biological effectiveness of UVR by adding another layer of complexity.

The angular response of PSF dosimeters, especially when housed in batches, must be considered during calibration, as it affects measurements at different angles of incidence. Furthermore, due to the slight difference between the PSF response curve and CIE erythema function, diurnal and annual correction factors need to be applied to ensure accuracy over time [25].

Finally, the calibration should be traceable to national or international standards to ensure comparability with other dosimeter types. This traceability is crucial; however, it can be difficult to achieve without specialized equipment and expertise. Overall, the calibration process for PSF dosimeters is complex and requires careful attention to ensure accurate and reliable measurement [26].

Despite these limitations, PSF dosimeters are still widely used and are considered reliable for many applications, particularly for mass measurements, because of their relatively low cost and mechanical robustness. However, for more detailed or long-term studies, electronic dosimeters may offer advantages in terms of data resolution and reproducibility [26,60]. The requirement for laboratory analysis introduces the possibility of human error or equipment malfunction, which can affect data accuracy.

4.3. Photochromic Dosimeters

Photochromic dosimeters, while not directly quantifying UVR exposure, indicate exposure levels through color change. This visual feedback can be particularly beneficial for individuals who require rapid and intuitive comprehension of their UVR exposure without the need for complex data interpretation [27,59,66].

The primary advantage of photochromic dosimeters is their simplicity and ease of use. The color-change mechanism enables users to readily monitor their UVR exposure in real time, rendering these dosimeters highly accessible and user-friendly. This feature is especially advantageous in environments in which immediate feedback is crucial for preventing overexposure to UVR [43,47–50].

However, this type of dosimeter has some limitations. The primary drawback is that photochromic dosimeters do not provide precise quantitative data on the UVR levels [15,28]. The absence of detailed measurements can be a significant limitation of scientific studies that require exact exposure data for analysis. Additionally, the accuracy of color change can be influenced by various factors such as the intensity and duration of UV exposure, potentially leading to variability in the results.

Despite these limitations, photochromic dosimeters appear highly reliable. Studies have conducted extensive validation and comparisons with established electronic UV dosimeters to ensure accuracy [27,43,47,59,66]. Key points include a strong correlation with Scienterra electronic dosimeters, which are widely used in research to measure personal UV exposure. Statistical analysis demonstrated high correlations between the UVA levels measured by Scienterra dosimeters and photochromic dosimeters picture analysis, UV sensor patch app readings and patch picture analysis, and Scienterra dosimeter readings and UV sensor patch app readings [15,27]. The total UV dose, including both UVA and UVB, measured by the Scienterra dosimeter and patch image analysis, was also highly correlated. Furthermore, photochromic dosimeters maintain accurate readouts even after exposure to challenging conditions such as ocean water, high heat and humidity, excessive sweat, skin care products, and sunscreens. The patch was calibrated against instruments at solar irradiance monitoring stations and compared with radiative transfer calculations using established radiation models. These multiple validation steps and strong correlations with existing reliable methods suggest that photochromic dosimeters are quite reliable for measuring personal UV exposure [15,27,66].

4.4. Cost of Dosimeters

Electronic dosimeters are the most expensive despite being the most commonly used dosimeters. However, their ability to detect UVA and UVB radiation and provide real-time measures justifies their high costs. Additionally, their versatility (worn as wristwatches or attached to clothing) enhances their practicality [17].

Although photosensitive dosimeters are used less commonly than electronic dosimeters, they are significantly less expensive. Their ability to measure both UVA and UVB is advantageous, but the need for laboratory measurements may be inconvenient [16,17].

Photochromic dosimeters, while not directly quantifying UV exposure, inform users of color changes. This feature is particularly useful for individuals requiring constant monitoring of UV exposure [15,27,28,58].

Nonelectronic UVR dosimeters, such as PSF and biological dosimeters, have several limitations that increase the overall cost of the measurement process. These limitations include the need for specialized laboratory equipment and trained personnel for analysis as well as the time-consuming nature of data retrieval and processing. Additionally, nonelectronic UVR dosimeters typically provide cumulative exposure measurements, making it challenging to obtain real-time or high-resolution temporal data [16]. The lack of immediate feedback and potential for data loss during transport or storage further contribute to the inefficiencies and increased costs associated with these traditional dosimetry methods. These dosimeters are single-use and require disposal after each measurement, incurring continuous replacement costs. The evaluation process requires them to be returned to the manufacturer for analysis in addition to their complexity and expense. Identifying defects or errors in individual nonelectronic dosimeter units presents significant challenges, potentially leading to measurement uncertainties and additional costs. Moreover, nonelectronic dosimeters provide only cumulative UV exposure data for the entire measurement period without temporal resolution, limiting the granularity of the data collected [16,17]. In contrast, electronic dosimeters are reusable, facilitate immediate data evaluation, and detect and correct variations in individual units, making them more cost-effective and efficient [17].

4.5. Selection of Dosimeter for Types Studies

The selection of a UV dosimeter depends on the study design and specific objectives, particularly in terms of accuracy, feasibility, and cost-effectiveness. Different dosimeters offer distinct advantages and limitations, depending on the type of study.

For observational studies that require long-term monitoring of large populations, electronic dosimeters appear to be the most suitable option because of their high accuracy and ability to provide continuous digital measurements of UV exposure. These dosimeters are ideal for studies in which detailed real-time data collection is essential, such as studies assessing occupational exposure in outdoor workers. Additionally, their data-logging capabilities make them suitable for longitudinal studies where cumulative UV exposure must be tracked over extended periods. While electronic dosimeters can be more expensive than other types of dosimeters, their reliability and precision justify their use in studies where accurate measurements are critical. Photochromic dosimeters are advantageous in interventional studies, particularly those that require comparison of UV exposure before and after a specific intervention (e.g., UV-blocking clothing or sunscreen efficacy). These dosimeters change color in response to UVR, thereby providing a simple and intuitive method for visualizing UV exposure. Their cost-effectiveness and ease of use make them suitable for studies involving participant compliance or behavior modification, in which simplicity and user engagement are key. However, their lower accuracy compared to that of electronic dosimeters may be a drawback in studies that require precise quantitative measurements. For cross-sectional studies, where UV exposure is measured at a single point in time or over a short period, photosensitive dosimeters (such as polysulphone films) may be sufficient. These dosimeters are cost-effective and provide reliable short-term measurements, making them suitable for studies with limited resources or those focused on capturing the UV exposure during specific activities or events. While they lack the data-logging capabilities of electronic dosimeters, their simplicity and low cost make them viable options for small-scale studies with a well-defined scope.

5. Conclusions

This study identified the most commonly used dosimeters for personal UVR monitoring, classifying them based on their construction and operation as photosensitive, photochromic, and electronic dosimeters. The distinct characteristics of each dosimeter type, including the physical aspects, technology used, UVR monitoring mode, and software utilization for data collection, allow for the broad applicability of these devices.

Dosimeters are available for various purposes ranging from raising awareness UVR exposure (where users are alerted to color changes in the dosimeter, as observed in photochromic dosimeters) to more detailed analyses of individual exposure with multiple Measurements conducted throughout the day.

The technology employed and method of data collection influence the cost and accuracy of the results. Despite limited research on the costs associated with dosimeter use, it remains clear that electronic dosimeters are the most cost-effective options for radiation monitoring. However, they are also the most precise in measuring UVR exposure. These devices were the most frequently used in the 30 analyzed studies, totaling 3632 measurements conducted across 52 studies. This demonstrates a significantly higher usage frequency compared to photochromic and photosensitive dosimeters, with values 2.8 times and 5 times higher, respectively, than those of photochromic and photosensitive dosimeters.

The versatility of electronic dosimeters allows for their application in cohort and cross-sectional studies, enabling quantification of exposure in occupational, leisure, occasional, and sports contexts. Although cohort studies provide long-term group tracking, cross-sectional studies provide immediate information regarding exposure and outcomes. Therefore, electronic dosimeters have been proven to be more reliable for measuring radiation exposure.

Future research should evaluate the three types of dosimeters (photosensitive, photochromic, and electronic) to determine the accuracy with which they measure the integrated spectrum of UVA/UVB radiation and the extent to which this corresponds to the erythemal action spectrum. This evaluation will contribute to a more comprehensive understanding of UVR exposure and enhance the accuracy and applicability of dosimeter data, thereby providing a more thorough assessment of UVR exposure.

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Appendix A

Table A1. Characteristics of the included studies.

Year	Country	Type of Study	Sample	UVA/UVB	Type of Dosimeter
2008 [59]	USA	Experimental study	11	UVA/UVB	Photochromic dosimeter
2010 [43]	Spain	Cross-sectional study	5	UVB	Photochromic dosimeter
2010 [46]	Austria	Cross-sectional study	12	UVA/UVB	Electronic dosimeter
2011 [47]	Spain	Cross-sectional study	10	UVB	Photochromic dosimeter
2011 [24]	Italy	Cross-sectional study	32	N/R	Film-based dosimeter
2012 [25]	Germany	Experimental study		N/R	Film-based dosimeter
2013 [41]	Denmark	Cross-sectional study	25	N/R	Electronic dosimeter
2013 [49]	Spain	Cross-sectional study	8	UVB	Photochromic dosimeter
2014 [55]	Denmark	Cohort study	152	UVA/UVB	Electronic dosimeter
2014 [21]	Italy	Other	7	UVA/UVB	Electronic dosimeter
2014 [20]	Italy	Other	6	UVA/UVB	Electronic dosimeter
2014 [48]	Spain	Cross-sectional study	15	UVB	Photochromic dosimeter
2014 [60]	Italy	Experimental study		UVB	Film-based dosimeter
2014 [26]	Australia	Cross-sectional study	1002	N/R	Film-based dosimeter
2014 [50]	Spain	Cross-sectional study	11	UVB	Photochromic dosimeter
2015 [54]	Denmark	Cohort study	397	N/R	Electronic dosimeter
2015 [66]	Spain	Case report	1	UVB	Photochromic dosimeter
2015 [57]	Denmark	Cohort study	205	N/R	Electronic dosimeter
2015 [63]	South Africa	Other	2	UVB	Electronic dosimeter
2015 [42]	Denmark	Cross-sectional study	98	N/R	Electronic dosimeter
2016 [33]	Serbia	Cross-sectional study		N/R	Electronic dosimeter
2016 [65]	Australia	Case–control study		UVA/UVB	N/A
2016 [52]	Canada	Cross-sectional study	73	UVB	Electronic dosimeter
2017 [19]	Denmark	Cross-sectional study	350	UVB	Electronic dosimeter
2017 [61]	Romania	Other	6	UVA/UVB	Electronic dosimeter
2017 [64]	Malaysia	Systematic review		UVA/UVB	N/A
2018 [34]	Denmark	Cross-sectional study	457	UVB	Electronic dosimeter
2018 [27]	USA	Experimental study		UVB	Photochromic dosimeter
2019 [32]	USA	Cross-sectional study	39	UVA/UVB	Electronic dosimeter
2019 [58]	Denmark	Experimental study	62	N/R	Photochromic dosimeter
2019 [56]	China	Cohort study	186	UVB	Film-based dosimeter
2019 [39]	Italy	Cross-sectional study	7	UVA/UVB	Electronic dosimeter
2020 [53]	England	Cohort study	312	UVA	Electronic dosimeter
2020 [35]	Italy	Cross-sectional study	14	UVA	Electronic dosimeter
2020 [36]	Italy	Cross-sectional study	3	UVA/UVB	Electronic dosimeter
2020 [37]	Croatia	Cross-sectional study	4	UVA/UVB	Electronic dosimeter
2020 [38]	Italy	Cross-sectional study	3	UVA/UVB	Electronic dosimeter
2020 [62]	Romania	Other	10	UVA/UVB	Electronic dosimeter
2020 [40]	Canada	Cross-sectional study	73	N/R	Electronic dosimeter
2020 [45]	Canada	Cross-sectional study	192	N/R	Electronic dosimeter
2020 [14]	Malaysia	Experimental study	16	UVA/UVB	Film-based dosimeter
2020 [8]	Germany	Cross-sectional study	33	UVA/UVB	Electronic dosimeter
2021 [16]	USA	Systematic review	13	UVA/UVB	N/A
2021 [18]	New Zealand	Systematic review	14	UVA/UVB	N/A
2021 [15]	Spain	Cross-sectional study	109	UVA/UVB	Photochromic dosimeter

Table A1. *Cont.*

Year	Country	Type of Study	Sample	UVA/UVB	Type of Dosimeter
2022 [23]	Bulgaria	Cohort study	10	UVA/UVB	Electronic dosimeter
2022 [22]	Germany	Cohort study	75	UVA/UVB	Electronic dosimeter
2022 [17]	USA	Systematic review	13	UVA/UVB	N/A
2022 [44]	Colombia	Cross-sectional study	37	N/R	Electronic dosimeter
2023 [28]	Spain	Cross-sectional study	128	N/R	Photochromic dosimeter
2023 [13]	Portugal	Other	30	UVA/UVB	Electronic dosimeter
2023 [51]	Germany	Cross-sectional study	1000	UVA/UVB	Electronic dosimeter

Key: N/R—not reported in the study; N/A—not assessable.

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