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Medium Mediated Effects Increase cell Killing in a Human Keratinocyte Cell Line Exposed to Solar Simulated Radiation

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Abstract

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Purpose: The objective of this study is to investigate whether cell culture medium is a biologically relevant exposure medium that can be employed in non-ionising photobiological investigations.

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Methods: The effect of solar simulated irradiation on cell culture medium and its ability to elicit cell death was studied. The role of reactive oxygen species (ROS), cell secreted factors, and the contribution of individual components of the medium were investigated.

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Results: Cell death was found to be primarily mediated through the formation of ROS via riboflavin photosensitisation and degradation in the cell culture medium. Phenol red was found to significantly reduce the cell killing ability of riboflavin. Exposures in riboflavin free medium resulted in significantly increased cell survival compared to identical exposures in riboflavin containing medium.

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Conclusions: This study has shown that solar radiation toxicity is augmented by cell culture medium due to the presence of riboflavin. Results suggest that exposures performed in phenol red free medium may serve to increase phototoxic effects if riboflavin is present. Riboflavin free media is recommended for solar radiation investigations to eliminate concerns regarding riboflavin photosensitisation and nutrient deprivation.

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Introduction

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The incidence of skin cancer is increasing and although solar ultraviolet (UV) radiation is known to be the main environmental risk factor (Assefa et al. 2005), the mechanisms through which radiation interacts with cellular processes are still poorly understood. This lack of understanding is, in part, due to the fact that in vitro studies employ different cell models, end points and, most fundamentally, different exposure parameters making laboratory inter comparisons of results difficult. Two such parameters are the radiation source and exposure media employed.

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Non ionising photobiological exposures are predominantly performed in either cell culture media or buffers such as phosphate buffered saline (PBS) however, rarely is the reasoning behind the choice of exposure medium specified. Previously, during a reciprocity study examining the effects of solar simulated radiation on HaCaT cells, an immortalised human keratinocyte cell line, we found significant differences in survival post irradiation when cells were irradiated in Dulbecco's Modified Eagle Medium: Nutrient Mixture F-12 medium (DMEM-F12; Sigma, Dorset, U.K) and PBS (Maguire et al. 2010). Despite significantly reduced transmissive properties, DMEM-F12 medium was found to be far more phototoxic than PBS. Furthermore, this effect was observed to be wavelength dependent.

104 These surprising results spurred a more in depth analysis to determine how DMEM-F12 medium accentuates cell death. The role of ROS, the role of radiation induced cellular secretions and the effects of irradiation on DMEM-F12 itself and its components were all investigated.

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126 **Materials and Methods**

128 **Cell culture and seeding**

130 HaCaT cells (a kind gift from Dr Petra Boukamp, DKFZ, Germany), are immortal but
132 non-malignant with a doubling time of 21 hours (Boukamp et al. 1988) and mutations in
134 both p53 alleles (Lehman et al. 1993). HaCaT cells were cultured in DMEM-F12 cell
136 culture medium containing 10% fetal bovine serum (FBS, Gibco, Irvine, U.K.), 1%
138 penicillin-streptomycin solution 1000IU (Gibco) and 1 µg/ml hydrocortisone (Sigma).
140 Cells were incubated under humid conditions at 37°C, with 5% CO₂ in air. Subculture
142 was routinely performed when cells were 80-90% confluent, using a 1:1 solution of 0.2%
144 trypsin (Sigma) and 1 mM versene (Sigma) at 37°C. A single cell solution was generated
146 in fresh DMEM-F12 and cell counts were determined using a haemocytometer. HaCaT
148 cells were determined to have a plating efficiency of $27.2 \pm 3.6\%$, thus, in order to obtain
a reasonable number of colonies, cells were seeded at 400 cells in 3 ml DMEM-F12 per
well in Nunclon 6 well plates (Biosciences, Dublin, Ireland) and incubated (conditions as
above) overnight (16 hours) prior to irradiation. The extended incubation period between
seeding and irradiation was employed for all experiments since PBS exposures required
cell washes which resulted in reduced and irregular control colony numbers compared to
non-washed controls when sufficient time for attachment was not allowed. However,
dishes were checked prior to irradiation to ensure that the plated cells had not divided and
that they were still single cells.

148 **Dosimetry**

150 All irradiation experiments in this study were performed using the Q-sun solar simulator
152 (Q-panel, Cleveland, Ohio, USA). The Q-sun was calibrated using spectroradiometry
154 which is described in detail elsewhere (Maguire et al. 2010). In brief, a miniature fibre
156 optic USB2000 spectrometer (Ocean Optics, Duiven, The Netherlands) with a response
158 over 200-1100 nm was calibrated using a Bentham CL6h spectral irradiance standard
(Bentham instruments Ltd, Berkshire, UK) which has a spectral irradiance from 250 to
3000 nm and is traceable to National Physical Laboratory (NPL) standards (NPL,
Teddington, UK). Incident radiation is transmitted to the spectrometer via a 600µm optic
fibre and cosine corrected using a CC-3-UV PTFE cosine diffuser (Ocean Optics). Once
calibrated, the spectrometer was employed to obtain the calibrated spectral distribution in
 Wm^{-2} at the exposure level of the Q-sun solar simulator which is shown in figure 1.
Integrating the spectral distribution from 280 nm to 400 nm yielded a total UV intensity
of 63.63 Wm^{-2} , 62.3 Wm^{-2} in the UVA (315-400 nm) and 1.33 Wm^{-2} in the UVB (280-
315 nm) region. Exposures are presented in terms of time but can be converted to energy
using the fact that 1 Wm^{-2} equals $1 \text{ Jm}^{-2}\text{s}^{-1}$. For example a 10 minute (600 second)
exposure at an intensity of 63.6 Wm^{-2} ($63.6 \text{ Jm}^{-2}\text{s}^{-1}$) provides a dose of 38,160 ($63.6 \times$
600) Jm^{-2} or 3.816 Jcm^{-2} .

168 **Exposures**

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Once ignited, the Q-sun was allowed to stabilise for a minimum of 15 minutes. Immediately before each irradiation, the exposure field of the Q-sun was sterilised using 100 % methanol which allows exposures to be performed without lids thus eliminating attenuation effects due to the plastic lid. Cells were irradiated for 2, 5 or 10 minutes in DMEM-F12 or 10, 30 or 60 minutes in PBS where a 2, 5, 10, 30 or 60 minute exposure corresponds to a UVA/B dose of 0.8, 1.9, 3.8, 11.4 and 22.9 Jcm⁻² respectively. Post exposure, the cells removed from the exposure field and returned to the incubator for 7 days before survival was assayed using the clonogenic assay. Controls were handled identically but received sham irradiation. Secondary controls termed ‘incubator controls’ were also included for each experiment to determine the effects, if any, of handling and antioxidant supplementation on the primary controls. No difference in survival was observed due to handling or antioxidant supplementation.

184 **Direct DMEM-F12 exposures;**

186 Cells were seeded and exposed as outlined above with no medium change before or after exposures.

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Direct DMEM-F12 exposures with antioxidants;

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Cells were seeded as outlined above. Before irradiation, cells were removed from the incubator and supplemented with an antioxidant. Antioxidant final concentrations of 20 µg/ml, 100 µg/ml and 5 mM in 3 ml DMEM-F12 for catalase (Sigma, EC 1.11.1.6), superoxide dismutase (SOD, Sigma, EC 1.15.1.1) and reduced glutathione (GSH, Sigma, EC 200-725-4) respectively were chosen based on values used in the literature (Dahle et al. 2005, Lyng et al. 2006). While a non-lethal concentration of 0.5 % v/v dimethyl sulfoxide (DMSO, Sigma) was pre-determined from dose response experiments performed (data not shown).

200 **Blank DMEM-F12 medium transfers;**

202 Pre warmed (37°C) blank DMEM-F12 medium (no cells) supplemented or not supplemented with antioxidants at the above final concentrations was exposed in 6-well plates at a volume of 3 ml per well. Post exposure, the irradiated blank media ± antioxidant was harvested, filtered and transferred to unirradiated recipient single cells immediately, 1 hour, 24 hours and 48 hours post exposure. Irradiated media for the 1, 24 and 48 hour transfer time points were incubated post exposure until the appropriate time at which each was harvested, filtered and transferred to recipient single cells. Recipient cells were seeded, as outlined above, 16 hours before receiving irradiated blank DMEM-F12 ± antioxidant. DMEM-F12 covering the recipient single cells was discarded and after transfer of irradiated blank DMEM-F12 ± antioxidant, recipient cells were returned to the incubator for 7 days.

214 **Donor cell DMEM-F12 medium transfers;**

216 Donor cells were seeded such that at the time of transfer post exposure densities of 0, 1×10^5 , 2×10^5 , 5×10^5 and 1×10^6 cells would be expected. Donor cells were irradiated as
218 outlined above in 3 ml of DMEM-F12 and returned to the incubator immediately post exposure. Irradiated donor cell medium was harvested, filtered and transferred to
220 unirradiated recipient cells immediately, 1 hour, 24 and 48 hours post exposure. Recipient cells were seeded, as outlined above, 16 hours before medium transfer. The DMEM-F12
222 covering recipient cells was discarded and the donor cell medium was transferred from the donor cells to the recipient cells after which the recipient cells were returned to the
224 incubator for 7 days.

226 The irradiated DMEM-F12 medium was filtered prior to transfer using 0.2 μm filter (Nalgene/Thermo Fisher Scientific, Roskilde, Denmark) to ensure that unexposed
228 recipient cells were treated with cell free supernatant from irradiated donor cells. Although cells were not present during blank medium irradiations, the medium was also
230 filtered to facilitate inter-comparisons of the donor cell and blank medium transfers.

232 **Direct PBS (with and without reagents) or L-15 exposures;**

234 Cells were seeded and exposed as outlined above. However prior to exposure, DMEM-F12 was removed from the cells, filtered and stored in the incubator. Cells were washed
236 once with 1 ml pre warmed (37°C) PBS and the wash discarded. Cells were covered in 3 ml fresh pre warmed exposure medium (PBS, phenol red (0.00863 g/l, Sigma) in PBS,
238 phenol red (0.00863 g/l) and riboflavin (0.00022 g/l, Sigma) together in PBS, riboflavin (0.00022 g/l) in PBS or Leibovitz riboflavin free cell culture medium (L-15, Sigma)
240 containing 10% FBS, 2 mM L-glutamine (Sigma), 1% penicillin-streptomycin and 1 $\mu\text{g}/\text{ml}$ hydrocortisone) and then exposed. Post exposure, the exposure media was
242 discarded and the stored DMEM-F12 replaced at 3 ml per well before the cells returned to the incubator for 7 days. All post exposure medium changes were carried out
244 immediately post exposure except for L-15 exposures which were changed 4 hours post exposure.

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Clonogenic assay

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250 Clonogenic expansion of single cells was determined using a method devised elsewhere (Puck and Marcus 1956). This method allows survival to be quantified post exposure to
252 some toxic event by the ability of single cells to form macroscopic colonies distinguishable from one another, where such a colony is said to be a group of
approximately 50 or more cells which should arise from a single cell.

254

256 With a doubling time of 21 hours, a 7 day incubation period is sufficient for HaCaT cells to form macroscopic colonies. Thus following treatment, cells were incubated for 7 days,
after which cells were stained using a 20 % carbol fuchsin solution for 5 minutes and
258 scored. Survival curves were determined from the data collected.

260 **Statistics**

262 Results represent 3 independent tests, normalised to controls and presented as the mean
+/- the standard deviation. Statistical analyses of variance (ANOVA) were performed on
264 the linear regressions and pair-wise data using the Bonferroni adjustment were obtained.
All analyses were done using statistical software package SAS 9.1 and SAS enterprise
266 guide 3.0. Significance was taken at a level of $p \leq 0.05$.

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308 **Results**

310 Figure 2 shows the survival of HaCaT cells directly exposed in DMEM-F12 medium with
and without the presence of antioxidants. Cells directly exposed in the presence of SOD
312 and DMSO showed no significant difference compared to cells exposed without
antioxidants, indicating that neither superoxide nor hydroxyl radicals play a significant
314 role in solar radiation induced cell death in DMEM-F12 medium. Survival was
significantly increased in cells exposed directly in DMEM-F12 medium supplemented
316 with GSH and catalase compared to cells directly exposed for the same duration in
DMEM-F12 medium without antioxidant supplementation. Since catalase is not cell
318 membrane permeable (Dahle et al. 2005) this suggested a significant role for extracellular
hydrogen peroxide mediating solar simulated radiation induced cell death in DMEM-F12
320 medium. Thus, the effect of irradiating DMEM-F12 alone was investigated.

322 Figure 3 shows the survival of unexposed recipient HaCaT cells treated with irradiated
blank DMEM-F12 medium. Increased cell death with increasing exposure time of blank
324 DMEM-F12 was observed, surprisingly, at all times of transfer. However, only blank
DMEM-F12 medium exposed for 10 minutes resulted in a significant decrease in survival
326 of recipient cells at all transfer times compared to their respective controls.

328 To establish if ROS contribute to the decrease in recipient cell survival observed in figure
3, irradiated blank DMEM-F12 medium transfer experiments were repeated with and
330 without the presence of antioxidants. Figure 4 illustrates the survival of unexposed
recipient cells treated with irradiated or sham irradiated blank DMEM-F12 medium with
332 and without antioxidants immediately post exposure. As expected, the presence of DMSO
conferred no protection, while unexposed recipient cells treated with blank DMEM-F12
334 medium supplemented with GSH or catalase showed significant increases in survival.

336 Although generation of ROS is known to be rapid and short lived, irradiated blank
DMEM-F12 medium transfers with and without antioxidants were also performed 1, 24
338 and 48 hours post exposure (data not shown). The rationale for carrying out blank
irradiated DMEM-F12 transfers in the presence of antioxidants at later time intervals was
340 based on the supposition that the reduced survival observed at the later times of transfer
in figure 3 may be due to ROS induced damage of one or more of the components of
342 DMEM-F12 medium at the time of irradiation. The results revealed that the presence of
DMSO and catalase did not have an effect on survival however GSH supplementation
344 produced increased survival for all exposure times (2, 5 and 10 minutes) at all times of
transfer (1, 24 and 48 hours).

346
348 To investigate the involvement of cell secreted factors, donor cell medium transfer
experiments were performed. Figure 5 illustrates the survival of unexposed recipient cells
350 treated with donor cell medium immediately post exposure, where a clear and significant
decrease in recipient cell survival with increasing donor cell density was observed. No
352 significant difference was found between control recipient cells despite receiving sham
irradiated DMEM-F12 medium from differing donor cell densities thus eliminating
reservations regarding nutrient consumption. In addition to significant differences

354 between all 10 minute exposures and their respective controls, all recipient cells treated
356 with exposed donor cell DMEM-F12 medium were found to be significantly different
358 from one another except the 1×10^5 donor cell density which was not significantly
360 different from the 0 and 2×10^5 cell densities. These results show that the presence of
362 cells during irradiation accentuates medium mediated cell killing effects of recipient cells
in a donor cell density dependent manner. However, this effect was found to be transient,
lasting less than 1 hour, since donor cell DMEM-F12 medium transfers carried out 1, 24
and 48 hours post exposure were found to elicit survival not significantly different from
controls at all times of transfer (data not shown).

364 To investigate the effect(s) of solar simulated radiation on DMEM-F12 and its
366 components further, fluorescence spectroscopy was employed to assess the possibility of
368 radiation induced structural changes at the molecular level that may in turn compromise
370 the functionality of a component in terms of nutrient value. Prior to fluorescence
372 spectroscopy, absorption spectroscopy was employed to determine appropriate excitation
374 wavelengths. In order to simplify presentation and avoid log-transformed data, the
376 absorption data are presented as transmittance spectra. Figure 6 shows the transmittance
378 spectra for select components of DMEM-F12 cell culture medium. It can be seen that
380 DMEM-F12 absorbs significantly below 600 nm with transmission minima observed at
382 410 nm and 558 nm. Analysis of the components of DMEM-F12 reveals how the
384 transmittance spectrum of DMEM-F12 is an amalgamation of the transmittance
386 properties of its components, particularly phenol red and FBS. At the same concentration
388 found in DMEM-F12, phenol red in PBS can be seen to have maximal absorption,
observed as troughs in the transmittance spectrum, at 435 nm and 558 nm which
coincides with the absorption troughs observed with DMEM-F12 but absent in phenol red
free DMEM-F12 with and without 10% FBS. However, the maximal absorption of
DMEM-F12 in the blue region occurs at 410 nm and not 435 nm as phenol red would
suggest. This discrepancy in maximal absorption is due to the presence of 10% FBS in
DMEM-F12, as verified by the transmittance spectra of undiluted FBS and phenol red
free DMEM-F12 containing 10% FBS, both of which can be seen to possess absorption
troughs at 410 nm as for DMEM-F12. Interestingly, the transmittance spectrum for
riboflavin in PBS shows that at a concentration analogous to that found in DMEM-F12,
riboflavin has minimal absorption but still retains absorption troughs at 370 nm and 440
nm as shown in the inset of figure 6, which concurs with values listed in the literature
(Ali and Naseem 2002).

390 Based on the transmittance spectra shown in figure 6, excitation wavelengths of 370 nm,
392 410 nm, 440 nm and 558 nm were chosen to perform fluorescence spectroscopy on all
394 eight solutions. Solutions were irradiated for 10 minutes in the Q-sun solar simulator and
396 compared to unexposed solutions examined under identical conditions. Although
398 fluorescence spectroscopy was performed using excitation wavelengths of 370 nm, 410
nm, 440 nm and 558 nm, the emission spectra obtained using an excitation wavelength of
370 nm was found to provide the most detailed account of changes incurred to irradiated
media, hence only these emission spectra are presented and discussed here.

400 Figure 7A shows the emission spectra of irradiated and unirradiated DMEM-F12 medium
402 with 10% FBS. Similar to the transmittance spectrum of DMEM-F12, the emission
404 spectrum for unexposed DMEM-F12 medium can be primarily attributed to the presence
406 of FBS and phenol red. Peak emission wavelengths for DMEM-F12 medium were
408 observed at 450 nm, 508 nm and 584 nm. Emission at 584 nm is attributed to the
410 presence of phenol red where irradiation of DMEM-F12 medium yields a reduction in
412 intensity at 584 nm similar to that observed for phenol red in PBS when irradiated as
414 shown in figure 7C. The emission peaks at 450 nm and 508 nm are attributed to the
presence of FBS where irradiation of DMEM-F12 yields a loss of the peak at 508 nm and
an increase in emission at 450 nm which is similar to the effect observed when undiluted
FBS is irradiated as shown in figure 7B. However, when undiluted FBS is irradiated the
peak emission is redistributed from 448 nm to 458 nm and may be the result of re-
absorption processes (Dalton et al. 2001, Sakuma et al. 2007) and /or radiation induced
structural changes to the emitting fluorophore(s) present in FBS. This effect is not
observed when DMEM-F12 is irradiated and may be due to the dilution of FBS in
DMEM-F12 and / or the presence of phenol red.

416 Comparing the emission spectra of three unirradiated solutions with and without phenol
418 red shows the presence of phenol red to reduce the fluorescence intensity of all three
420 solutions. The emission spectra for unirradiated PBS with and without phenol red are
422 shown in figures 7C and 7G. The fluorescence spectrum of PBS without phenol red
424 (figure 7G) shows PBS to have an emission peak at 420 nm despite PBS being minimally
426 absorbing as previously shown (Maguire et al. 2010). In the presence of phenol red, the
428 emission peak of unirradiated PBS is still visible at 420 nm (figure 7C). However, the
430 intensity can be seen to be reduced by 70-75% due to the presence of phenol red.
432 Similarly for DMEM-F12, the unirradiated emission spectra of the cell culture medium
434 with and without phenol red presented in figures 7A and 7F show the presence of phenol
436 red to reduce the peak emission intensity by approximately 25%. The third solution
438 examined was riboflavin in PBS with and without phenol red, shown in figures 7E and
440 7D respectively, where the peak emission can be seen to be reduced by more than 50%
442 due to the presence of phenol red. It is clear from these results that phenol red reduces the
fluorescence emission of different fluorophores excited at 370 nm. This suggests that
phenol red acts as a quencher due to a combination of the facts that phenol red is a potent
absorber of radiation below 600 nm (figure 6), and yet is minimally fluorescent (figure
7C). When a solution is irradiated, the ability of that solution to absorb incident radiation
is dependent on the abilities of the absorbing species present in the solution to absorb at a
given wavelength. Thus, it is reasonable to assume that the emission spectrum of a given
solution is dependent on the absorbing potential of the different fluorophores present in
the solution. Compared to phenol red free DMEM-F12, riboflavin in PBS, and PBS alone
(Maguire et al. 2010), the absorption potential of phenol red in PBS at 370 nm far
exceeds that of the aforementioned solutions (figure 6). Hence inclusion of phenol red in
DMEM-F12 medium, PBS and riboflavin in PBS reduces the intensity of their respective
emission spectra since the number of incident photons available for absorption to initiate
fluorescence is much reduced compared to the availability in the absence of phenol red.

444 Furthermore, since phenol red is minimally fluorescent, its presence in the emission
446 spectrum of a solution can be poorly represented despite its ability to modify the optical
448 properties of the solution. This is demonstrated by the visibility of riboflavin in the
450 emission spectrum of DMEM-F12 in the presence (figure 7A) and absence (figure 7F) of
452 phenol red. The peak emission of unirradiated riboflavin occurs at 515-520 nm as shown
454 in both figures 7D and 7E where the presence of phenol red reduces the fluorescence
456 intensity of this peak emission by approximately 50% (figure 7E). Thus, only in the
458 absence of phenol red can the presence of riboflavin be detected in the emission spectrum
460 of unirradiated DMEM-F12, peaking at 515 nm and over shadowing the emission of 10%
462 FBS at 508 nm as shown in figure 7F. Moreover, irradiating riboflavin in the absence or
464 presence of phenol red can be seen to reduce emissions at 515-520 nm and introduce a
new emission peak at 460 nm. This new feature at 460 nm is attributed to radiation
induced structural alterations of the riboflavin molecule leading to a blue shift (i.e.
spectral movement toward shorter wavelengths) in the absorption and emission spectra of
the modified riboflavin molecule, thus reducing emissions at 515-520 nm. However, it
can be seen that the emission at 515-520 nm is still the dominant emission in the presence
of phenol red (figure 7E). This is attributed to the ability of phenol red to absorb incident
radiation more effectively than riboflavin resulting in fewer alterations of riboflavin
molecules and thus less emission at 460 nm compared to the emission spectrum of
irradiated riboflavin in the absence of phenol red.

464
466 Based on the fluorescence results, the effects of phenol red and riboflavin on cell survival
468 were investigated. All medium changes were carried out immediately post exposure for
470 all variant PBS exposures to limit the length of time cells were without nutrients. To
472 minimise differences between direct DMEM-F12 and L-15 exposures, cells irradiated in
474 L-15 cell culture medium would ideally be maintained in L-15 for the full 7 days prior to
476 clonogenic assay with no medium change post exposure. However, HaCaT cells cultured
478 in L-15 showed reduced proliferative abilities compared to cells cultured in DMEM-F12,
480 which concurs with the results of Werner et al. (2005) who observed decreased
482 proliferative rates in HepG2 cells cultured in riboflavin deficient medium, thus
484 eliminating the possibility of L-15 clonogenic expansion. Hence, it was necessary to find
a time point to perform medium changes at which changing the medium of direct
DMEM-F12 exposures would yield survival not significantly different from DMEM-F12
exposures with no medium change. This medium change time point was found to occur
24 hours post exposure (figure 8) which was deemed unsuitable for L-15 exposures due
to the reduced proliferative capacity of HaCaT cells in L-15. Medium changes performed
1 to 8 hours post exposure yielded survival not significantly different from one another
but all significantly increased with respect to no medium change (figure 8). Since there
was no difference between changing the medium 1 to 8 hours post irradiation, a median
time point of 4 hours was employed for cells exposed in L-15 before the stored DMEM-
F12 was re-introduced.

486 The survival curves for cells irradiated in the aforementioned solutions are shown in
488 figure 9. All media resulted in reduced but not significantly different survival following a
10 minute exposure (figure 9) which concurs with the survival of cells irradiated in
DMEM-F12 medium for 10 minutes and receiving a medium change immediately post

490 exposure (figure 8). A 60 minute exposure resulted in little or no survival irrespective of
the exposure medium. However, a 30 minute exposure resulted in mean survival rates of
492 37% for PBS, 23% for L-15, 17% for phenol red, 14% for phenol red and riboflavin
together and less than 1% survival for cells irradiated in riboflavin. The results
494 demonstrate that riboflavin in PBS is the most phototoxic solution which suggests that
riboflavin is the primary component responsible for the dramatic dose response observed
496 in direct DMEM-F12 medium exposures. In agreement with the fluorescence results, the
survival curves shown in figure 9, demonstrate that the presence of phenol red with
498 riboflavin during irradiation, lessens the cell killing effect of riboflavin.

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536 Discussion

538 Previously, it was observed that the survival of HaCaT cells irradiated in DMEM-F12
540 medium was significantly reduced compared to identical exposures in PBS, despite PBS
542 possessing superior optical transmittance properties that ensures cells irradiated in PBS
544 would receive a larger dose than their counterparts irradiated in DMEM-F12 medium
(Maguire et al. 2010). Interestingly, this effect was observed when cells were irradiated
with two different solar simulators but not a UVB fluorescent lamp which suggests this
effect is wavelength dependent. Based on these intriguing observations, the augmented
cell killing abilities of DMEM-F12 medium was further investigated in the present study.

546 The potential role of ROS in DMEM-F12 medium mediated cell death was investigated
548 using antioxidants. Both GSH and catalase, which are potent inhibitors of hydrogen
peroxide, were found to increase survival significantly, with catalase being significantly
550 more effective than GSH. This was surmised to be due to differences in cellular uptake
since cells can readily uptake GSH but not catalase (Dahle et al. 2005), which in turn
552 suggests that hydrogen peroxide is produced predominantly in the extracellular medium.
This was confirmed when cell death incurred in unexposed recipient cells treated with
554 irradiated blank DMEM-F12 medium immediately post exposure was diminished by both
GSH and catalase but GSH was found to be more effective than catalase and GSH
556 supplemented direct exposures. The increased efficacy of GSH is attributed to the
absence of cells and thus no reduction in the extracellular concentration of GSH present
558 during blank DMEM-F12 irradiation. These results provide strong evidence that solar
simulated radiation induced cell death in DMEM-F12 medium is mediated by the
560 extracellular generation of hydrogen peroxide.

562 Direct exposures were found to incur increased cell killing compared to indirect
exposures. This may be the results of (i) the time taken to exact immediate medium
564 transfers thus treating recipient cells with DMEM-F12 with reduced levels of ROS
compared to cells directly exposed, (ii) direct interaction of incident radiation with cells
566 during exposure and / or (iii) factors secreted by irradiated cells. This latter possibility
was investigated by irradiating cells of varying density in DMEM-F12 medium,
568 harvesting the medium immediately post exposure and transferring to unirradiated
recipient cells. A clear and significant reduction in recipient cell survival was observed
570 with increasing donor cell density. This donor cell density dependent reduction in
survival may be the result of cell mediated increases in extracellular ROS. When
572 examining the effect of hydrogen peroxide supplementation on intracellular ROS, Garg
and Chang (2004) found that fluorescence of the oxidised derivative of 2',7'-
574 dichlorodihydrofluorescein diacetate (H₂DCF-DA), 2',7'-dichlorofluorescein diacetate
(DCF-DA), was predominantly extracellular. Due to the fact that hydrogen peroxide
576 could not oxidise H₂DCF-DA in the absence of cells, Garg and Chang (2004) concluded
that hydrogen peroxide permeabilised the plasma membrane thereby facilitating the efflux
578 of intracellular ROS into the extracellular environment. Thus, it is probable that radiation
induced extracellular generation of hydrogen peroxide in DMEM-F12 medium promotes
580 increased intracellular ROS that diffuse out into the extracellular environment due to
hydrogen peroxide mediated plasma membrane permeabilisation. In addition to the

582 extended lifespan of hydrogen peroxide with respect to other ROS such as the hydroxyl
584 radical and superoxide (Bergendi et al. 1999), the high reactivity of the ROS like the
586 hydroxyl radical causes it to exert its effects in the vicinity of their formation (Valko et al.
2007). Thus, if irradiated donor cells do 'leak' ROS into their extracellular environment,
it is highly probable that the species involved is hydrogen peroxide.

588 While both the direct exposures and the medium transfers performed immediately post
590 exposure can be adequately explained in terms of ROS generation, the medium transfer
592 experiments performed 1, 24 and 48 hours post exposure are not as straightforward. In
594 ionising radiation studies, cell secreted factors can increase cell killing in an effect termed
596 the bystander effect which has been demonstrated to be donor cell density dependent
598 using medium transfer techniques (Mothersill and Seymour 1997, and has also been
600 reported in response to UV radiation (Banerjee et al. 2005, Whiteside and McMillan
602 2009). Irradiated blank non-supplemented DMEM-F12 medium transfers at 1, 24 and 48
604 hours post exposure were performed to serve as controls for donor cell medium transfer
606 experiments since Mothersill and Seymour (1997) found that irradiated blank medium
608 had no effect on recipient cell survival. Thus, cell death incurred when recipient cells
610 were treated with irradiated blank DMEM-F12 medium 1, 24 and 48 hours post exposure
612 (figure 3) was highly unexpected and further confounded when it was found that donor
614 cell medium transfers performed 1, 24 and 48 hours post exposure did not incur cell death
616 (data not shown). In fact, donor cell medium transfers were found to yield survival not
618 significantly different from controls at all the late times of transfer (1, 24 and 48 hours)
620 and irrespective of donor cell density. These results infer that solar simulated radiation
622 degrades the nutrient quality of DMEM-F12 but the presence of cells during irradiation
624 provides a protective effect when the medium is transferred to unirradiated recipient cells
626 at or later than 1 hour post exposure. It has been reported that hydrogen peroxide is stable
in cell free solutions (Garg and Chang 2004), in fact it has been reported that hydrogen
peroxide produced in cell free solutions in response to UVA irradiation retained its
cytotoxicity for at least 40 minutes post irradiation (Sato et al. 1995). Thus, blank
DMEM-F12 transfer experiments were repeated in the presence of antioxidants. As
mentioned, DMSO and catalase had no effect on survival but similar to the immediate
GSH blank medium transfers, blank GSH supplemented DMEM-F12 was also found to
result in survival not significantly different to controls at all the late times of transfer
(data not shown). Since no protective effect was observed due to the presence of catalase
at the late transfer times, this eliminates the possibility that hydrogen peroxide maintains
a cytotoxic threshold in blank DMEM-F12 medium for 1 hour or longer. Thus, cell death
incurred by irradiated blank DMEM-F12 medium at the late times of transfer (figure 3)
must be due to solar simulated radiation induced degradation of DMEM-F12 which GSH
has the capacity to overcome. The fluorescence results show that solar simulated
irradiation of riboflavin causes blue shifts in the emission spectrum of riboflavin that
persists for at least 48 hours. Such spectral movements toward higher energy wavelengths
(blue shifts) are indicative of structural changes in the form of conjugation losses
(Candeias et al. 2001). Thus, it is surmised that solar simulated radiation degrades and
defunctionalises riboflavin in DMEM-F12 in a dose dependent manner. Therefore, it is
concluded that the survival of unirradiated recipient cells treated with blank irradiated
DMEM-F12 post exposure (figure 3) is dependent on the exposure duration (which

628 determines the degree of nutrient degradation) of DMEM-F12. These dose response
630 curves are not dependent on the time of transfer post irradiation for two reasons; (1) all
632 unirradiated recipient cells treated with blank irradiated DMEM-F12 were seeded 16
634 hours prior to treatment and are thus assumed to be identical in terms of density and
636 growth phase at the time of treatment regardless of the time of medium transfer post
638 irradiation and (2) the nutrient content of irradiated DMEM-F12 cannot recover or further
640 degrade post irradiation unless further treatments are administered. The enhanced cell
642 death observed at the immediate transfer time point in figure 3 is attributed to the
644 transient production of ROS in blank DMEM-F12 in addition to the nutrient degradation.
646 This conjecture agrees with observations that cell culture media degrade when exposed to
648 background lighting (Grzelak et al. 2001). Riboflavin is the precursor to coenzymes
650 flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD) (Campbell 1996,
652 Werner et al. 2005). FAD is involved in various metabolic processes such as protein
654 folding in the endoplasmic reticulum (Papp et al. 2005, Werner et al. 2005) and the redox
656 cycle of glutathione where FAD is a coenzyme for glutathione reductase (Schulz et al.
658 1982, Becker et al. 1995, Werner et al. 2005). In light of the fluorescence results
660 supporting defunctionalisation of riboflavin, it is believed that GSH supplementation not
662 only serves to increase the capacity of cells to process endogenous ROS by increasing the
664 intracellular ratio of reduced to oxidised glutathione (GSH:GSSG), but also enables
666 coenzymes formed from the remaining functional riboflavin to participate in metabolic
668 processes other than the redox cycle of glutathione such as protein folding. The increased
670 survival of recipient cells treated with DMEM-F12 irradiated in the presence of donor
672 cells is attributed to cell secreted factors. This effect is currently under investigation and
may be due to transforming growth factor beta (TGF- β 1) secreted into DMEM-F12
medium by the donor cells since similar effects have been reported in α -particle radiation
bystander investigations (Lehnert et al. 1997, Narayanan et al. 1997, Iyer et al. 2000).

654 Furthermore riboflavin has been reported to produce hydrogen peroxide when irradiated
656 (Jernigan 1985, Grzelak et al. 2000). However, absorption spectroscopy clearly
658 demonstrated that DMEM-F12 is optically dominated by the presence of FBS and phenol
660 red while riboflavin, at the concentration employed in DMEM-F12, was found to be
662 minimally absorbing. Despite this, the effect of directly irradiating cells in the presence of
664 riboflavin was investigated. Both individual and composite solutions of riboflavin and
666 phenol red at the same concentrations found in DMEM-F12 medium and riboflavin free
668 cell culture medium L-15 and PBS alone were investigated. The production of ROS in
670 cell culture media when irradiated with visible or UVA radiation has been previously
672 reported to be reduced when supplemented with 10% FBS (Edwards and Silva 2001,
Mahns et al. 2003), thus FBS was not investigated for photosensitising effects.

666 It was found that the presence of phenol red in PBS produced increased cell killing above
668 that observed with PBS alone ($p \leq 0.05$). However, the results also show the presence of
670 phenol red to reduce the cell killing abilities of riboflavin, which in the absence of phenol
672 red results in virtually no survival following a 30 minute exposure. Although exposures
performed in phenol red with and without riboflavin produce survival not significantly
different from one another ($p=1.00$), exposures with phenol red alone exhibit a slight
positive effect in the absence of riboflavin. These results concur with the literature

674 (Grzelak et al. 2000, 2001) and the fluorescence results by showing phenol red to be a
676 mild photosensitiser that possesses significant quenching abilities.

678 It is clear from the 30 minute exposures in figure 9 that the most phototoxic solution is
680 riboflavin supplemented PBS which suggests that riboflavin is the primary component
682 responsible for the dramatic dose response observed when cells are irradiated in DMEM-
684 F12 medium. This conjecture is supported by preliminary results (two independent tests
686 with 3 replicates per independent test) for cells irradiated in DMEM-F12 medium for 30
688 minutes and receiving a medium change immediately post exposure. Cells irradiated for
690 30 minutes in DMEM-F12 medium resulted in survival rates between 0.5% and 4% (data
692 not shown) which was found to be not significantly different ($p=1.00$) to the survival of
694 cells irradiated for 30 minutes in riboflavin supplemented PBS. The phototoxic abilities
696 of riboflavin are further demonstrated by the absence and presence of riboflavin in cell
698 culture media during irradiation. A 10 minute exposure in L-15 and DMEM-F12 medium
700 resulted in significantly different survival rates ($p\leq 0.05$) of approximately 80% and 35%
702 respectively when the exposure medium is replaced 4 hours post exposure. Furthermore,
704 the survival of cells irradiated for 30 minutes in L-15 medium was found to be
706 significantly increased ($p\leq 0.05$) with respect to the survival of cell irradiated for 30
708 minutes in DMEM-F12 medium despite receiving a medium change 4 hours later than the
710 DMEM-F12 exposures. It is possible that further increases in cell survival would be
712 observed if cells irradiated in L-15 medium received medium changes immediately post
714 exposure, since it is unlikely that riboflavin is the only photosensitiser present in cell
716 culture media. This may explain the reduced survival of cells irradiated for 30 minutes in
718 L-15 medium compared to their respective counterparts irradiated in PBS. However, this
reduced survival is attributed to the presence of phenol red, since phenol red
supplemented PBS exposures produced cell survival similar to cells irradiated in L-15
medium. Additionally, tryptophan and tyrosine among others have been found to be
negligibly oxidising when irradiated in the absence of riboflavin (Grzelak et al. 2001).

702 The results present strong evidence that the photosensitiser in DMEM-F12 medium
704 responsible for the extracellular production of hydrogen peroxide is riboflavin.
706 Photosensitisation by riboflavin has been demonstrated to occur by both type I and type II
708 photosensitising mechanisms (Edwards and Silva 2001). It is known that singlet oxygen,
710 which is formed by type II mechanisms, inactivates the enzymatic activity of catalase
712 (Escobar et al. 1996, Kim et al. 2001). However, the presence of catalase during solar
714 simulated irradiation does not appear to impair its antioxidant properties which suggests
716 that riboflavin photosensitisation in DMEM-F12 medium occurs primarily by electron
718 transfer processes (type I mechanisms) similar to that previously reported (Ito et al.
1993). However, Edwards and Silva (2001) observed reduced catalase activity that
saturated at 30% deactivation when catalase was irradiated with visible radiation in the
presence of riboflavin. Thus, it is possible that type II mechanisms also occur, but to a
lesser extent than type I mechanisms, when DMEM-F12 medium is irradiated with solar
simulated radiation. This may serve to explain the difference in efficacy between GSH
and catalase induced survival in unexposed recipient cells treated with irradiated blank
DMEM-F12 medium supplemented with GSH or catalase. Furthermore, Kim et al (1993)
have reported that the type and quantum yield of oxidative species generated by flavin

720 photosensitisers, such as riboflavin, is dependent on the concentration of electron donors
and acceptors in solution with the flavin photosensitiser which may serve to explain the
722 slight, albeit not significant, reduction in cell survival post direct irradiation in the
presence of SOD. It is possible that superoxide is generated in DMEM-F12 also via
724 riboflavin photosensitisation that may, as a result of the dismutation process in the
presence of SOD, further increase radiation induced extracellular concentrations of
726 hydrogen peroxide. This was not further investigated at present since the effect of SOD
was not significant.

728
It is well documented in the literature that riboflavin is a photosensitiser (Joshi et al.
730 1987, Kim et al. 1993, Edwards and Silva 2001, Keynes et al. 2003, Besaratinia et al.
2007) that absorbs at 365 nm and 420 nm (Ali and Naseem 2002). In fact, it is for this
732 reason that Mahns et al (2003) recommends using PBS as the exposure medium during
UVA irradiation. In non ionising radiation studies, cell culture medium with or without
734 phenol red and PBS appear to be the primary exposure media employed in the literature,
with a possible bias toward the use of PBS. However, rarely is it mentioned why a
736 particular media was chosen. Previously we have demonstrated that the response of cells
during irradiation is not only dependent on the spectral distribution and irradiance of the
738 irradiator employed but also the exposure medium (Maguire et al. 2010). Although we
showed differences in cell survival elicited when cells were irradiated in PBS and
740 DMEM-F12, differences also exist between studies that employ seemingly identical
exposure media. For example, Sato et al. (1995) concluded that hydrogen peroxide is the
742 primary source of toxicity in a riboflavin supplemented PBS solution irradiated with
UVA radiation. In contrast, Mahns et al. (2003) found that hydrogen peroxide was not
744 generated in a riboflavin supplemented PBS solution unless tryptophan was also present
during UVA irradiation. Since the quantum yield for superoxide is high in flavin
746 photosensitisers in the absence of electron donors (Kim et al. 1993), it is probable that the
discrepancy lies in the PBS supplementation where Sato et al (1995) employed PBS
748 supplemented with inorganic salts and glucose while Mahns et al. (2003) used non
supplemented PBS.

750
Such discrepancies highlight the need to identify a suitable exposure medium that can be
752 employed in UVA, UVB and solar simulated radiation investigations with minimal
modifications, in order to aid not only the biological relevance of an investigation but
754 also inter lab comparison. Although we have demonstrated that PBS possesses superior
transmittance properties (Maguire et al. 2010), it is known that the capacity of radiation
756 to penetrate the skin decreases with decreasing wavelength (Freeman et al. 1989, de
Gruijl 1997). Using ex vivo full thickness epidermal samples, it has been shown that UV
758 radiation is predominantly absorbed in the epidermal layer of the skin with less than 20 %
of the incident radiation at 365 nm exiting the basal layer (Bruls et al. 1984). Thus, PBS
760 does not simulate in vivo conditions by permitting increased transmission of short
wavelengths to proliferating cells which are found predominantly in the basal layer,
762 which would not occur in vivo due to absorption in suprabasal layers. The biological
irrelevance of PBS is further demonstrated by the absence of nutrients in the extracellular
764 environment during irradiation since keratinocytes in the non vascularised epidermal
layer obtain nutrients that diffuse across the basal membrane into the extracellular space

766 (Schallreuter and Wood 1995). Thus under ‘normal’ conditions, in vivo epidermal
768 keratinocytes are not devoid of nutrients in their extracellular environment during solar
irradiation. The importance of this has been demonstrated in vitro (Kuhn et al. 1999) and
770 in vivo (Lewis et al. 2009) where human keratinocytes irradiated with UVB radiation in
the absence of exogenous growth factors that activate IGF-IR (insulin like growth factor I
772 IR receptor) were significantly more apoptotic than those irradiated in the presence of IGF-
IR activators. The pro-survival response of IGF-IR activation was found to result in post
774 mitotic cells whereas IGF-IR inactivated cells that survived irradiation were fully capable
of proliferating with potentially mutagenic genomes.

776 Although cell death is a convenient end point to examine, it is important to note that cells
may achieve this outcome through very different means. As discussed above, the
778 presence or absence of electron donors during irradiation appears to determine the type of
ROS generated when riboflavin is photosensitised. Thus, while no significant difference
780 in cell survival was observed between cells irradiated for 30 minutes in riboflavin
supplemented PBS and DMEM-F12 medium (data not shown), the mechanisms by which
782 cell death is achieved may be significantly different. This emphasises the need for both
mechanistic and mutagenic investigations. Such studies are currently underway.

784 Whilst it is recognised that in vitro experimentation will never truly mimic the in vivo
786 situation, it is imperative that in vitro studies attempt to bridge the gap separating them in
order for progress to be made in skin carcinogenesis investigations. Thus, based on
788 evidence in the literature and the results presented here, it is recommended that serum
supplemented riboflavin free cell culture media is employed as the exposure medium
790 during non-ionising radiation investigations. Since radiation is not only capable of
riboflavin photosensitisation but also defunctionalisation, it has the potential to further
792 confound investigations if cells are maintained in the exposed medium for extended
durations post irradiation. Furthermore, the ability of phenol red to quench riboflavin
794 photosensitisation suggests that phenol red free cell culture media are substantially more
phototoxic not only because of uninhibited photosensitisation of riboflavin but also
796 because amino acids such as tryptophan and tyrosine have been demonstrated to augment
the oxidising potential of riboflavin (Grzelak et al. 2001). Thus, it is further
798 recommended that phenol red free cell culture media are not used during non ionising
radiation investigations.

800

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802

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810

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948 **Figure legends**

950

952 Figure 1 Spectral irradiance of the Q-sun solar simulator at the exposure level (—) measured using a Ocean Optics USB2000 miniature fibre optic spectrometer calibrated using spectroradiometry and typical solar irradiance for Florida at noon midsummer (---) as provided by the manufacturer Q-Panel demonstrating the environmental relevance of the Q-sun solar spectrum

956

958 Figure 2 Direct exposure dose response plots for HaCaT cells irradiated in DMEM-F12 with and without the presence of SOD (1 mg/ml), DMSO (0.5% v/v), GSH (5mM) or catalase (20µg/ml). Cells were irradiated using the Q-sun solar simulator for (□) 2 minutes (0.8 Jcm⁻²), (■) 5 minutes (1.9 Jcm⁻²), (■) 10 minutes (3.8 Jcm⁻²) or (■) sham irradiated (0 Jcm⁻²) where solid and thatched bars indicate the absence and presence of antioxidants respectively; data presented as the mean ± standard deviation for n = 3 independent experiments, * indicates significant difference between time matched exposures, p ≤ 0.05.

966

968 Figure 3 Indirect exposure dose response plots; blank (no cells) DMEM-F12 irradiated, harvested, filtered and transferred to unirradiated recipient cells immediately (0hr), 1, 24 and 48 hours post exposure. Recipient cells were treated with blank DMEM-F12 irradiated in the Q-sun solar simulator for (□) 2 minutes (0.8 Jcm⁻²), (■) 5 minutes (1.9 Jcm⁻²), (■) 10 minutes (3.8 Jcm⁻²) or (■) sham irradiated (0 Jcm⁻²); data presented as the mean ± standard deviation for n = 3 independent experiments, * indicates significant difference between the starred dose and its respective control, p ≤ 0.05.

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978 Figure 4 Indirect exposure dose response plots with and without antioxidants. Blank (no cells) DMEM-F12 with and without antioxidants (DMSO (0.5 % v/v), GSH (5 mM) or catalase (20 µg/ml)) irradiated, harvested, filtered and transferred to unirradiated recipient cells immediately post exposure. Recipient cells were treated with blank DMEM-F12 irradiated in the Q-sun solar simulator for (□) 2 minutes (0.8 Jcm⁻²), (■) 5 minutes (1.9 Jcm⁻²), (■) 10 minutes (3.8 Jcm⁻²) where solid and thatched bars indicate the absence and presence of antioxidants respectively; data presented as the mean ± standard deviation for n = 3 independent experiments, * indicates significant difference between time matched exposures, p ≤ 0.05.

986

988 Figure 5 Donor cell medium transfer dose response plots. Donor cells seeded at a density of 0, 1x10⁵, 2 x10⁵, 5 x10⁵ or 1 x10⁶ cells per well in 3 ml DMEM-F12 were irradiated for 10 minutes (3.8 Jcm⁻², ▨) in the Q-sun solar simulator or sham irradiated (0 Jcm⁻², ■). Immediately post exposure the donor cell medium was harvested, filtered and transferred to unirradiated recipient cells. Data presented as the mean ± standard deviation for n = 3 independent experiments; * indicates significant difference between irradiated and sham irradiated controls, all exposures tagged with ¥ are significantly

994

different to one another; § indicates significant difference with respect to donor cell
996 density 1×10^5 , $p \leq 0.05$.

998 Figure 6 Transmittance spectra for DMEM-F12 (1 —), undiluted FBS (2 ****), phenol red
1000 in PBS (3 ----), phenol red and riboflavin in PBS (4 -*-), Riboflavin in PBS (5 ----),
1002 phenol free DMEM-F12 (6 ———), and phenol free DMEM-F12 with 10 % FBS (7
-*-) where the troughs indicate absorption maxima.

1004 Figure 7 Emission spectra of irradiated (****) and unirradiated (—) DMEM-F12 cell
1006 culture medium (A), FBS (B), 0.00863 g/l phenol red in PBS (C), 0.00022 g/l riboflavin
1008 in PBS (D), 0.00863 g/l phenol red and 0.00022 g/l riboflavin in PBS (E), phenol free
1010 DMEM-F12 with 10 % FBS (F), PBS (G) excited at 370 nm. Irradiated solutions were
irradiated for 10 minutes (3.8 Jcm^{-2}) in the Q-sun solar simulator and the emission spectra
measured immediately post exposure.

1012 Figure 8 Survival of HaCaT cells irradiated in the Q-sun for 10 minutes (3.8 Jcm^{-2}) in
1014 DMEM-F12 and receiving a medium change post exposure or not (none). Data presented
1016 as the mean \pm standard deviation for $n = 3$ independent experiments; * implies significant
difference with respect to the 10 minute exposure that did not receive a medium change
post exposure (i.e. none), $p \leq 0.05$.

1018 Figure 9 Direct exposure dose response curves for cells irradiated in the Q-sun solar
1020 simulator. Cells were irradiated in PBS (○), Phenol red (0.00863 g/l) in PBS (●), Phenol
1022 red (0.00863 g/l) and Riboflavin (0.00022 g/l) together in PBS (△), riboflavin (0.00022
1024 g/l) in PBS (▲) and L-15 riboflavin free cell culture medium (□) where a 10, 30 or 60
minute exposure corresponds to a dose of 3.8, 11.4 and 22.9 Jcm^{-2} . Data are presented as
the mean \pm standard deviation for $n = 3$ independent experiments.