



International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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DOI 10.25039/x051.2025/62xbgg

This article is also published as part of:

Proceedings of the CIE 2025 Midterm Meeting Vienna, Austria, July 4-11, 2025:
Scientific Conference (July 7-9, 2025)

DOI 10.25039/x051.2025

in

Proceedings of the CIE (International Commission on Illumination)

ISSN no. 3061-015X (print), 3061-0168 (online)

The paper has undergone double-blind peer review and its final version has been presented at the CIE 2025 Midterm Meeting, Vienna, Austria, July 4–11, 2025.

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CHARACTERISING INTER-INDIVIDUAL VARIABILITY IN SIMULATED PERSONAL LIGHT EXPOSURE: IMPACT OF BODY MORPHOLOGY ON LIGHT-DOSIMETRY

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Abstract

Recordings of personal light exposure, i.e. the illumination received at the eye(s) over time, are valuable for research on human health and well-being. To record these patterns, light-dosimeters (sensors) are worn on the body, acting as a proxy for measurements at the eye. Chest-worn dosimeters have become more utilised in recent years since this position strikes a balance between measurement accuracy and unobtrusiveness for the wearer. Although various studies investigated differences between chest and eye-level measurements, much remains unknown about the inter-individual variability in chest-worn dosimeter measurements. Here, we demonstrate how an individual's body shape impacts chest-worn dosimeter measurements using body scans of approximately three thousand individuals. Dosimeters placed on the upper chest show the most consistent device orientations and measurements across individuals. At this position, dosimeter measurements relative to the eyes, are within a 20 % spread for half of the population, with a maximum range up to 79 %.

Keywords: Light-Dosimetry, Personal Light Exposure, Chest, Dosimeter, Light Sensor, Measurement Accuracy

1 Introduction

Often referred to as the non-image forming (NIF) effects of lighting, personal light exposure (PLE) is known to impact human health and well-being (Lucas et al., 2014). To investigate the potential for NIF effects, recordings of the intensity and spectrum of PLE are needed. In real world settings, this is typically achieved using light-dosimetry, a method in which subjects wear a small light sensor on the body, referred to as a dosimeter. Dosimeters typically measure (planar) illuminances or irradiances, i.e. the integral of the cosine projected hemispherical luminance or radiance. Light-dosimetry has been applied in various studies, for example, for investigations on the variations in PLE patterns across different populations (van Duijnhoven et al., 2021; Peeters et al., 2020), associations between PLE and myopia development (Read et al., 2014, 2018), and links between PLE and NIF outcomes through a variety of physiological and behavioural markers (Figueiro et al., 2019; Didikoglu et al., 2023; Hubalek et al., 2010; Figueiro et al., 2017; Aries et al., 2024).

1.1 Proxy for illumination at the eyes

A dosimeter worn on the body of a subject acts as a proxy for measuring actual illumination at the eyes and hence, ideally, should be worn as close to the eyes as possible, e.g. at the side of the head attached to glasses (Hartmeyer et al., 2023; de Vries et al., 2025). However, in practice, dosimeters are often worn elsewhere on the body. Commonly used positions in light-dosimetry field studies are the wrist (similar to wearing a watch) and the chest (as a pendant or clip) (Hartmeyer et al., 2023). The differences between simultaneously measured illumination at both of these positions have been previously investigated and compared to actual illumination at the eyes (Okudaira et al., 1983; Figueiro et al., 2013; Aarts et al., 2017; Yoshimura et al., 2022; Bhandari et al., 2021; Stampfli et al., 2023; Mohammadian et al., 2024). Generally, these studies indicate that for predicting illumination at the eyes, dosimeters worn attached to glasses are, of course, the most accurate, followed by those placed on the chest. Wrist-worn dosimeter

measurements are the least accurate. Notwithstanding the proven accuracy, dosimeters worn near the eyes are often experienced as more intrusive and less comfortable than dosimeters worn at the chest or wrist (Duijnhoven et al., 2017), resulting in a trade-off between accuracy and user acceptance (Spitschan et al., 2022). While high accuracy is essential for collecting reliable data, subjects may be less likely to wear a dosimeter if it is too obtrusive, leading to data loss and reduced data quality. The recommended placement of dosimeters, whether at the eyes (Stampfli et al., 2023; Hartmeyer et al., 2023; de Vries et al., 2025), chest (Webler et al., 2021; Hartmeyer et al., 2023), or wrist (Mohammadian et al., 2024), varies among researchers based on the relative importance they assign to accuracy and user comfort. The chest position appears to strike a reasonable compromise, suggesting that more light-dosimetry field studies may adopt chest-worn dosimeters in the future.

1.2 Inter-individual variability

For PLE data recorded by chest-worn dosimeters to be of value for research, for each subject, the recorded illumination must correspond to the illumination at the eyes with an acceptable accuracy. Previous studies that assessed the differences in illumination at the chest and eyes averaged dosimeter recordings across subjects. While this approach reveals general trends, it fails to capture how these differences may vary between subjects. Since chest-worn dosimeters are usually attached to the body using a pendant or clip, their orientation is largely influenced by the body's surface contours. As a result, a subject's body shape (morphology) will affect the dosimeter's orientation and, consequently, what illumination it records. Accurately characterising PLE on a per-subject basis, and facilitating comparisons across study participants, requires an understanding of the discrepancies introduced by body shape.

Identifying differences that stem solely from an individual's body shape is not straightforward. If we were to replicate the method used in previous studies, i.e. placing dosimeters at both the chest and eyes, the found differences in measured illumination between both positions would be influenced by a combination of factors, including the subject's posture and the surrounding lighting conditions (Yoshimura et al., 2022; Mohammadian et al., 2024). Additionally, there may be considerable differences in the intrinsic photometrical sensor accuracies of multiple dosimeters (Markvart et al., 2015). To isolate the impact of a subject's body shape on dosimeter recordings, it is therefore essential to control for posture, lighting context, and intrinsic sensor accuracy. In this study, we employed a simulation-based approach to quantify the variability in chest-worn dosimeter measurements that can be attributed solely to differences in body shape, based on approximately three thousand body scans of standing individuals.

2 Method

To investigate the inter-individual variability of chest-worn dosimeter measurements, we applied an approach consisting of four steps. First, models from a database of body scans of standing individuals were converted to a format suitable for lighting simulations. Second, on each model, we identified four theoretical dosimeter positions on the chest and one reference position just in front of the eyes. Third, for each chest position, we calculated the orientation of the dosimeter relative to the view direction of the subject model and quantified self-shading by the body. Finally, we conducted simulations using an indoor scene to illustrate the resulting inter-individual variability in measured illumination of chest-worn dosimeters, relative to the reference dosimeter at the eyes. The method and the terminology used are adapted from our recent work investigating general differences between dosimeter measurements on the chest and at the eyes using 3D scans of actual people (de Vries et al., under review).

2.1 Subject models

The largest currently available dataset of 3D body scans is CEASAR (Robinette et al., 2002), consisting of 2 375 North American and 2 056 European individuals. Individuals were selected to represent a wide range of age and ethnicity for both sexes, aiming to approximate broad population distributions, although the dataset is not fully representative of current global body shape statistics (Osman et al., 2020). All individuals were scanned in a standardised standing posture and without clothing, except for underwear. While the original CEASAR dataset is only commercially available, an adapted version, with approximately three thousand of the models converted to closed, standardised meshes, is freely available for research (Yang et al., 2014), and was used in the present study.

To make these models suitable for lighting simulations, we converted the mesh geometry to surface (i.e. polygon) models using Grasshopper, a plugin for Rhinoceros 8. This resulted in models with on average 68 633 polygons (standard deviation: 1 792). A model from the dataset is shown in Figure 1. All models were set at the origin and with their view direction (the expected gaze direction of the eyes based on the orientation of the head) along the positive y-axis. The resulting models were converted to Radiance (6.0a) (Ward, 1994) geometry using Radiance's *obj2rad* program. We refer to these processed models as subject models.

2.2 Dosimeter positions

Five dosimeter positions were defined on each subject model: one just in front of the eyes and four on the chest. For this study, a necessary working assumption is that the contours of the clothed subject follow that of the unclothed 3D model. The eye position served as a reference and was determined by identifying the (body) surface point on the head with the largest y-coordinate, typically corresponding to the tip of the nose. The dosimeter position was then defined as a point 2,5 cm above this point (along the z-axis), approximating the position of a dosimeter integrated into or mounted on spectacle frames. The orientation of the dosimeter at this position (its sensor normal) was set equal to the view direction of the subject model. Since the actual position of the dosimeter on the chest may differ, four positions were considered, two on the centre of the chest (upper and lower central) and two on the left chest (upper and lower lateral). No positions were defined on the right side of the chest under the assumption of anatomical symmetry. The four positions were arranged in a 10 cm by 10 cm grid, with the positions on the central chest located 25 cm below the eye position (Figure 1a). The orientation of each of these dosimeters was aligned with the normal of the subject model's (body) surface at its respective location.

Identification of these positions was automated. A front-facing image of each subject model showing the identified positions was generated to determine and correct for any misidentifications. After processing, 1 442 female and 1 499 male subject models were included in the analysis.

2.3 Inter-individual variability in dosimeter orientation and shading

We consider two effects that influence the measurements of a chest-worn dosimeter relative to measurements at the eyes: its orientation and shading by the subject. A third effect, the translational dosimeter displacement (TDD), or the Euclidean distance between the chest-worn dosimeter and the eye point, can also contribute to differences in measured illumination. However, in the current approach, chest dosimeter positions were defined relative to each subject's eye position, making this distance consistent across subjects and thus not a source of inter-individual variability.

The orientation effect, referred to as the rotational dosimeter displacement (RDD), is defined as the angular deviation between the dosimeter's orientation (i.e. the sensor normal) and the subject's forward-facing view direction. For each of the four chest positions, the RDD was computed in terms of the azimuth (in the horizontal plane) and elevation (in the vertical plane) angles (Figure 1b). The self-shading effect, referred to as body self occlusion (BSO), is defined as the percentage of the (hemispherical) field of view of a dosimeter, at a given position on the body, that is obstructed by the subject's own body (Figure 1c). The BSO was computed by defining a uniform spherical light source with a radiance of $\pi^{-1} \text{ W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$. Under this uniform illumination, and in the absence of any obstructions, a dosimeter would record an irradiance of $1 \text{ W}\cdot\text{m}^{-2}$, corresponding to a BSO of 0 %. If the entire field of view of the dosimeter is blocked by the subject model, the irradiance drops to zero, corresponding to a BSO of 100 %. Each subject model was placed under this uniform illumination to calculate the BSO at the four chest positions.

2.4 Inter-individual variability in dosimeter measurements

To illustrate the impact of inter-individual variability in RDD and BSO effects of chest-worn dosimeters on measured illumination, lighting simulations were conducted using a simplified indoor scene. The extent to which these effects influence the measurements is strongly dependent on the lighting in the scene. Hence, we focus on relative rather than absolute differences in illumination between the chest and eye positions. Therefore, the absolute

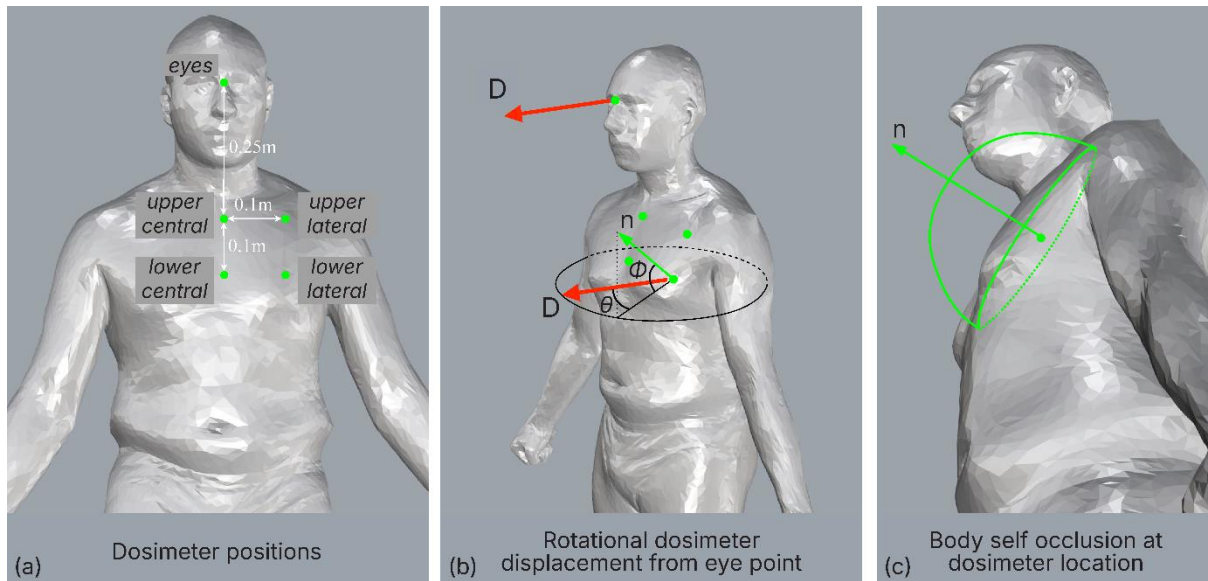


Figure 1 – Dosimeter placement and effects influencing chest-worn dosimeters. a) Dosimeter positions at the eyes and chest (*upper-central, lower-central, upper-lateral, lower-lateral*). b) Subject’s view direction D and dosimeter (sensor) normal n . The difference between both is the rotational dosimeter displacement (RDD), expressed by azimuth angle θ and elevation angle Φ . c) Body self occlusion (BSO) at the dosimeter’s location.

intensity of the light sources is not critical; instead, the spatial distribution of those sources is of primary interest. To capture a range of typical indoor lighting conditions, we consider two idealised scenarios: diffuse top lighting to represent ceiling-mounted electric luminaires and diffuse side lighting to represent daylight entering through a (vertical) window, Figure 2.

The ceiling of the room (for the side lit daylight scenario) was given a reflectance of 0.7, the walls of 0.5, and the floor of 0.3. The subject models were assigned a surface reflectance of 0.4 and positioned 3 meters away from the wall with the window. The impact of the subject’s distance from the window on the results is investigated in our other work (de Vries et al., under review). The (planar) illuminances recorded at each dosimeter position were simulated using Radiance’s *rtrace* program with one inter reflection. All simulations were automated using Python and executed on a high-performance computing system. Running the 29 410 simulations (2 scenarios, 5 dosimeter positions, and 2 941 subjects) was completed within twelve hours.

3 Results

The magnitudes of RDD and BSO effects of the four chest-worn dosimeters are given in Figures 3 and 4. The box plots show the standard quartile ranges, with the mean shown by a cross and outliers using circles. In terms of the elevation angle, dosimeters placed on the lower chest exhibit greater inter-individual variability but generally lower RDD values (in both median and mean) compared to those on the upper chest. Azimuthal RDD values are relatively small for central chest positions, whereas the lateral chest positions tend to show more negative azimuthal angles and variability, consistent with the curvature of the torso. BSO values are relatively consistent across all chest positions and fall within a narrow range, with the exception of some subjects.

The relative differences between illumination measured by chest-worn dosimeters compared to a dosimeter at the eyes, under idealised electric lighting and daylighting, are given in Figure 5. In general, dosimeters positioned on the lower chest show greater inter-individual variability compared to those on the upper chest. The variability observed for the upper-lateral chest position is comparable to that of the upper-central position. Focusing on the dosimeter positioned on the upper-central chest, under idealised electric lighting, the interquartile range of the relative deviation to measurements at the eyes for females spans from 23 % to 43 %, a 20 % spread. This means that for half of the female subjects, the relative difference in illumination falls within a 20 % range, and for the other half, the difference is at least 20 %. For

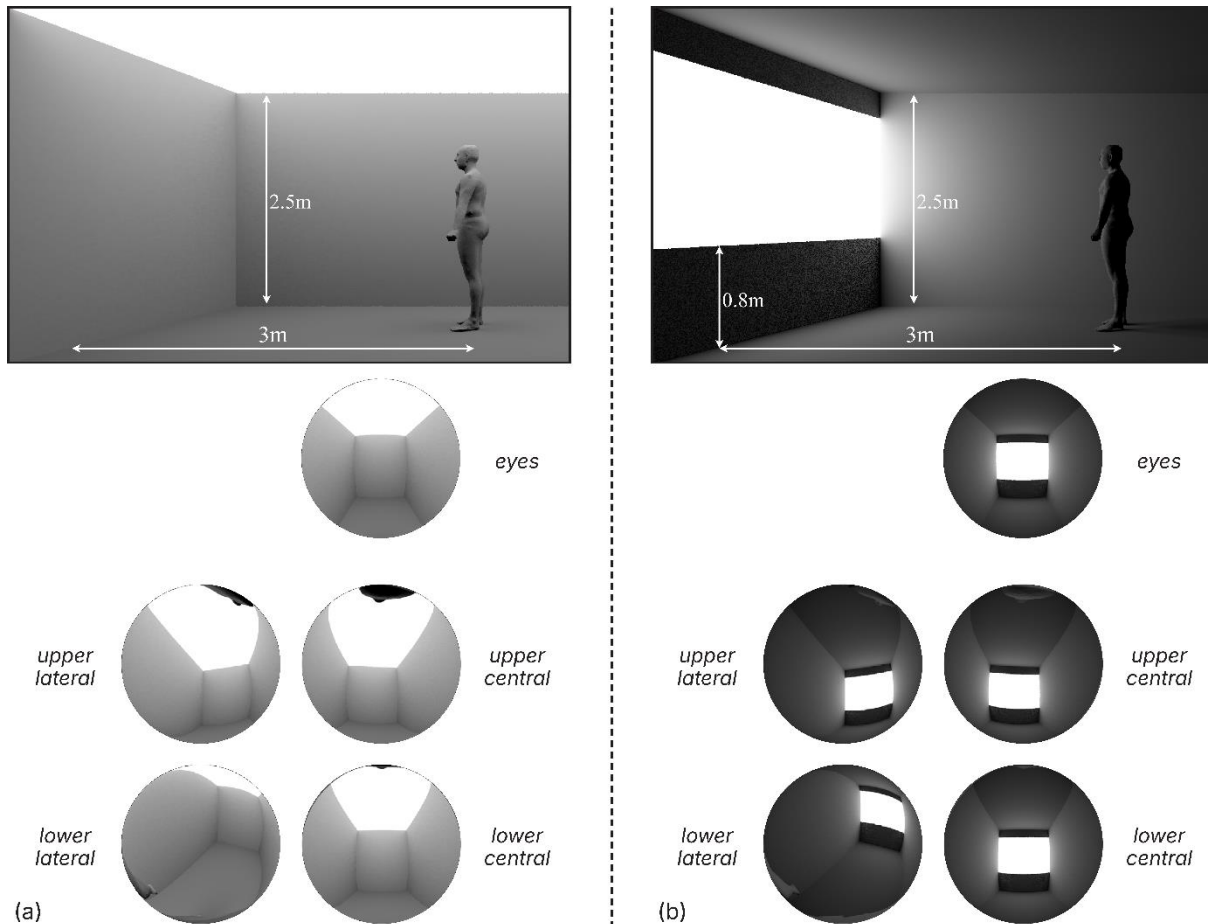


Figure 2 – Indoor scenes and examples of dosimeter views of a subject at 3 m from the window under a) idealised electric lighting and b) idealised daylighting.

males, the interquartile range is slightly narrower at 14 %. Under idealised daylighting, inter-individual variability is lower, with the interquartile range spanning from -19 % to -9 % for females (a 10 % spread) and from -14 % to -6 % for males (an 8 % spread).

While the primary aim of this study is to assess inter-individual variability, the results also provide insight into typical discrepancies between illumination measured on the chest and at the eyes. For standing subjects, dosimeters positioned on the upper chest exhibit mean differences ranging from -23 % to 35 % for females and -20 % to 28 % for males, relative to illumination at the eyes. Lower chest positions show negative differences, with mean relative differences ranging from -25 % to -6 % for females and -15 % to -2 % for males.

4 Discussion

Chest-worn dosimeters, acting as a proxy for illumination at the eyes, are expected to be more adapted in lighting research due to their practicality, having higher user comfort than a device on the head, while still providing acceptable accuracy. Since the placement of a dosimeter on the chest typically follows the contour of the body, the orientation (RDD) of the device, and thus its measurement, may vary depending on a subject's body shape. This study investigated the extent of such inter-individual variability using a simulation-based approach applied to a large database of 3D body scans.

4.1 Inter-individual variability in dosimeter orientation and shading

While the results are based on simulations and a fixed (standing) posture, they offer insight into the potential range of variation that can occur when using actual dosimeters. Generally, positions on the upper chest, i.e. 25 cm below the eyes, have less inter-individual variability in RDD in terms of elevation angle, although dosimeters on the lower chest are, on average,

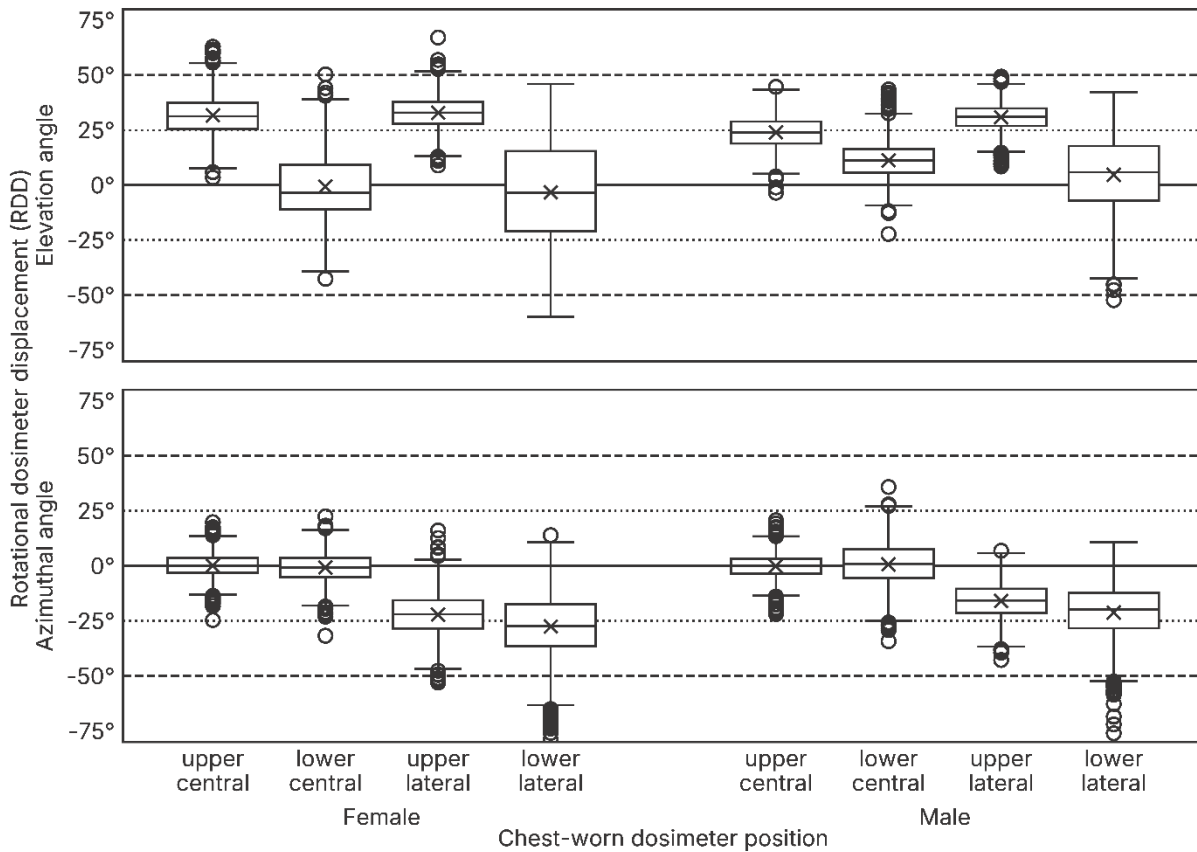


Figure 3 – Rotational dosimeter displacement (RDD) of four chest-worn dosimeters. A positive elevation angle indicates an upward tilt, and a positive azimuthal angle a rightward tilt, both relative to the subject’s view direction.

more in line with the subjects’ view directions. Among female subjects, this variability is particularly pronounced for the lower positions, which is likely attributable to differences in chest morphology. Self-shading of the dosimeter by the subject’s body (BSO) was found to be relatively consistent across subjects and chest positions, although with some outliers, suggesting that generally self occlusion by the body is a relatively stable factor regardless of the subject and the position on the chest.

4.2 Inter-individual variability in dosimeter measurements

Considering both illumination scenarios, for a dosimeter placed on the upper-central chest, the inter-individual difference in measured illumination relative to the eyes falls within 20 % for half of the female population, and within 14 % for half of the male population (Figure 5). Meaning that the remaining half of each population will experience differences exceeding these values. Moreover, the full range shows much larger variability: under idealised electric lighting, one female subject may measure up to 71 % higher illumination at the chest compared to the eyes, while another may record up to 8 % lower. No substantial differences in inter-individual variability were observed between measurements at the upper-central and upper-lateral chest positions. Dosimeters on the lower chest, both central and lateral, showed greater measurement variability, consistent with the greater variation in RDD at those positions (Figure 3).

The results indicate that to reduce inter-individual variability in chest-worn illumination measurements, dosimeters are best placed on the upper chest, where body shape is more uniform across subjects in terms of RDD. This position leads to more consistent device orientations and hence lower variability in measured illumination. However, a dosimeter at this position tends to have a slight upward tilt for nearly all subjects. While this shared tilt helps reduce inter-individual variability, it also causes a consistent over-prediction of illumination compared to measurements at the eyes. To balance measurement accuracy and variability between subjects, it may be worthwhile to adopt a more individualised placement strategy:

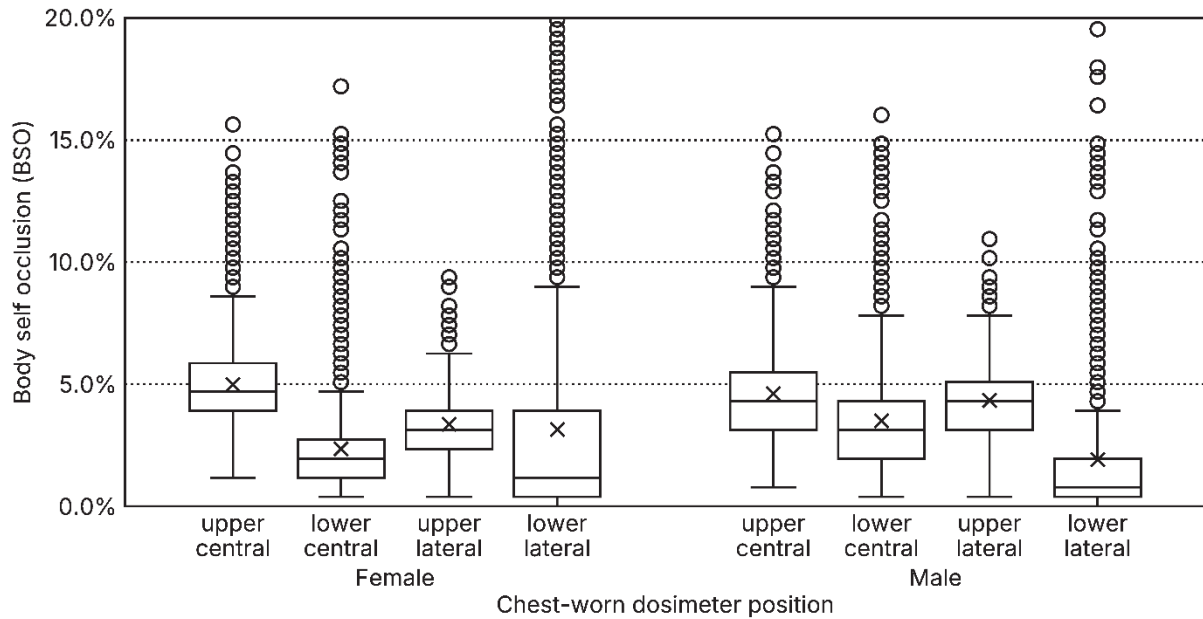


Figure 4 – Body self occlusion (BSO) of four chest-worn dosimeters.

selecting, for each subject, a position on the chest with a low RDD, i.e. where the dosimeter's orientation closely matches the subject's view direction for typical postures.

4.3 Limitations

The simulation-based approach used in this study, using a database of body scans of standing, unclothed individuals, incorporates several limitations. While the inter-individual variability in RDD is expected to be relatively stable across postures, different postures may lead to different results. Moreover, since the subjects were in a standing posture, they were simulated in an open space without nearby reflective surfaces, which may impact the dosimeter's measurement. Wearing clothing could also influence the RDD and BSO of the dosimeter on the body. Finally, the simulations used ideal dosimeters, while real dosimeters are subject to intrinsic photometric sensor inaccuracies, potentially introducing additional measurement variability between subjects.

The two illumination scenarios used in this study represent idealised generalisations of the two most common lighting conditions experienced in buildings: electric lighting from above (i.e. ceiling luminaires) and daylight illumination from the side (i.e. vertical windows). As such, the observed differences between dosimeter measurements at the chest and eyes represent bounding cases for these *particular* illumination conditions only. Real world illumination fields are invariably more heterogeneous than illumination from directional (i.e. from the side or above) but still ideal diffuse light sources. For example, overhead electric lighting is generally designed to have a strongly directional downwards component – for reasons of both efficient illumination of the task area and reducing the likelihood of glare to surrounding occupants in the space. Consequently, effects resulting from differences in the periphery of the view (fisheye images in Figure 2a) would now carry a greater weight in the overall assessment. And, of course, real world daylight illumination from a window (at any one instant) generally has more complex spatial patterns of variation than the idealised diffuse 'window' light source shown in Figure 2b. Thus, for both scenarios, the bounds of real world variation in dosimeter performance are almost certainly *greater* than that revealed in this study.

Lastly, the presented illumination is relative to a dosimeter just in front of the eyes with an unshaded hemispherical field of view. However, the human visual field is not hemispherical and is partially occluded by facial features such as the brow, nose, and eyelids (Spitschan et al., 2022; Sliney, 1983). Therefore, characterising the inter-individual variability in visual field occlusion, and its potential impact on eye-level light exposure, may be relevant future research.

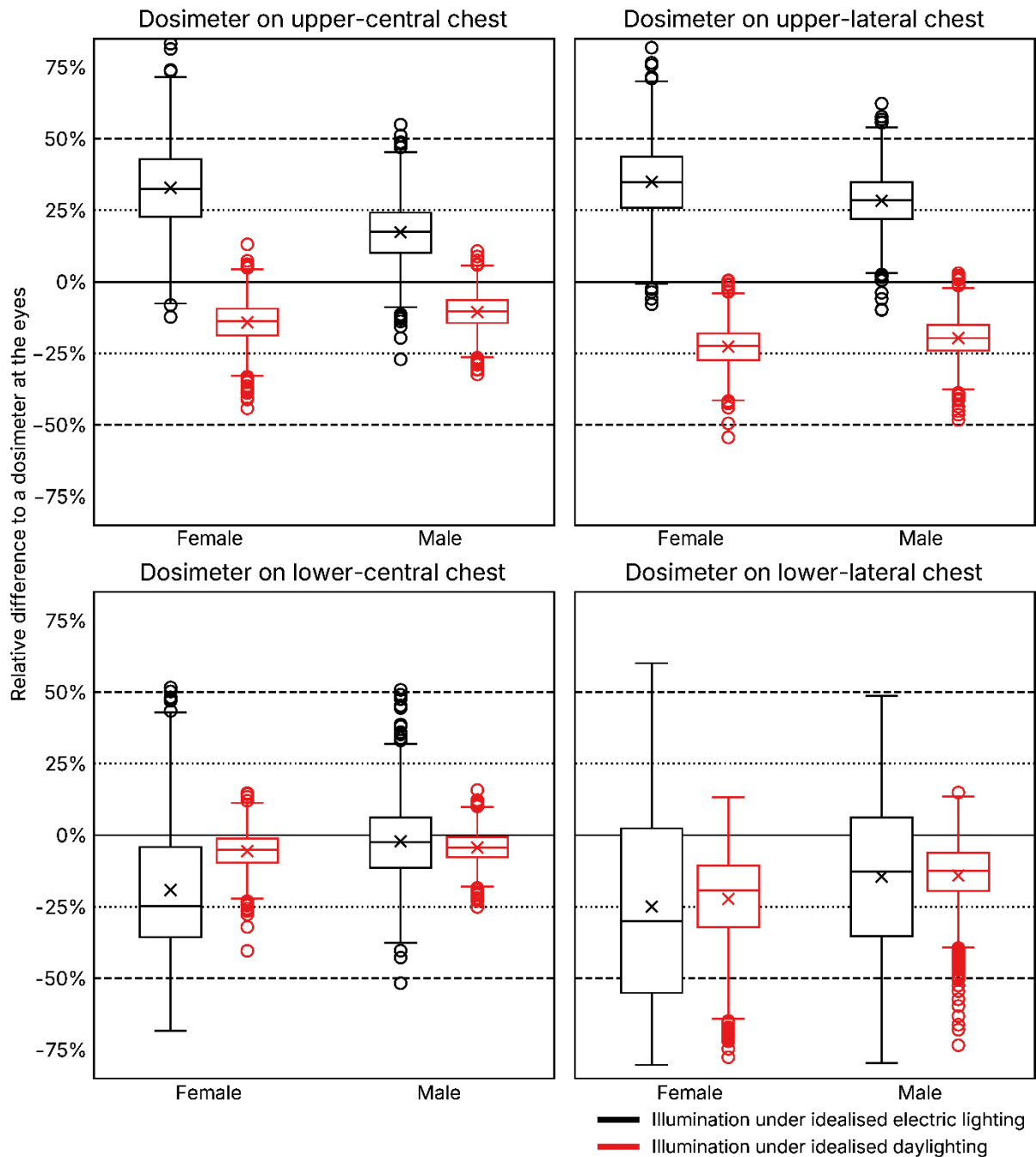


Figure 5 – Relative differences between illumination (illuminances) measured by a chest-worn dosimeter to a dosimeter at the eyes. A positive value indicates that illumination at the chest was higher than at the eyes.

5 Conclusion

Chest-worn dosimeters, serving as a proxy for measuring illumination at the eyes, are increasingly adopted in personal light exposure research due to their balance between measurement accuracy and comfort for the subject. This study investigated how inter-individual differences in body shape influence chest-worn dosimeter measurements, using a simulation-based approach and a dataset of approximately three thousand body scans. Dosimeters placed on the upper chest showed the lowest inter-individual variability in both device orientation and measured illumination. While dosimeters placed on the lower chest showed slightly greater variability, they tended to align more closely with the subjects' view directions, resulting in measurements that, on average, more closely approximated illumination at the eyes. When selecting a chest position for the dosimeter, it is essential to ensure that its orientation aligns

with the subject's view direction (for typical postures), as this is key to minimising inter-individual variability and thus illumination measurements representative of that received at the eye(s).

Acknowledgements

During the preparation of this work, to improve readability, Grammarly was used by the first author.

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