RESEARCH PAPER

Biologically effective solar ultraviolet exposures and the potential skin cancer risk for individual gold medalists of the 2020 Tokyo Summer Olympic Games

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ABSTRACT

Personal solar ultraviolet radiation exposure models were developed for 144 Olympic events scheduled outdoors from across the 33 sport disciplines that will compete in Tokyo between 24 July and 9 August 2020. Ambient exposure models were developed from existing atmospheric parameters measured over Tokyo (35.7°N 139.7°E) and were used to weight erythemally effective solar ultraviolet exposure to gold medalists, taking into account body posture and expected protection by competitor's clothing which was assessed in comparison to respective medalists of the 2016 Rio Olympics. Individual exposure models consider the ultraviolet surface albedo (lawn, concrete, water or sand) and timing of daily events held within Olympic venues. Exposure assessments are presented, including assessments of all preliminary rounds and qualifiers. Within scheduled outdoor events, we award first place (representing the highest and most harmful UV exposure) to the women's tennis singles (1680 J/m²), second to men's golf (1530 J/m²) and third to the men's cycling road race (941 J/m²) for the highest expected erythemally effective solar ultraviolet radiation exposures of the 2020 Tokyo Games. The highest expected solar ultraviolet exposures for nations expected to win greater than three gold medals among the outdoor events were found to occur in athletes from Kenya followed closely by the United States and Hungary. Gold medalists from South Korea were found to demonstrate the highest level of sun protection due to clothing at the 2016 Rio Games, and are thus expected to receive the greatest relative reduction in erythemally effective exposure during the 2020 Tokyo Games.

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Introduction

The Summer Olympic Games provide an ongoing platform to study the evolution of sport and sporting behaviors of elite athletes across a wide range of disciplines that are also practiced by millions of amateur sportsmen and sportswomen worldwide. Summer Olympic sports have been televised for more than seven decades with a growing international audience now exceeding 35 billion viewers [1,2]. Every current Olympic event is broadcast (and recorded) on television and extensively distributed on a variety of social media platforms for current and future audiences interested in viewing or participating in sport [3–5]. Thus, each Olympic Games provide a legacy of data available for studying the evolution of elite competition. The first fundamental principle of Olympism as outlined by the International Olympic Committee endeavors to “...create a way of life based on the joy of effort, the educational value of good example, social

responsibility and respect for universal fundamental ethical principles” [6,p.11]. What elite athletes do, how they behave and how governing sporting authorities run events has the potential to showcase and influence the attitudes and behaviors modeled by Olympism in both amateur athletes and the public in general. What sporting role models do, however, can also reinforce potentially negative behaviors [7,8].

Sport itself plays a significant role in motivating the public by encouraging general fitness and an active lifestyle, with clear benefits in terms of improved cardiovascular health [9], the prevention of type 2 diabetes [10]; both are diseases associated with growing worldwide obesity rates [11,12], as well as the prevention of some cancers [13]. Poor diet and limited access to exercise contribute to chronic diseases that are estimated to cost \$147 billion annually in the United States alone [14]. Encouraging greater activity through sport and the promotion of elite

sporting events such as the Olympics has clear potential benefits to the community; however, these benefits must also be delicately balanced by considering the potential for harm to Olympic athletes and members of the public interested in sport participation through pathways such as extreme environmental exposures.

Recent interest in the 2020 Tokyo Summer Olympic Games has focused on the possibility of record summertime temperatures, placing additional stress on Olympic competitors across a variety of disciplines [15–17]. Intuitively, elite athletes at risk of heat stress are likely to wear “cool” clothing and select apparel that may provide a competitive advantage (e.g. minimal material to increase cooling and avoid wind drag). Such apparel and the requirement to train and compete in an outdoor environment may place athletes at risk of excessive exposure to summertime solar ultraviolet (UV) radiation throughout their life [18,19]; an established carcinogenic risk factor for several skin cancers [20,21].

For melanoma skin cancer, the most aggressive form of skin cancer in humans, the highest rates of prevalence are reported in Australasia, followed by North America, Eastern, Western and Central Europe [22]. Excluding Australia and New Zealand, national Olympic medal tallies closely match global trends in melanoma skin cancer incidence. Thus, nations with predominately fair-skinned populations and those touted with achieving the highest level of success at the Summer Olympic Games are also those which shoulder the highest burden of disease due to environmental exposure to solar UV. These nations include (in order of total Olympic medals), the United States, Russia, Germany, Great Britain and France [23]. Annual costs for the treatment of melanoma and keratinocyte skin cancers in the United States currently exceed 500 million Euros (~ \$600 million US), with annual treatment costs in Australia, Germany and Great Britain also exceeding \$100 million [24]. Excessive environmental exposure to solar UV results in the loss of approximately 60,000 lives annually [25,26] and contributes to skin cancer being the most commonly diagnosed malignancy in fair-skinned populations worldwide [27,28].

In this research, the biologically effective solar UV likely to be received as a total dosage by gold

medal competitors of the 2020 Tokyo Olympic Games will be presented for each individual sporting discipline and Olympic event where a period of outdoor exposure to sunlight is expected. Each gold medalist must compete in all preliminary, semi and final rounds that make up an event and will often represent the minimum threshold exposure of all competitors of single round events, such as the marathon or cycling road race. Exposure analysis is performed for gold medalists only to ensure personal exposure estimates are compared fairly between each outdoor Olympic event. The gold medalist is also chosen for analysis as winning Olympic competitors are those most likely to represent aspirational role models for their chosen sport and will have the largest public viewing audience.

Materials and methods

Ambient solar ultraviolet radiation

Competition at the 2020 Tokyo Summer Olympic Games will be decided among 33 different sports, each divided into various disciplines, with a total of 334 separate medal events. These events will take place (excluding football and baseball/softball, which begin two days prior to the opening ceremony) between 24 July and 9 August 2020. Of the 334 medal events scheduled for the 2020 Tokyo Games, 144 events (43%) will be decided in outdoor venues or locations, situated in and about Tokyo (35.7°N 139.7°E). Most scheduled outdoor events will take place within 30 km of the 2020 Tokyo Olympic Stadium (southern Shinjuku ward) in an area encompassing the wider business district of Tokyo and Tokyo Bay. Outdoor events scheduled outside this central region include golf, which will be held at Kasumigaseki Country Club, 37 km to the north-west, as well as some cycling events to be held at Fuji International Raceway, 80 to 90 km south-west of Shinjuku ward. Events scheduled on water outside of Tokyo Bay will be held at Enoshima Yacht harbor, which will host sailing events 47 km to the south-west of the Olympic Stadium, and Tsurigasaki beach which will host surfing events on the Pacific Coast, 70 km to the south-east (Table 1). Team baseball/softball and football events are the only other Olympic events scheduled to be played in stadiums outside the central district of Tokyo. Olympic venue sites are shown in Figure 1.

Table 1. Olympic events scheduled outdoors at the 2020 Tokyo Games, including location, radiation model type, Normalized Clothing Factor (NCF), expected number of outdoor rounds (including final) and likely total outdoor exposure duration for gold medalists.

Sport	Medal Event no. (Women's Event no.)	Venue	Location	Cylinder Model	Albedo Category	Men's outdoor rounds		Men's total exposure duration (Women's duration)
						Men's NCF (Women's NCF)	Men's rounds (Women's rounds)	
Aquatics	1(2). 10 km marathon	Odaiba Marine Park	Tokyo Bay	Prone	Water	0.4 (0.4)	1 (1)	1 h 53 m (1 h 57 m)
	1(2). Individual competition	Yumenoshima Park Archery Field	Tokyo	Upright	Lawn	0.6 (0.8)	7 (7)	0 h 49 m (0 h 49 m)
Archery	3(4). Team competition	Yumenoshima Park Archery Field	Tokyo	Upright	Lawn	0.8 (0.8)	4 (4)	1 h 0 m (1 h 0 m)
	5. Mixed Team	Yumenoshima Park Archery Field	Tokyo	Upright	Lawn	0.8* (0.8)*	4	1 h 0 m
Athletics	1(2). 100 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	3 (3)	0 h 3 m (0 h 3 m)
	3(4). 200 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	3 (3)	0 h 3 m (0 h 3 m)
	5(6). 400 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	3 (3)	0 h 3 m (0 h 3 m)
	7(8). 800 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.2)	3 (3)	0 h 6 m (0 h 6 m)
	9(10). 1500 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	3 (3)	0 h 12 m (0 h 13 m)
	11(12). 5000 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	2 (2)	0 h 27 m (0 h 30 m)
	13(14). 10,000 m	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	1 (1)	0 h 28 m (0 h 30 m)
	15. 110 m Hurdles	Olympic Stadium	Tokyo	Upright	Lawn	0.2	3	0 h 3 m
	(16). 100 m Hurdles	Olympic Stadium	Tokyo	Upright	Lawn	(0.0)	3	(0 h 3 m)
	17(18). 400 m Hurdles	Olympic Stadium	Tokyo	Upright	Lawn	0.4 (0.0)	3 (3)	0 h 3 m (0 h 3 m)
	19(20). 3000 m Steeplechase	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	2 (2)	0 h 17 m (0 h 19 m)
	21(22). 4 × 100 m Relay	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.0)	2 (2)	0 h 2 m (0 h 2 m)
	23(24). 4 × 400 m Relay	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.2)	2 (2)	0 h 6 m (0 h 7 m)
	25. 4 × 400 m Mixed Relay	Olympic Stadium	Tokyo	Upright	Lawn	0.2* (0.2)*	2	0 h 7 m*
	26(27). High Jump	Olympic Stadium	Tokyo	Averaged	Lawn	0.2 (0.2)	2 (2)	0 h 24 m (0 h 24 m)
	28(29). Pole Vault	Olympic Stadium	Tokyo	Averaged	Lawn	0.2 (0.2)	2 (2)	0 h 32 m (0 h 32 m)
	30(31). Long Jump	Olympic Stadium	Tokyo	Averaged	Lawn	0.2 (0.0)	2 (2)	0 h 26 m (0 h 26 m)
	32(33). Triple Jump	Olympic Stadium	Tokyo	Averaged	Lawn	0.2 (0.2)	2 (2)	0 h 26 m (0 h 26 m)
	34(35). Shot Put	Olympic Stadium	Tokyo	Upright	Lawn	0.4 (0.2)	2 (2)	1 h 4 m (0 h 54 m)
	36(37). Discus Throw	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.4)	2 (1)	0 h 46 m (0 h 12 m)
	38(39). Hammer Throw	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.2)	2 (1)	0 h 30 m (0 h 30 m)
	40(41). Javelin Throw	Olympic Stadium	Tokyo	Upright	Lawn	0.2 (0.4)	2 (2)	0 h 20 m (0 h 20 m)
	42(43). 20 km Race Walk	Central Tokyo	Tokyo	Upright	Dry Concrete	0.2 (0.0)	1 (1)	1 h 20 m (1 h 29 m)
	44(45). Marathon	Central Tokyo	Tokyo	Upright	Dry Concrete	0.2 (0.2)	1 (1)	2 h 9 m (2 h 25 m)
	46. 50 km Race Walk	Central Tokyo	Tokyo	Upright	Dry Concrete	0.4	1	3 h 41 m
	47. Decathlon	Olympic Stadium	Tokyo	Upright	Lawn	0.2	10	1 h 53 m
	(48). Heptathlon	Olympic Stadium	Tokyo	Upright	Lawn	0.0	(7)	(1 h 6 m)
	1. Baseball	Yokohama/Fukushima Azuma stadium	4xYokohama & 1xFukushima	Upright	Lawn	0.8	5	7 h 25 m
Baseball/Softball	(2). Softball	Yokohama/Fukushima Azuma stadium	1xFukushima	Upright	Lawn	0.6	6	4 h 30 m
Canoe	1(2). Slalom Kayak (K1)	Kasai Canoe Slalom Centre	Tokyo	Averaged	Water	0.6 (0.6)	3 (4)	0 h 6 m (0 h 8 m)
	3(4). Slalom Canoe (C1)	Kasai Canoe Slalom Centre	Tokyo	Averaged	Water	0.6 (0.6)*	4 (4)	0 h 7 m (0 h 8 m)*
	5(6). Sprint Kayak(K1) 200m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.6 (0.2)	3 (3)	0 h 3 m (0 h 3 m)
	7. Sprint Kayak(K1) 1000m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2	3	0 h 11 m
	(8). Sprint Kayak(K1) 500m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	(0.2)	(3)	(0 h 6 m)

(Continued)

Table 1. (Continued).

Sport	Medal Event no. (Women's Event no.)	Venue	Location	Cylinder Model	Albedo Category	Men's NCF (Women's NCF)	Men's outdoor rounds (Women's rounds)	Men's total exposure duration (Women's duration)
Cycling	9. Sprint Kayak(K2)1000m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.4 (0.2)	2 (2)	0 h 7 m 0 h 4 m
	10. Sprint Kayak(K2) 500m	Sea Forest Waterway	Tokyo Bay	Averaged	Water		2(2)	0 h 4 m* (0 h 4 m)
	11(12). Sprint Kayak(K4) 500m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.4 (0.4)		
	13. Sprint Canoe(C1)1000m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2 (0.2)*	2 (3)	0 h 8 m 0 h 3 m*
	14. Sprint Canoe(C1) 200m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2 (0.2)*	2 (2)	0 h 8 m 0 h 5 m*
	15. Sprint Canoe(C2)1000m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2 (0.2)*	2 (2)	0 h 8 m 0 h 10 m* (0 h 10 m)*
	16. Sprint Canoe(C2) 500m	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.6(0.6)	2*(2)*	0 h 10 m* (0 h 10 m)*
	1(2). BMX Park	Ariake Urban Sports Park	Tokyo	Averaged	Lawn	1.0 (1.0)	8 (5)	0 h 8 m (0 h 5 m)
	3(4). BMX Race	Ariake Urban Sports Park	Tokyo	Averaged	Lawn	0.4 (0.4)	1 (1)	1 h 34 m (1 h 31 m)
	5(6). Mount. Bike Crss. Cnty.	Izu MTB Course	Izu (35.0°N 139.0°E)	Averaged	Lawn			
Equestrian [#]	7(8). Road Race	Fuji International Speedway	Oyama (35.4°N 138.9°E)	Averaged	Dry Concrete	0.4 (0.4)	1 (1)	6 h 11 m (3 h 52 m)
	9(10). Individual Time Trial	Fuji International Speedway	Oyama (35.4°N 138.9°E)	Averaged	Dry Concrete	0.4 (0.6)	1 (1)	1 h 13 m (0 h 45 m)
	1. Dressage Individual	Equestrian Park	Tokyo	Averaged	Sand	0.8	2	0 h 20 m
	2. Dressage Team	Equestrian Park	Tokyo	Averaged	Sand	0.8	2	0 h 20 m
	3. Eventing Individual	Eq. Park & Sea Forest Crss Country	Tokyo	Averaged	Sand	0.8/0.6/0.8	4	0 h 25 m
	4. Eventing Team	Eq. Park & Sea Forest Crss Country	Tokyo	Averaged	Sand	0.8/0.6/0.8	4	0 h 25 m
	5. Jumping Individual	Equestrian Park	Tokyo	Averaged	Sand	0.8	6	0 h 12 m
	6. Jumping Team	Equestrian Park	Tokyo	Averaged	Sand	0.8	6	0 h 12 m
	1. 16-Team	Tokyo Stadium & Kashima Stadium & Sapporo Dome & Miyagi Stadium & Saitama Stadium & Yokohama International Stadium	Tokyo & Kashima & Sapporo & Sendai & Saitama & Yokohama	Upright	Lawn	0.4	5	7 h 55 m
	(2). 12-Team	Tokyo Stadium & Kashima Stadium & Sapporo Dome & Miyagi Stadium & Saitama Stadium & Yokohama International Stadium	Tokyo & Kashima & Sapporo & Sendai & Saitama & Yokohama	Upright	Lawn	(0.4)	(5)	(7 h 55 m)
Golf Hockey Mod. Pentathlon [^] Rowing	1(2). Stroke	Kasumigaseki Country Club	Saitama	Upright	Lawn	0.6 (0.6)	4(4)	15 h 40 m (15 h 40 m)
	1(2). 12-Team	Oi Hockey Stadium	Tokyo	Upright	Water	0.4 (0.4)	8 (8)	8 h 0 m (8 h 0 m)
	1(2). Individual	Tokyo Stadium	Tokyo	Av/Up	Lawn/Sand	0.6/0.4 (0.8/0.0)	2 (2)	0 h 14 m (0 h 15 m)
	1(2). Single Sculls(1x)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.4 (0.4)	4 (4)	0 h 28 m (0 h 32 m)
	3(4). Pair(2-)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.4 (0.4)	3 (3)	0 h 21 m (0 h 22m)
	5(6). Doubles(2x)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2 (0.2)	3 (3)	0 h 20 m (0 h 22 m)
	7(8). Four(4-)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2 (0.2)*	3 (3)	0 h 19 m (0 h 21 m)*
	9(10). Quadruple Sculls(4x)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.6 (0.4)	3 (2)	0 h 18 m (0 h 14 m)
	11(12). Eight(8-)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.2 (0.4)	2 (2)	0 h 12 m (0 h 13 m)
	13(14). Lightweight Dbl. Sculls(2x)	Sea Forest Waterway	Tokyo Bay	Averaged	Water	0.4 (0.6)	3 (3)	0 h 20 m (0 h 22 m)
Rugby	1(2). 12-Team	Tokyo Stadium	Tokyo	Averaged	Lawn	0.2 (0.2)	6 (6)	2 h 0 m (2 h 0 m)

(Continued)

Table 1. (Continued).

Sport	Medal Event no. (Women's Event no.)	Venue	Location	Cylinder Model	Albedo Category	Men's NCF (Women's NCF)	Men's outdoor rounds (Women's rounds)	Men's total exposure duration (Women's duration)
Sailing	1(2). RS: X Windsurfer	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	0.2 (0.4)	2 (2)	0 h 28 m (0 h 28 m)
	3. Laser-One Pers. Dingy	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	0.8	1	0 h 32 m
	(4). Lsr.Radial-O Pers. Dgy.	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	(0.8)	(2)	(1 h 28 m)
	5. Finn-One Pers. Dingy	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	0.6	1	0 h 12 m
	6(7). 470-Two Pers. Dingy	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	0.8 (0.6)	1 (1)	0 h 49 m (0 h 49 m)
	8. 49er-Skiff	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	0.4	1	0 h 29 m
	(9). 49er FX-Skiff	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	(0.8)	1	(0 h 29 m)
	10. Nacra 17 Foil Mixed Muti.	Enoshima Yacht Harbour	Sagami Bay (35.3° N 139.5°E)	Averaged	Water	0.6 (0.8)	2	0 h 22 m
	Shooting	Asaka Shooting Range	Tokyo	Upright	Lawn	0.4 (0.4)	3 (3)	0 h 12 m (0 h 12 m)
	3(4). Skeet	Asaka Shooting Range	Tokyo	Upright	Lawn	0.4 (0.4)	3 (3)	0 h 21 m (0 h 21 m)
Skateboarding	5. Trap Mixed Team	Asaka Shooting Range	Tokyo	Upright	Lawn	0.4* (0.4)*	3	0 h 24 m*
	1(2). Park	Ariake Urban Sport Park	Tokyo	Averaged	Dry Concrete	0.6* (0.6)*	3*(3)*	0 h 9 m* (0 h 9 m)*
Surfing	3(4). Street	Ariake Urban Sport Park	Tokyo	Averaged	Dry Concrete	0.6* (0.2)*	3*(3)*	0 h 9 m (0 h 9 m)
	1(2). Shortboard	Tsurigasaki Surfing Beach	Ichinomiya (35.4° N 140.4°E)	Averaged	Water	0.2* (0.2)*	4*(4)*	1 h 20 m* (1 h 20 m)*
Tennis	1(2). Singles	Ariake Tennis Park	Tokyo	Upright	Dry Concrete	0.4 (0.2)	6 (6)	10 h 45 m (10 h 30 m)
	3(4). Doubles	Ariake Tennis Park	Tokyo	Upright	Dry Concrete	0.2 (0.4)	5 (5)	8 h 45 m (8 h 45 m)
	5. Mixed Doubles	Ariake Tennis Park	Tokyo	Upright	Dry Concrete	0.4 (0.6)	4	7 h 0 m
Triathlon	1(2). Individual	Odaiba Marine Park	Tokyo Bay	Pr/Av/Up	Dry Concrete	0.2 (0.2)	1 (1)	1 h 46 m (1 h 57 m)
	3. Mixed Relay	Odaiba Marine Park	Tokyo Bay	Pr/Av/Up	Dry Concrete	0.2*(0.2)*	1	0 h 21 m ^{&}
Beach Volleyball	1(2). 24-Team	Shiokaze Park	Tokyo	Averaged	Sand	0.4 (0.2)	7 (7)	5 h 15 m (5 h 15 m)

[#]Men and Women compete collectively in all Olympic Equestrian events.

[^]Separate Show Jumping (NCF 0.6, Cylinder Model: Averaged, Albedo: Sand) and Run & Shoot (NCF 0.4, Cylinder Model: Upright, Albedo: Lawn) models were combined for Modern Pentathlon.

^{*}New events for Tokyo 2020: Assessments based on previous non-Olympic recordings.

[&]Mixed Relay Triathlon times based on time per individual recorded at the 2018 Commonwealth Games.

Figure 1. Tokyo (yellow circle) and surrounding sites (red circles) of outdoor events scheduled for the 2020 Olympic Games.

Football and baseball/softball events held in venues more than 30 km from the Olympic Stadium include (in order of respective distance) those held at Ibaraki Kashima Stadium – Kashima (36.0°N 140.6°E), Fukushima Azuma Baseball Stadium – Fukushima (37.7°N 140.4°E), and Miyagi Stadium – Sendai (38.3°N 141.0°E). Sapporo Dome, Sapporo (43.0°N 141.4°E), located in Northern Hokkaido is the furthest Olympic venue from Tokyo. This stadium was excluded from the current study given Sapporo Dome utilizes a retractable football pitch which will be located within the enclosed stadium dome during Olympic football matches.

Events held during daylight hours and outside the protection of an enclosed venue are subject to atmospheric and diurnal variation in solar UV radiation. Conditions that affect the ambient solar UV at the time of an Olympic event final, qualifying round, or preliminary heat can be predicted, provided that the four predominant factors that affect the solar UV radiation at the time are known. These factors include, in order of significance: the solar zenith angle (SZA) – the angle subtended by the sun and the zenith; the level and type of cloud cover; the total ozone column; and the atmospheric aerosol concentration [29,30]. The SZA can be predicted accurately for the duration of each scheduled event and was calculated here in one-minute time steps for Tokyo (35.7°N , 139.7°E),

Yokohama (35.5°N 139.6°E), Kashima (36.0°N 140.6°E), Fukushima (37.7°N 140.4°E), Sendai (38.3°N 141.0°E), Izu (35.0°N 139.0°E), Ichinomiya (35.4°N 140.4°E), Oyama (35.4°N 138.9°E), Saitama (35.9°N 139.4°E), and Sagami Bay (35.3°N 139.5°E) by application of the astronomical almanac's algorithm for solar position [31]. Radiative cloud cover fraction, Total Ozone Column (TOC) and Aerosol Optical Depth (AOD) at 354 nm, were used to model the influence of cloud, ozone, and aerosol respectively and were sourced from NASA's GIOVANNI remote sensing data acquisition center [32]. These satellite observations were used to develop a standard atmospheric profile for each Olympic venue from the observed parameters acquired over the period 24 July to 9 August 2018, sourced remotely for the Tokyo region.

To evaluate the horizontal plane ambient solar UV irradiance, each remotely sensed atmospheric parameter was averaged over the 17-day 2018 sample range, giving model parameters of 2 Octa (25%), 292 DU and 0.45, for cloud fraction, TOC and AOD respectively. The terrestrial UV irradiance, modeled by the application of each atmospheric parameter and changing SZA, was determined using the semi-empirical solar UV radiation algorithms of Green, Sawada and Shettle [33], Green, Cross and Smith [34], and Rundel [35]. This included a constant attenuation of 2 Octa cloud cover for each Olympic site [36]. These ambient UV exposure models calculate the direct (shadow causing) and diffuse (sky-light) contribution to the incident horizontal plane solar UV. In the model calculations, the diffuse UV contribution was influenced by the reflectivity of the scattering ground surface. For each Olympic event, a scattering surface of lawn, dry concrete, water or sand was applied to the ambient UV model where scattering UV albedo values of 3%, 10%, 6% and 15% were applied for each respective surface [37,38].

Modeled ambient solar UV radiation was weighted to the biologically effective erythema action spectrum for human skin [39], and expressed in W/m^2 . The erythemal solar radiation is analogous to the World Meteorological Organization's (WMO) UV index [40], where 1 UV index unit is the equivalent of $25 \text{ mW}/\text{m}^2$ of incident erythemal solar ultraviolet radiation. To determine the erythemal (or sunburning effective) exposure to an Olympic athlete, the ambient UV radiation modeled in this

study was expressed as a biologically effective exposure in joules per min per square metre. This value was calculated for the duration of the 2020 Olympic Games in one-minute intervals by multiplying the modeled erythemal solar UV irradiance for each discrete one-minute interval in time in W/m^2 (J/s/m^2) by 60 seconds. The ambient horizontal plane erythemally effective UV exposure, modeled using our standard atmospheric profile, is presented for Tokyo between 24 July and 9 August 2020 (35.7°N 139.7°E) in Figure 2(a).

Body surface models

The ambient solar UV received upon a horizontal plane is not a good indicator of the likely solar UV exposure received by the varied topology of the human body surface, especially for athletes competing in a variety of sports in which the body may be at various orientations to the incident solar radiation. A body lying in a prone position will often receive a higher exposure than a body in an upright position for example, by virtue of the fact that a greater body surface area is exposed to the incident (direct and

diffuse) radiation source when oriented with respect to the horizontal plane. Many studies have been conducted in a variety of sports showing reductions in the incident body surface solar UV radiation expressed relative to the available ambient [41–45]. These exposures can vary greatly with respect to the horizontal plane surface exposure at any given measurement site on the competitor's body depending on the predominant orientation and aspect experienced by the measurement site during competition.

Pope and Godar [46] derived Geometric Conversion Factors (GCF) expressing the incident radiation received by a cylindrical simplification of the human body that can be expressed relative to the horizontal plane for body surfaces oriented at a range of zenith and aspect angles. The GCFs of a cylindrical body model can be expressed as a function of SZA. The GCF functions derived by Pope and Godar [46] were applied here for respective SZA in the range 16 to 90° occurring during the Tokyo 2020 Olympics for Upright (tilt 0°), Prone (tilt 90°), and Averaged (range of tilt angles from 0 to 90°) cylindrical body models, representing the likely exposure fraction of Olympic athletes competing in separate events.

Figure 2. (a) Ambient ultraviolet irradiance for Tokyo city (35.7°N 139.7°E) from 24 July to 9 August 2020 modeled for an AOD of 0.45, total ozone column of 272 DU, 2 Okta cloud cover and a lawn surface albedo of 3%. (b) Scheduled outdoor exposure periods for gold medal place winners in events likely to receive the highest UV exposure for each of the 20 outdoor Olympic sport categories listed in Table 1.

These include events such as marathon swimming (Prone GCF), running (Upright GCF) and rowing (Averaged GCF). Cylindrical body CGFs for each of the 144 outdoor Olympic events modeled for 2020 Tokyo are listed in Table 1. Depending on the chosen body model and SZA at the time of an event, the relative fraction of the horizontal plane ambient body exposure ranges from between approximately 0.2 to 0.6, peaking for prone body surfaces at 70° in SZA [46].

Olympic event schedule

Preliminary event schedules for 2020 Tokyo were available at the time of writing [47] showing the start and end times of each Olympic sport, but not necessarily the start and end times of Olympic events within each sport discipline. To determine the duration of each studied Olympic event, publicly available recordings of each gold medal place winner in the 2016 Rio Summer Olympics were analyzed. Information on the total number of heats, including quarter final, semi-final, and final for each sport were also examined from 2016 Rio to estimate the expected number of times a gold medal place winner in 2020 would venture into a sun exposed environment [48]. Given a limited number of publicly available recordings of quarter finals, semi-finals, and heats, total exposure times for each event, including all heats and finals, were assumed to be the same as the publicly available recorded gold medal final exposure duration. Minimum Olympic event lengths are expressed in minute long intervals.

In many instances, the total time of an event for gold medal winners in 2016 Rio was available [48] and could be used as an estimate of total competitive event duration in 2020 Tokyo. This estimate from Rio may have included timed events or team field sports known to be of a set duration. Where these times were not available, the duration of the medal final, measured from past recordings of the same events at the 2016 Rio Games, were multiplied by the number of preliminary events, quarters, semis and finals (rounds) scheduled for the 2020 Tokyo Games. For example, the individual women's archery total exposure time for 2020 Tokyo was estimated to be 49 minutes, assuming 7 minutes outdoor exposure from the 2016 Rio recorded final time multiplied by 4 expected preliminary rounds and 3

finals for 2020 Tokyo. Total outdoor exposure times, including all preliminary event rounds and gold medal finals, are listed in Table 1. Event durations do not include time for medal presentations, warm-ups or preparation time which are also likely to add to the total exposure time of all listed competitors.

Event schedules, for the 2020 Tokyo Games including start, end and round durations estimated to the nearest minute, are plotted in Figure 2(b) for single Olympic events scheduled within each of 20 outdoor sport disciplines, showing the number of expected rounds in each event and the event timing relative to peak UV exposure periods. In Figure 2, the x-axes of Figure 2(a,b) are aligned, showing that some sports are scheduled outside daylight hours (minimum UV exposure). Where event schedules are estimated from available sports schedules (wide range of possible event times) that include both day and night time slots, the event was shared in an alternative fashion between day and night time slots. This method for scheduling is based on the likelihood that athletes are probably not expected to compete in a medal final directly after a preliminary event. Alternate day-night round schedules were also chosen in this study to fairly distribute the total expected outdoor exposure time (Table 1) between day and night, where such scheduling was possible, i.e. where day and night time slots were available in the 2020 Tokyo event schedule [47]. For example, men's high jump, consists of a preliminary round and a final. In the developed exposure model, the preliminary round is scheduled at 11:00 am 4 August 2020 and the final is scheduled at 9:00 pm 5 August 2020.

Normalized clothing factor (NCF)

The etiology of skin cancer in humans has been studied in detail for several decades in a range of populations and countries. The common body distribution of Squamous cell carcinoma and Basal cell carcinoma, collectively known as the keratinocyte skin cancers (KSC), show a very high frequency on the head and neck [49–53]. The face, neck and scalp, are often the most sun exposed regions of the body [54,55]. This has led to a common hypothesis linking the causative role of sunlight with frequent observations of skin damage and KSC prevalence to the face, neck and scalp. Furthermore, increased frequency of

melanocytic nevi, an established biomarker for malignant melanoma, have recently been shown to occur more frequently in exposed body surface areas not protected by clothing [56,57]. These findings have led us to introduce a Normalized Clothing Factor (NCF). The NCF is used in this study to represent the relative high weighting of cancer and sun exposure incidence to the head and neck, but also to indicate the relative proportion of the body exposed to solar UV radiation that is not protected by clothing.

In its application to Olympic athletes, the NCF is used to estimate the relative proportion of the body protected by clothing, where an NCF 1 is the equivalent of complete body coverage and NCF 0 represents no effective body coverage. Similar clothing metrics, including the Garment Protection Factor (GPF) have recently been proposed for assessing UV protection provided by clothing [58]. The NCF is introduced here as a novel simplification to allow comparative assessments of athletic apparel by remote video analysis without having to have direct access to the clothing worn. In deriving the NCF, four standard body sites are chosen as presented in Figure 3 [59]. If a site is covered or protected by clothing, the body site is deemed protected ($NCF_{site} = 1$). Each protected shin, navel, and forearm site collectively add to 3 ($NCF_{site} = 1$ each). To represent the higher effective prevalence of head and neck skin cancer, NCF_{site} for the face is weighted out of 2. The weighting of 2 for the facial site is used to also take into account protection by hats. If a facial site is not completely covered by a helmet, scarf or goggles, but the individual is wearing a hat, the facial site is weighted NCF_{site} 1 (rather than 2 for full coverage). An unprotected facial site of an individual not wearing a hat is rated NCF_{site} 0. To convert all four NCF_{site} measurements into a single normalized numeric, they are collectively summed and divided by 5.

In the current study, the NCF was derived for all gold medal winning competitors of the 2016 Rio Summer Olympics. For 2020 Tokyo, the protected body surface is assessed assuming gold medal athletes will wear similar clothing to the respective 2016 Rio Games winners for the duration of each modeled event. The approximate surface fraction of the body exposed to solar UV

radiation is calculated as $1 - NCF$. For example, from Table 1, the men's 100 m Athletics event is rated NCF 0.2 (navel site protected by clothing). This equates to a rough body surface exposure fraction of 0.8 by application of the NCF (taking into account the higher effective weighting applied to the unprotected facial site and no protection of the forearm or shin). Where a new Olympic event is scheduled for the 2020 Tokyo Games that was not included in the 2016 Rio schedule (surfing, skateboarding, etc), previous World championship or Commonwealth Games observations were used to derive the expected NCF.

Figure 3. Spot locations for assessing the Normalized Clothing Factor (NCF): $NCF_{site}(\text{head}) = 2$; $NCF_{site}(\text{navel}) = 1$; $NCF_{site}(\text{forearm}) = 1$; $NCF_{site}(\text{shin}) = 1$. For this model the $NCF = 0.2$ (shin protected by clothing).

Total ultraviolet exposure

Personal biological skin damage due to sun exposure is a function of total dosage, measured in joules [54]. An individual's dosage, (i.e. the radiation that penetrates the skin), is dependent upon the total solar radiation that reaches the skin surface. The solar radiation that reaches the unprotected skin surface is termed an exposure, and is also measured in joules. The total erythemal solar UV exposure, and hence, the radiation that influences an individual dose, for a gold medal winning athlete at 2020 Tokyo may be calculated according to Equation (1),

$$E_{ery} = (1 - NCF)GCF \left[\int_{t=0}^{t=1} I_{ery}(t)dt + \int_{t=1}^{t=2} I_{ery}(t)dt + \int_{t=n-1}^{t=n} I_{ery}(t)dt \right]. \quad (1)$$

Here, E_{ery} is the erythemal UV exposure received by the Olympic competitor in J/m^2 , NCF is the Normalized Clothing Factor, GCF is Geometric Conversion Factor [46] and $I_{ery}(t)$ is the ambient erythemal UV irradiance modeled at time t , taking into account the relative SZA and averaged atmospheric parameters at the time of each respective event round ($t = 1$), qualifier ($t = 2$) or final ($t = n$).

Results

Modelled erythemal UV exposure for gold medal event winners of the 2020 Tokyo Olympics are listed in Figure 4 by each of the scheduled 20 outdoor sport categories. (Individual Olympic event exposures are also presented as a supplementary Table). High erythemal exposure events were dependent primarily upon event exposure duration and the exposure schedule (Figure 2). Personal factors also played

Figure 4. Total erythemal ultraviolet exposure of 144 gold medal events scheduled to compete in an outdoor environment arranged by sport category for the 2020 Tokyo Summer Olympics. Events within categories (colored segments) correspond with listed event numbers provided in column 2 of Table 1 and are arranged here from bar base (event no. 1 within category, e.g. Athletics men's 100 m) to bar top (terminating event no. within category). Athletics includes 48 outdoor events, terminating with Heptathlon (no. 48, light gray), while sports such as golf include only two events (men's stroke – dark green; women's stroke – light green) .

a role, including measured NCF and body aspect (prone, averaged or upright postures).

Of all outdoor sports, tennis, golf, cycling, volleyball and field hockey showed significant potential for high erythematic individual exposure. This is the result of two causative factors: long event duration; and daytime exposure schedule. For Olympic tennis players, sun exposure risks are remarkably high and have the potential to cause the most harm, given the likelihood that a tennis player may compete in all singles, doubles and mixed doubles events. For the current analysis, women's singles exposure was higher than men's because the 2016 Rio winner of the men's event wore a cap, giving a total expected NCF of 0.4 compared to NCF 0.2 for women (with only the navel site protected from sunlight exposure). Playing on a dry concrete reflective surface (assumed for 2020 Tokyo) also contributed to the predicted high sun exposure to tennis players. However, the total event duration during daylight (which often exceeded 8 hours in tennis events – [Table 1](#)) is likely to be the most important contributing factor. In the current analysis, tennis rounds were alternated between both daylight and night time round schedules. If tennis players are exposed to a greater number of daylight rounds in the 2020 Tokyo Olympics, then the expected erythematic exposure would be higher than presented in [Figure 4](#).

Of all 144 Olympic events, golfers received the second highest exposure risk. As golf is played only in daylight hours and often played during peak midday periods, and given that the duration of each competitive golf round during a stroke event can exceed 4 hours, the exposure potential to golfers will always be high. Personal protection in the form of quality clothing and hat wear made a significant impact on the potential sun exposure risk faced by Olympic golfers. For men, long trousers, shirts and caps reduced the modeled exposure presented in [Figure 4](#) (NCF 0.6). Women golfers received a similar erythematic exposure which was enhanced due to the likelihood that the shin site would not be protected by clothing, with a skirt being the preferred attire by the 2016 Rio women's golf winner. Hence, the women's golf winner for 2020 Tokyo received an exposure almost as high as the men's golf Olympic event which is estimated at $1,530 \text{ J/m}^2$.

Within each outdoor sport discipline, the men's cycling road race received the third highest event

exposure (excluding women's golf which was also high at $1,515 \text{ J/m}^2$). This ranking again is the result of a high daytime exposure duration, occurring over the middle part of the day when solar UV exposure is at its peak. Of all 144 outdoor Olympic events, the men's cycling road race has the greatest single day event duration, extending over a likely 6 hours. Compared with tennis and golf, which are also played in a predominantly upright posture, the cycling road race will place the winning athlete in a posture in which the back, arms and neck approach a horizontal plane. This position, combined with the lateral movement of the legs, places the cyclist's body posture in an orientation more likely to receive a greater proportion of the available ambient solar UV radiation [[43,44](#)]. For the current model used here, an averaged cylinder body approximation was used to model the effective erythematic exposure during the men's road race. Expected body posture, high surface reflection for a dry concrete surface, and the expected NCF of 0.4 (torso and helmet protection only) contributed to the high solar UV exposure expected to be received by the men's cycling road race winner at 2020 Tokyo. Indeed, given no preliminary rounds for this event, all cycling road race competitors will receive very high levels of exposure.

Higher daytime exposure durations for field hockey and beach volleyball made these sports other likely events in which a high biologically effective solar ultraviolet exposure is possible. These two sports both experienced total combined event durations in excess of 7 hours, albeit with some event rounds scheduled during the evening. In addition, Olympic hockey fields are covered by a water surface atop of an artificial playing surface. For hockey, an ultraviolet albedo of 6% for water surfaces [[37](#)] was assumed. Given water has a higher UV albedo than a natural lawn surface [[37](#)], and in the absence of ultraviolet albedo measurements for artificial turf, (which is also likely to be dependent on color and surface texture) we assume Olympic field hockey players will experience elevated exposures compared with similar team sports played over lawn surfaces. Similarly, individual UV exposures of beach volleyballers were modeled over highly reflective sand surfaces. This was the highest UV albedo surface applied in this study at 15% UV albedo [[37](#)]. This, along with an expected low NCF, places Olympic beach volleyballers at risk of elevated ultraviolet

exposure compared to other sport disciplines of similar event duration.

Rugby, baseball/softball, marathon swimming, triathlon and football were the other sport disciplines in which the total number of events within the sport discipline were low, with only men's and women's events (and a team event for triathlon) scheduled within each discipline. High exposures for team tournament events such as hockey, football, baseball/softball were mitigated to some extent by the number of events scheduled outside daylight hours, or during hours when the SZA was near the horizon at sunset. This was especially the case for men's and women's football (soccer) events which were largely scheduled during night, resulting in this team tournament having the lowest of all team sport gold medal erythematic ultraviolet exposures, despite football also having an outside exposure time of greater than 7 hours. Even though the triathlon events are held during a high exposure time and the NCF rating or clothing worn is minimal, this sport was not the highest for high erythematic individual exposure as there is only one event/round, unlike the sports ranked higher in erythematic individual exposure which consist of multiple rounds and finals and therefore increased exposures.

Expected ultraviolet exposures for each of the highest calculated exposure events of all 20 outdoor Olympic sports are listed in Table 2. Events listed in Table 2 represent the greatest erythematic exposures of the 20 disciplines as presented in Figure 4.

From Table 2, all events with a duration nearing 2 hours or greater had modeled personal erythematic exposures exceeding 200 J/m^2 . For type I skin, the fairest skin type on the Fitzpatrick scale [60], noticeable sunburn would be expected to appear in gold medalists competing in singles tennis, golf, the cycling road race, beach volleyball, hockey, rugby, decathlon, triathlon, football, softball, and the 10 km marathon swim. Given each sunburn is a contributing risk factor to the later development of skin cancer [21,61,62], athletes competing in these events are at elevated risk of developing skin cancer later in life. Minimizing personal sunlight exposure by scheduling outside periods of peak UV exposure, scheduling at night, or by protecting the skin through active use of protective attire will reduce the risk of developing disease associated with

exposure to solar UV radiation. Figure 5 presents the modeled erythematic exposure to gold medalists of the same 20 outdoor sports presented in Table 2 assuming an NCF of 0 (no effective clothing protection) and the current modeled NCF of each event.

In the comparison of Figure 5, events with high personal erythematic exposures modeled for 2020 Tokyo are not necessarily those with the highest expected personal exposures modeled without protection by clothing. Sports such as golf and sailing, in which a higher level of personal protection from solar radiation are applied by clothing and hat wear, can reduce the effective erythematic exposure received by individuals. Long pants and caps for Olympic golfers (NCF 0.6) and a full wetsuit and hat (NCF 0.8) for the laser-radial one-person dinghy sailing event show noticeably reduced potential exposure to the body from what may have been received if no effective protection were worn. Conversely, sports such as triathlon, rugby, and decathlon (NCF 0.2) receive a much higher proportion of the available body surface UV radiation as the shins, forearms and head were always exposed in these events.

National exposure risks

Table 3 lists the expected erythematic ultraviolet exposure per gold medal won in an Olympic event with a scheduled outdoor component during the 2020 Tokyo Games (newly introduced events for the 2020 Tokyo Games are excluded). Exposure summaries for competitors of each nation are also divided by gender and expected body site protection by clothing, assuming winners of the Tokyo events will wear the same apparel and come from the same countries as the winners from 2016 Rio. A total of 131 events are listed in Table 3. The table includes leading erythematic exposure events, including the 2020 women's tennis singles, men's and women's golf and the cycling road race. Given the winners of these high exposure events may exclusively represent nations with low expected gold medal tallies (For example, Puerto Rico again representing the women's tennis gold medalist), the expected exposure per medal (Column 3, Table 3) is often greater for these nations compared to nations with higher expected medal tallies. For nations with an expected gold medal tally of 3 or more, the average erythematic exposure per medal equates to 139 J/m^2 .

Table 2. Olympic events with the highest calculated erythematic ultraviolet individual exposure within each of the 20 sport categories scheduled outdoors during the 2020 Tokyo Summer Olympic Games. () = women's event.

Sport	Event	NCF	Expected Olympic Schedule	Exposure duration	Erythematic Exposure (J/m ²)
Tennis	(Singles)	0.2	(25 July 17:00–18:44) (26 July 11:00–12:44) (27 July 17:00–18:44) (28 July 11:00–12:44) (29 July 17:00–18:44) (31 July 12:00–13:44)	10 h 30 m	1 680.4
Golf	Golf Stroke	0.6	(30 Jul 7:30–11:24) (31 Jul 9:30–13:24) (1 August 11:30–15:24) (2 August 12:05–15:59)	15 h 40 m	1 530.3
Cycling	Road Race	0.4	(25 July 11:00–17:10)	6 h 11 m	941.1
Beach Volleyball	(Beach Volleyball)	0.2	(26 Jul 9:00–9:44) (28 July 14:20–15:04) (30 July 20:00–20:44) (1 August 10:00–10:44) (5 August 10:00–10:44) (7 August 21:00–21:44) (9 August 10:00–10:44)	5 h 15 m	909.8
Hockey	Hockey	0.4	(25 Jul 9:30–10:29) (27 July 18:30–19:29) (29 July 10:00–10:59) (30 July 19:00–19:59) (31 July 10:30–11:29) (2 August 11:30–12:29) (4 August 19:00–19:59) (6 August 10:30–11:29)	8 h 0 m	832.7
Rugby	Rugby	0.2	(27 July 10:30–10:49) (27 July 11:30–11:49) (27 July 16:30–16:49) (28 July 10:30–10:49) (29 July 13:00–13:19) (29 July 17:00–17:19)	2 h 0 m	392.4
Athletics	Decathlon	0.2	(31 July 12:30–12:31) (31 July 12:45–12:57) (31 July 13:00–13:30) (31 July 21:30–21:31) (31 July 21:45–21:46) (1 August 11:00–11:01) (1 August 11:30–11:52) (1 August 12:00–12:15) (1 August 12:30–12:39) (1 August 21:50–21:54)	1 h 53 m	353.8
Triathlon	(Individual)	0.2	(28 Jul 8:00–8:38) (28 Jul 8:39–9:17) (28 Jul 9:18–9:56)	1 h 57 m	349.5
Football	(Football)	0.4	(22 July 16:30–18:29) (28 July 19:30–20:29) (31 July 18:00–19:59) (3 August 18:00–19:59) (7 August 11:00–12:59)	7 h 55 m	295.9
Baseball /Softball	(Softball)	0.6	(22 July 10:00–10:44) (23 July 14:30–15:14) (25 July 19:00–19:45) (26 July 10:00–10:44) (27 July 14:30–15:14) (28 July 19:00–19:45)	4 h 30 m	287.1
Aquatics	(10 km Marathon swim)	0.4	(6 Aug 8:00–9:57)	1 h 57 m	282.5
Surfing	(Shortboard)	0.2	(26 Jul 8:00–8:19) (27 July 17:00–17:19) (28 Jul 7:00–7:19) (29 July 12:20–12:39)	1 h 20 m	167.1
Sailing	(Laser-Radial One Person Dinghy)	0.8	(31 July 12:00–12:43) (2 August 14:00–14:43)	1 h 28 m	90.3
Rowing	(Single sculls (1x))	0.4	(24 Jul 8:40–8:47) (25 Jul 9:40–9:47) (28 Jul 8:40–8:47) (28 July 11:30–11:37)	0 h 32 m	87.4
Archery	Individual	0.6	(Jul 28 9:30–9:36) (Jul 28 16:30–16:36) (29 Jul 9:30–9:36) (30 Jul 9:30–9:36) (1 Aug 9:30–9:36) (1 August 11:15–11:21) (1 August 14:45–14:51)	0 h 49 m	77.2
Shooting	Trap Mixed Team	0.4	(26 July 10:00–10:07) (29 July 10:00–10:07) (1 August 14:30–14:37)	0 h 24 m	60.6
Canoe	Sprint Kayak (K1) 1000 m	0.2	(5 Aug 9:30–9:34) (6 Aug 9:30–9:33) (6 August 13:10–13:14)	0 h 11 m	42.9
Skateboarding	(Street)	0.2	(27 Jul 9:00–9:02) (27 July 11:00–11:02) (27 July 13:00–13:02)	0 h 9 m	38.2
Equestrian	Eventing Individual	0.8	(31 Jul 8:00–8:09) (1 Aug 10:00–10:01) (2 August 11:00–11:10) (3 August 17:00–17:01)	0 h 25 m	33.4
Modern Pentathlon	Modern Pentathlon	0.6/0.4	(8 August 16:00–16:01) (8 August 20:00–20:11)	0 h 14 m	1.9

Nations with exposures expected to exceed this average include: Brazil; Netherlands; Spain; Argentina; Britain; and South Korea. Of these nations, the poorest level of average body site protection by clothing and hat wear are likely to include (in order of averaged NCF): Spain (NCF 0.3); Argentina (NCF 0.4);

and the Netherlands (NCF 0.4). The expected NCF improves for the remaining three nations with erythematic exposures exceeding the global average for nations with 3 or more gold medals. These are Brazil (NCF 0.5), Britain (NCF 0.5) and South Korea (NCF 0.7).

Figure 5. Calculated total erythemal ultraviolet exposure with (yellow) and without (dark) expected protection by clothing (measured NCF) for each of the leading individual exposure events of the 20 outdoor sports scheduled for 2020 Tokyo.

In all assessed South Korean gold medal winners, the level of body site protection was high at each body site, with the lowest average site NCF occurring for women's shins (NCF 0.7). The reduction in shin site NCF was the result of an unprotected shin in the 2016 Rio women's golf winner. Across all nations listed in Table 3, South Korea obtained the highest average NCF for both men's and women's Olympic events. The poorest level of protection in nations expected to win greater than 3 gold medals included Kenya (NCF 0.1) followed by the United States (NCF 0.3) and Hungary (NCF 0.3). Clothing coverage by Kenyans was low due to the expected gold medals being won in athletics events (no hat, forearm, or shin protected and limited torso protection for Kenyan women). Similarly, low national NCF was found in Hungarian Olympic competitors as a result of medals being won in rowing (a discipline in which hat wearing, shin and forearm protection was low). Low national NCF for the United States can be attributed again to the high number of expected athletic medals (12 of 16 gold medals, where forearm, shin and hat protection was not often observed).

In total, comparisons between all men's and women's outdoor Olympic event winners showed that protection by clothing was identical in both

sexes, with the exception of navel site protection in women which showed an average site NCF_{navel} of 0.7, compared to men at NCF_{navel} 1. Similarly, global erythemal UV exposure measured across all gold medal winning competitors was shown to be higher in women (173 J/m^2) compared with male Olympic winners (156 J/m^2). This is a likely result of less skin surface protection in women's competitive clothing compared with men.

Discussion

Modeled erythemal ultraviolet exposures are presented in this research for each gold medalist competing in an outdoor environment at the 2020 Tokyo Olympic Games. In this assessment, expected body posture, event duration, event schedule, expected atmospheric parameters, surface albedo, and protection by clothing were considered for each of 144 events scheduled across 20 outdoor sporting disciplines. Estimates were made for gold medalists exposed to the sun. Compared with indoor competitors, this cohort of athletes represent those who will be exposed to elevated levels of environmental stress [63].

Individual assessments presented in the current work have some limitations, which were not directly assessed in our individual exposure predictions for

Table 3. Erythematic ultraviolet exposure per gold medal and expected average body site clothing coverage listed by nation for potential outdoor Olympic gold medalists at 2020 Tokyo.

Nation	Gold Medals	Exposure/ medal (J/m ²)	Men's Events						Women's Events				
			NCF	Exposure/ medal (J/ m ²)	NCF _{head}	NCF _{navel}	NCF _{forearm}	NCF _{Shin}	Exposure /medal (J/m ²)	NCF _{head}	NCF _{navel}	NCF _{forearm}	NCF _{Shin}
Puerto Rico	1	1 680	0.2						1 680	0	1	0	0
Belgium	2	560	0.2	941	1	1	0	0	179	0	0	0	0
Fiji	1	392	0.2	392	0	1	0	0					
Russia	2	345	0.5	2	0.5	1	0	0	688	1	1	0	0
South Korea	6	327	0.7	125	0.7	1	1	1	529	1	1	1	0.7
Japan	1	287	0.6						286	1	1	0	1
Britain	15	263	0.5	271	0.6	1	0.1	0.5	243	0.5	1	0.5	0.8
Argentina	3	292	0.4	427	0	1	0.5	1	21	0.5	1	0.5	1
Slovakia	1	281	0.4	281	1	1	0	0					
Spain	4	255	0.3	472	0	1	0	0	38	0.5	0.5	0	1
Switzerland	2	240	0.4	230	1	1	0	0					
Netherlands	5	230	0.4	170	0	1	0	0.5	270	0.7	1	0.3	0.3
Brazil	4	212	0.5	254	0.3	1	0	0.3	35	1	1	1	1
Sweden	1	204	0.4						204	1	1	0	0
China	3	129	0.3	124	0	1	0	0	132	0.5	0.5	0.5	0.5
Germany	13	121	0.4	35	0.3	1	0.2	0.4	312	0.5	0.8	0.5	0.5
Kenya	6	114	0.1	97	0	1	0	0	131	0	0.3	0	0
Australia	5	109	0.4	39	1	1	1	1	126	0.5	0.8	0	0
United States	18	105	0.3	136	0.3	1	0.1	0.4	129	0.3	0.5	0.1	0.2
Greece	1	77	0.2						77	0	0	0	1
Poland	2	71	0.2						71	0	1	0	0
Canada	1	56	0.2	56	0	1	0	0					
Tajikistan	1	56	0.2	56	0	1	0	0					
New Zealand	4	54	0.4	69	0.7	1	0	0.3	12	0	1	0	0
Italy	3	53	0.4	55	1	1	0	0	55	1	1	0	0
Bahrain	1	46	0.0						46	0	0	0	0
Croatia	5	45	0.4	54	0.7	1	0.3	0.3	31	0	1	0	0
Columbia	2	31	0.6						31	1	0.5	0.5	1
France	5	28	0.6	22	1	1	0.5	0.8	55	1	1	0	0
Hungary	3	18	0.3						18	0	1	0	0.3
Jamaica	6	5	0.1	6	0	1	0	0	4	0	0	0	0
South Africa	2	5	0.2	3	0	1	0	0	7	0	1	0	0
Bahamas	1	0	0.0						0	0	0	0	0
Ethiopia	1	0	0.0						0	0	0	0	0
Global Average		163	0.4	156	0.4	1	0.2	0.4	173	0.4	0.7	0.2	0.4

gold medal winners. The analysis provided assumes firstly, that gold medal winners of the 2020 Tokyo Games will wear apparel similar to that of the same event winners of 2016 Rio. The tropical climate of Rio, and apparel worn during the 2016 Games may be very similar in Tokyo given the expected high temperature and humidity likely to be observed in 2020 [64] although there is no guarantee that apparel will be identical. Exposures modelled for each gold medalist in this study are estimates. The derivation of personal exposure for the gold medalist will in many cases be representative of the personal exposure likely to be received by other competitors of the same event. Often, the gold medalist's exposure will represent the minimum exposure threshold (particularly in cases where events are timed). What an

individual competitor receives is however also dependent on the environment. Here, a standard atmospheric profile was assumed for each Olympic event. Ambient UV exposure was modelled assuming a constant 2 Okta cloud cover over all days and at all Olympic sites. Cloud cover, the weather, and shade provided by buildings, structures and natural vegetation, are significant factors that have the potential to reduce sun exposure risk. What shade is provided by the Olympic venues and actual competition environments, and if athletes are able to use the shade on breaks and warm-ups, will influence the total biologically effective exposure received by each gold medalist during the Tokyo Games. This factor was not assessed in this research. Novel methodologies are currently being developed to assess shade

quality in natural and built spaces [65,66]. These have significant potential to add to the current analysis, which has been performed across 144 distinct sporting events, each held across a variety of different environments.

In the current analysis, we report UV exposures but do not estimate the use of sunscreen by competitors, which would reduce the chance of burning from a given UV dose. Sunscreen has clear benefits in terms of reducing sunburn and provides some benefit for the prevention of skin cancer [67,68], especially the prevention of Squamous cell carcinoma [69]. However, to be most effective, sunscreen must be reapplied regularly, applied at the correct dosage, applied well before the expected outdoor exposure time, and in a manner that gives full skin surface coverage [70]. Further, many athletes may not use sunscreen due to concerns of it impacting performance, for example, causing greasy hands, causing thermal discomfort or affecting sweating [71,72], or getting sunscreen and sweat in their eyes. The use of sunscreen decreases thermoregulatory effectiveness; however, thermoregulatory effectiveness of sunburned skin is also reduced [72]. Thus, protecting with sunscreen and clothing as much as possible in prior weeks, practice, warm up and acclimatization to warm summer conditions [73] are all important strategies for athletes who will be competing in their Olympic uniforms. Sunscreen provides the best protection when implemented alongside other personal sun exposure reduction strategies [74]. Further analysis of competitor behavior in regard to sunscreen use at the Olympic Games has the potential to add considerably to the effective personal exposures predicted in this paper, especially in those events identified with high UV exposure potential.

A validation study is planned that compares predictions in each of the 144 studied events, using the same methodology employed within the current study, to assess event exposures following the 2020 Tokyo Summer Olympics. Future analysis using measured personal ultraviolet exposures from each of the studied events would also add significantly to this research, as would a thorough assessment of outdoor events scheduled for the 2020 Tokyo Paralympic Games. Currently, erythemally effective solar ultraviolet exposures have been measured in situ in research studies for a number of sports

that are included in the Tokyo 2020 Olympic schedule. These include golf [42,75], cycling [43,44,76], triathlon [77,78], tennis [79], and athletics [41,45]. Although not directly comparable, some of these previously measured UV exposures yield similar exposure results to those derived here. Serrano et al. [43] has previously shown cycling to be a high exposure sport, listing personal exposures as high as 3,224 J/m² recorded over two days. The same group [79] reported high personal erythemally effective UV exposures in tennis players over two days (1,065 J/m²) and runners over five days (762 J/m²). Personal exposures in ironman events (an endurance form of triathlon) have been reported above the equivalent of 2000 J/m² [77], while recreational golfers can receive exposures high enough to cause sunburn, reaching 320 J/m² in the late afternoon [75]. Sport has the clear potential to cause harm as a consequence of exposure to solar ultraviolet radiation, yet there remains significant potential to examine personal solar UV exposure to a large number of the available 144 outdoor Olympic events that were considered here for the 2020 Tokyo Olympic Games.

For each of the leading exposure events listed in Table 2 for all 20 outdoor Olympic sport categories, the first eleven (Tennis through Aquatics) have an expected personal exposure that exceeds 200 J/m². For type I fair skin, this may be enough to produce noticeable sunburn [60]. For competitors with darker skin types, the potential for sunburn is less, given the propensity to burn reduces with increasing skin pigmentation [60]. However, given there is likely to be a range of skin types represented in competitors from a range of nations, priority for consideration of the rescheduling of the event timing to times with lower UV irradiance should be given according to the rank order listed in Table 2. Such rescheduling may also lessen the likelihood for heat stress in spectators or athletes [64,80].

An important avenue for cooling during most physical activities is evaporative cooling through sweating, particularly in the warmer summer weather conditions. Research has shown that sweating, along with wetting of the skin with water and friction from movement, can increase the photosensitivity of skin, making the athletes more susceptible to erythematic exposure effects [81,82]. Additionally, excess and long-term sweating can result in

sunscreen being washed off [18]. Furthermore, some sports have internal rules, such as minimal breaks, that inhibit sun protective behaviors [81]. The effect of sweating on the current results are the subject of a further study.

Exposure to solar UV radiation during sport and recreation has clear potential to cause harm [81,83,84] and personal protection remains an issue in a number of Olympic sports [85]. Currently it is unclear if the International Olympic Committee (IOC) has any type of tangible athlete sun exposure protection policy in place. From the results presented in this study, it is clear that for Olympic events held during daylight hours, specific sun exposure regulations should be encouraged in order to protect competitors from the long-term negative effects produced by harmful solar UV radiation. Athletes competing in environments that are subjected to the highest levels of continuous solar UV exposure (tennis, golf, cycling, beach volleyball and field hockey) would benefit most significantly from the use of sun protective behaviors, shade provision, and introduction of a set of enforceable sun protection guidelines. Furthermore, educational training interventions with elite athletes have been shown to significantly improve sun protective behaviors [19]. Consequently, before the beginning of any high UV exposure event, it is recommended that athletes are made aware of the potential exposures, and are provided proper clothing for warm-up that is comfortable and sun protective. In situations where it is not feasible to increase the amount of clothing worn by an athlete, a supply of sweat-resistant high SPF sunscreen along with sunscreen application guidelines should be provided and prescribed freely. More research is required in this area, however, to ensure that sunscreen is able to provide protection without affecting thermoregulation, blood flow, and sweating.

As observers of sun exposure risk in sport, particularly sports such as those promoted as part of the Olympic Games, we might ask: is it socially, or ethically responsible to promote events without giving due attention to the safety of athletes who model behavior that demonstrates the potential for elevated risk of developing skin cancer? Perhaps this is best left to those who aspire to the fundamental principle of Olympism; the wider viewing audience; the general public; and the competitors of the 2020 Tokyo Summer Olympic Games.

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Abbreviations

AOD:	aerosol optical depth;
DU:	dobson units;
GCF:	geometric conversion factor;
GIOVANNI:	Goddard earth sciences data and information services center, and interactive online visualization and analysis infrastructure;
GPF:	Garment protection factor;
IOC:	international Olympic committee;
KSC:	keratinocyte skin cancer;
NCF:	normalized clothing factor;
SPF:	Sun protection factor;
SZA:	solar zenith angle;
TOC:	total ozone column;
UV:	ultraviolet;
WMO:	world meteorological organization

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