Acta Derm Venereol 2016; 96: 910–916

INVESTIGATIVE REPORT

Kinetic Profile of Inflammation Markers in Human Skin *In vivo* Following Exposure to Ultraviolet B Indicates Synchronic Release of Cytokines and Prostanoids

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Ultraviolet B (UVB) irradiation affects epidermal cells, which respond via a cascade of inflammation markers. After initial *in vitro* and *ex vivo* experiments, this study used cutaneous microdialysis to generate a kinetic profile for 16 cytokines and 4 prostanoids in human skin *in vivo*. Skin areas 9 cm² were irradiated with UVB (2× minimal erythematous dose) 16 h after catheter placement in the dermis of the volar forearms of healthy volunteers. Dialysates were collected at 4-h intervals up to 64 h and analysed for 5- and 8-iso-$PGF_{2\alpha}$, 9α,11α-$PGF_{2\alpha}$ and PGE_2 by gas chromatography–mass spectrometry (GC/MS). Dialysates were also analysed for interleukin (IL)-1β, IL-2, IL-3, IL-4, IL-5, IL-6, IL-8, IL-10, tumour necrosis factor (TNF)-α, Fas ligand (FasL), interferon-γ–inducible protein-10 (IP-10), monocyte chemoattractant protein 1 (MCP-1), RANTES, eotaxin, and granulocyte-macrophage colony-stimulating factor (GM-CSF) using a multiplex-based cytometric-bead-array. In conclusion, 3 peaks with synchronic release of T helper (TH) 1-directed inflammatory cytokines and prostanoids could be detected post-UVB: an early phase (4–12 h), an intermediate phase (16–24 h) and a late phase (32–40 h). A TH2-directed cytokine response was detectable at intermediate and late phases. *Key words: cytokines; prostanoids; cutaneous microdialysis; UVB; skin inflammation*.

Accepted Mar 10, 2016; Epub ahead of print Mar 17, 2016

Acta Derm Venereol 2016; 96: 910–916.

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Ultraviolet (UV) radiation, especially UVB (280–320 nm) radiation, is known as a major skin carcinogen that mainly affects epidermal cells, which mostly consist of keratinocytes. A complex cascade of acute inflammation of the skin, characterized by erythema, oedema, and immunosuppression, is induced by UVB irradiation, which, in cases of chronic exposure, can subsequently be linked to the initiation and progression of skin cancer. The role of inflammatory mediators, which include cytokines, nitric oxide, and oxidized arachidonic acid derivatives, in orchestrating cell-cell communication in the intercellular space in response to UVB irradiation is of critical importance. In addition to direct photochemical damage mediated by the generation of specific pyrimidine dimers, UVB generates high levels of reactive oxygen species (ROS) in the skin, presenting a risk of photo-oxidative damage to cells and the extracellular matrix. ROS can regulate not only the expression of inflammatory cytokines, such as tumour necrosis factor alpha (TNF-α), through nuclear factor kappaB (NF-kB) activation and tyrosine kinase-dependent pathways, but also cell death, as a mediator of apoptosis (1). Therefore, we analysed the kinetic profile of both cytokines and prostanoids, and especially 9α,11α-$PGF_{2\alpha}$, PGE2, and 5- and 8-iso-$PGF_{2\alpha}$ (2–4). Based on our initial *in vitro* studies presented here we knew that irradiation of keratinocytes results in alteration of their expression of surface molecules and secretion of cytokines, such as interleukin (IL)-1β, IL-6, IL-8, and TNF-α, in addition to prostanoids, such as PGE_2.

For a long time, microdialysis has been used to study tissue chemistry within the interstitium, pharmacokinetic drug profiles in various tissue compartments *in vivo* (5–8) and the inflammatory response by collecting inflammatory mediators from e.g. the skin (4, 9–11). The microdialysis technique seems to be superior to other techniques, such as suction blisters or biopsies, which destroy the tissue and lack the ability to elaborate a complete kinetic profile for the compounds of interest (9, 12). The principle of microdialysis is simple (7). The main problems in studying *in vivo* inflammatory responses in the skin are the low levels of mediators that can be found in the microdialysate, which need a highly sensitive analytical work-up, and the catheter placement in the skin (dermis or subcutis), which itself induces a relatively strong inflammatory response for several hours, making it difficult to separate the response to the tissue damage from the response of interest. There is also a need to establish in an animal model, using so called retrodialysis, the recovery of cytokines in *ex vivo* microdialysis experiments, before starting the experiments in humans.

In the clinical trial presented herein, we used microdialysis to establish a complete kinetic profile for inflammation markers released into the dermal inter-

 doi: 10.2340/00015555-2406
 ISSN 0001-5555

cellular space *in vivo*, over a period of 48 h after UVB irradiation (2× minimal erythematous dose (MED). For the first time, we studied the release of markers of oxidative stress (8- and 5-iso-$PGF_{2\alpha}$) and inflammation (9α,11α-$PGF_{2\alpha}$ and PGE_2) as well as of cytokines and chemokines. In particular, we examined Fas ligand (FasL), RANTES, eotaxin, granulocyte-macrophage colony-stimulating factor (GM-CSF), IL-5, and IL-13, which have not previously been studied *in vivo* in this context, and IL-1β, IL-2, IL-4, IL-6, IL-8, IL-10, TNF-α, and interferon-γ–inducible protein-10 (IP-10), which we studied more precisely and for a much longer period after irradiation than in past studies.

METHODS

In vitro *cell culture experiments (see Appendix S1[1])*

Animal model: ex vivo *recovery experiments (see Appendix S1[1])*

Clinical microdialysis experiments

Six healthy volunteers aged 26–45 years and without UVB exposure or any signs of skin inflammation within the test region within the last 6 weeks were included in this clinical trial after their informed consent and approval by the local review board of the Medical Faculty, Otto-von-Guericke-University Magdeburg, Germany (Approval 81/07). The principles of the Declaration of Helsinki were followed. The MED for each volunteer was first determined by the application of 5 increasing doses of UVB (Waldmann UV 3003K, Herbert Waldmann GmbH & Co. KG, Villingen-Schwenningen, Germany) to the contralateral forearm, ranging from 50 to 250 mJ/cm^2. Six microdialysis catheters (20 kDa cut-off membranes for the detection of prostanoids: CMA70 60/20 membranes and 100 kDa cut-off membranes: CMA71 60/20 membranes for the detection of cytokines, both from CMA Microdialysis, Sweden) were placed in the dermis on the volunteer's volar forearm at a depth of 0.7–1.2 mm with the aid of 22 MHz ultrasound. As it is known that placement of a microdialysis catheter induces an inflammatory response that is clearly detectable for up to 10–16 h post-placement (19), UVB irradiation was performed 16 h after catheter placement. The membranes were first flushed with equilibration and basal microdialysis buffers at 5 µl/min for 2 h to eliminate the initial mediators induced by catheter insertion. The membranes were then perfused with 0.9% NaCl at a flow rate of 0.5 µl/min for the collection of prostanoids and with Dextran 60 (Deltadex 60®, Deltaselect, Germany) at a flow rate of 0.2 µl/min for the collection of cytokines using a mobile CMA107 microdialysis pump (CMA Microdialysis, Sweden), which allowed free mobility throughout the whole experiment. A lower flow rate of 0.2 µl/min was used to collect the cytokines, based on the results of the recovery experiments and the high molecular weight of cytokines relative to low-molecular-weight prostanoids (20, 21). The set-up is illustrated in Fig. S1[1]. Microdialysate samples were collected after 2 h and then at 4 h intervals up to 62 h and immediately stored in liquid nitrogen. In case of prostanoid collection, 0.5 µl of the antioxidant BHT (end concentration 0.01%) was added. A total of 16 h after catheter placement, skin areas of 3×3 cm^2 above the dermal catheters were irradiated with 2×MED (350–450 mJ/cm^2). For negative controls, the same set-up was used, but without irradiation, and microdialysates were also collected for 62 h in the same way. The prostanoid and cytokine content in the microdialysates was quantified altogether using sensitive gas chromatography-mass spectrometry/negative-ion chemical ionization for lipid mediators, markers of oxidative stress (the F2-isoprostanes 5- and 8-iso-$PGF_{2\alpha}$) and markers of inflammation (the prostaglandins 9α,11α-$PGF_{2\alpha}$ and PGE_2) and a cytokine multiplex array (22), or the CBA Flex Set for the FACSCanto II (BD Bioscience, Heidelberg, Germany), respectively. The levels of the following cytokines were measured, with a limit of detection of 2.5 pg/ml: IL-1 beta, IL-2, IL-3, IL-4, IL-5, IL-6, IL-8, IL-10, TNF-α, FasL, IP-10, MCP-1, RANTES, eotaxin, and GM-CSF. Significance, where indicated, was tested using a paired 2-sample Student's *t*-test in XLSTAT 2009® and MS Excel®. The area under the curve (AUC) was calculated using MedCal® (MedCal, Belgium), and cytokine levels detected by the FACSCanto II were quantified with FCAP Array v1.0.1 (BD Biosciences, Heidelberg, Germany).

RESULTS

In vitro *cell culture experiments*

Cell culture experiments showed strong release of 9α,11α-$PGF_{2\alpha}$, PGE_2, IL-6 and TNF-α into the cell-free supernatant from the same HaCaT keratinocytes within the first 24 h after irradiation, with a maximum at 8–12 h, whereas IL-8 was elevated up to 40 h after UVB irradiation. 5- and 8-iso-$PGF_{2\alpha}$ isoprostanes, were mainly detectable intracellular (Fig. 1A, C and D), which is consistent with previous reports (4, 9, 23). However, when we compared the intracellular vs. extracellular generation of prostanoids into the surrounding medium, we observed a second peak of 9α,11α-$PGF_{2\alpha}$, released at 28 h and 36 h (Fig. 1A, C and D). Furthermore, the levels of prostanoids did not seem to increase continuously, which may result from certain instability of prostanoid mediators within the supernatant when cells were cultured up to 48 h and then collected.

Animal model: ex vivo *recovery experiments*

To switch from the *in vitro* situation to the *in vivo* situation using microdialysis, recovery of these mediators, meaning the amounts of specific mediators that can be found in a microdialysate, from the concentration in real tissue must be determined first. For this purpose, we used the method of retrodialysis *in vivo* to determine the recovery of cytokines in the skin, as *in vitro* approaches to determine recovery do not reflect the *in vivo* situation (20, 21). The recovery of prostanoids *in vivo* using porcine skin has already been determined and reported by us previously (18). As expected, high-molecular-weight cytokines are much more difficult to collect due to ultrafiltration of the dialysate, protein interactions or binding to the extracellular matrix of the dermis and to the outer microdialysis membrane (Appendix S1; SFig. 1C[1]). To avoid ultrafiltration and to ensure the highest concentration of cytokines in the

[1]https://doi.org/10.2340/00015555-2406

dialysate in the shortest period, we used a solution of the colloid Dextran 60 as the perfusate. The recovery of cytokines correlated with the flow rate and the molecular weight of the individual cytokines, with very low recovery for a flow rate of 1 µl/min and for higher molecular-weight chemokines and cytokines such as IL-6 and higher recovery for flow rates of 0.5 and 0.2 µl/min and for lower molecular-weight chemokines and cytokines (IL-8, eotaxin, and RANTES) (Appendix S1; SFig. 1C[1]).

Clinical microdialysis experiments

In our approach, we compared the release of prostanoids and cytokines and analysed the release of these mediators in human skin *in vivo* until 48 h post-irradiation. Furthermore, we investigated different cytokines, such as FasL; the chemokines RANTES, eotaxin, and GM-CSF; and IL-13, which are mediators of the TH2 response. For cytokine detection in microdialysates, we used a different method, a cytometric-based cytokine array, which allows the detection of up to 36 cytokines (which can be individually selected) in a single 50 µl sample, with a lower limit of detection at 2.5–5 pg/ml. This method allows collection intervals of 4 h and, therefore, a more precise kinetic profile for cytokines until 48 h after UVB irradiation. Unfortunately, IL-5 remained undetectable throughout the study, as its concentration was below 2.5 pg/ml. Placement of the microdialysis catheters strongly induced a TH1-related immune response, which is consistent with previous reports (10, 24), as levels of IL-6, IL-8, and IL-1 beta were strongly increased, with much higher levels than after UVB irradiation. However, increased levels of prostanoids, and especially 8-iso-PGF2α; elevated levels of TNF-α, FasL, IL-10, IL-13, IP-10, and GM-CSF; and interestingly relatively high levels of RANTES were detected (Figs 2 and 3) after catheter placement and tissue trauma. After UVB irradiation, we could identify 3 time periods in which cytokines and prostanoids were increasingly detectable: an early phase, at 4–12 h; an intermediate phase, at 16–24 h; and a late phase, at 32–40 h. The prostanoids PGE2 and 8-iso-$PGF_{2\alpha}$ showed increasing levels within these time periods, whereas the levels of 9α,11α-$PGF_{2\alpha}$ were strongly increased at 8–12 h and 32–36 h (Fig. 2A–C). The early-phase increase in cytokine levels was more TH1 dominated, and the late phase was more TH2 dominated, whereas, in the intermediate phase, a mixed TH1/TH2 response was detectable (Figs 2 and 3). These findings indicate a slow TH1-to-TH2 shift within 40 h after UVB irradiation (Figs 2 and 3). Because not all cytokines reached baseline at UVB challenge, we compared AUC values after UVB irradiation with the AUC values for negative control dialysates without UVB irradiation. The mean AUC was clearly superior for all mediators except IL-1 beta and IL-13 (Table I). However, the negative controls showed a completely different profile, as they were nearly at baseline until 44 h, but at 44–48 h, an increase of some mediators could be recognized: IL–6, IL-8, IP-10, MCP-1 and 9α,11α-PGF2α, indicating that this release may be induced by beginning tissue-catheter irritations triggered by the immune system 58–62 h after placement (data not shown). This phenomenon is also the reason not

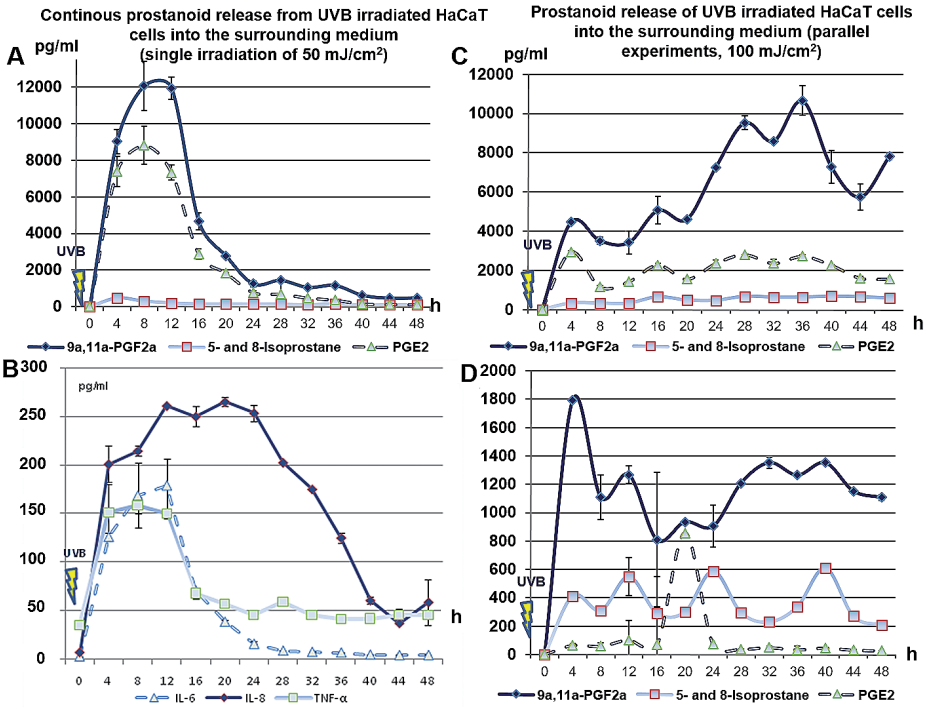

Fig. 1. Release of prostanoids and cytokines *in vitro* after ultraviolet B (UVB) irradiation of HaCaT cells (2.2 × 107). Supernatants were repeatedly collected every 4 h in supernatants after UVB irradiation of HaCaT cells at 50 mJ/cm². Continous release of prostanoids ((A) isoprostanes 5- and 8-iso-PGF2α and prostaglandins 9α,11α-PGF2α and PGE2) cytokines ((B) IL-6, IL-8 and TNF-α) into the surrounding medium. (C) Comparison of extracellular release vs. (D) intracellular generation of prostanoids after UVB irradiation (100 mJ/cm²) of HaCaT keratinocytes in parallel experiments. Cells and supernatants were harvested simultaneously every 4 h up to 48 h after irradiation.

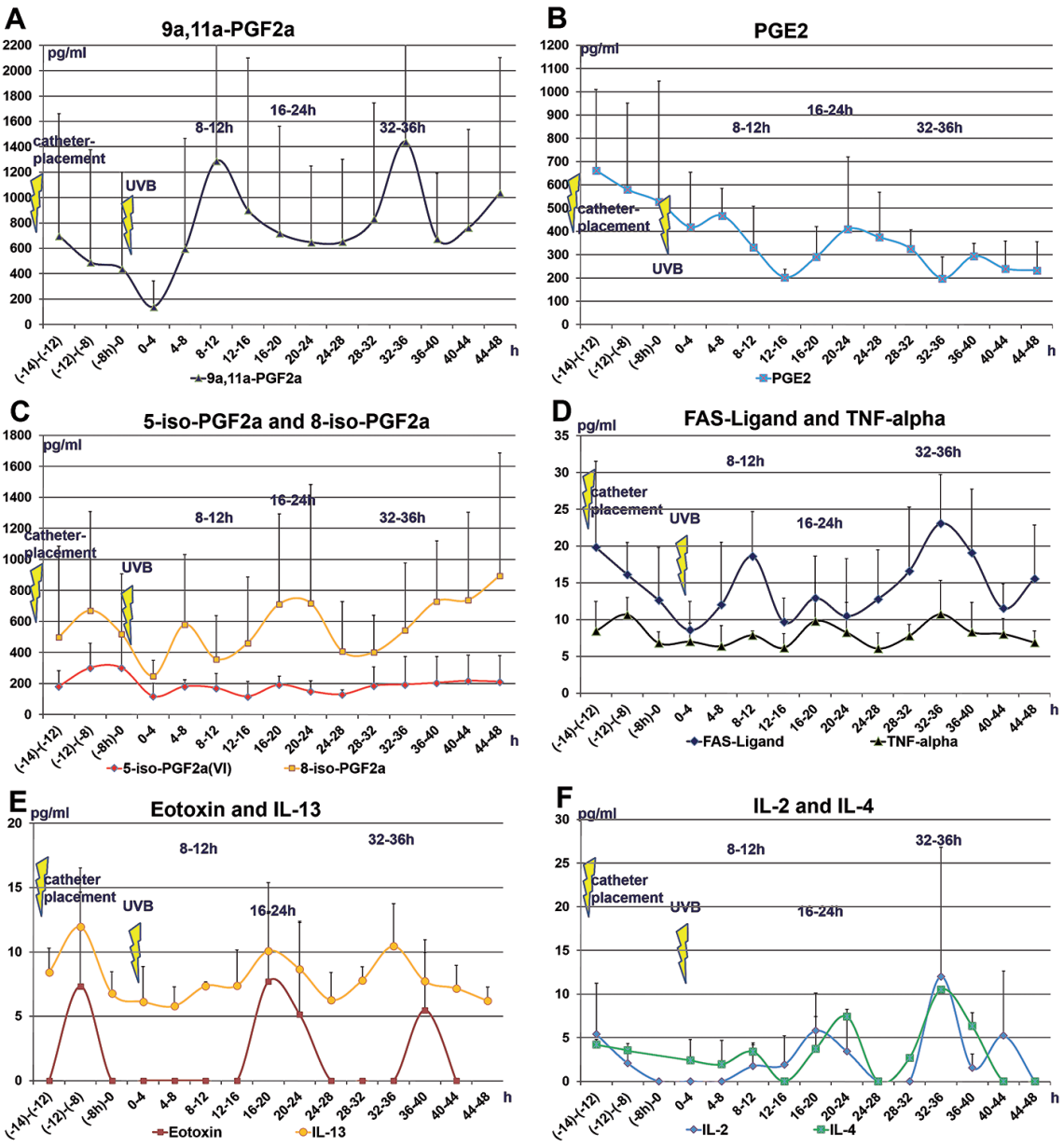

Fig. 2. Kinetic profiles of (A, B) prostanoids and (C-F) cytokines, indicating a synchronic increase in the release of these mediators in different time periods: early phase (4–12 h), intermediate phase (16–24 h) and late phase (32–40 h) (mean with standard deviation).

all differences between UVB treatment and the control reached statistical significance, as shown for TNF-α, FasL, IL-3, IL-4, IL-10, GM-CSF, RANTES and all prostanoids (9α,11α-$PGF_{2\alpha}$, PGE2, and 5- and 8-iso-$PGF_{2\alpha}$) (Table I). Interestingly, FasL and 9α,11α-PGF2α showed relatively synchronic release (Fig. 2A and D).

DISCUSSION

Using clinical microdialysis, we elaborated, for the first time, a complete kinetic profile for prostanoids, cytokines, and chemokines released into the dermal intercellular space *in vivo* 14 h before and up to 48 h after UVB irradiation (2×MED) at 4 h intervals. We identified 3 time-periods in which cytokines and prostanoids were increased: an early phase, at 4–12 h after UVB; an intermediate phase, at 16–24 h after UVB; and a late phase, at 32–40 h after UVB. The prostanoids PGE2 and 8-iso-$PGF_{2\alpha}$ showed increasing levels within these time periods, whereas the levels of 9α,11α-$PGF_{2\alpha}$ were strongly increased at 8–12 h and 32–36 h. Furthermore, we could identify an early-phase increase in cytokine levels that was more TH1 directed, and a late phase that was more TH2 directed, whereas, in the intermediate phase, we observed a mixed TH1/TH2, indicating a slow TH1-to-TH2 shift within 40 h post-irradiation.

Prostanoid mediators are formed by 2 different pathways: that is, enzymatically and non-enzymatically. Arachidonic acid is a key player whose liberation from membrane phospholipids and the formation of

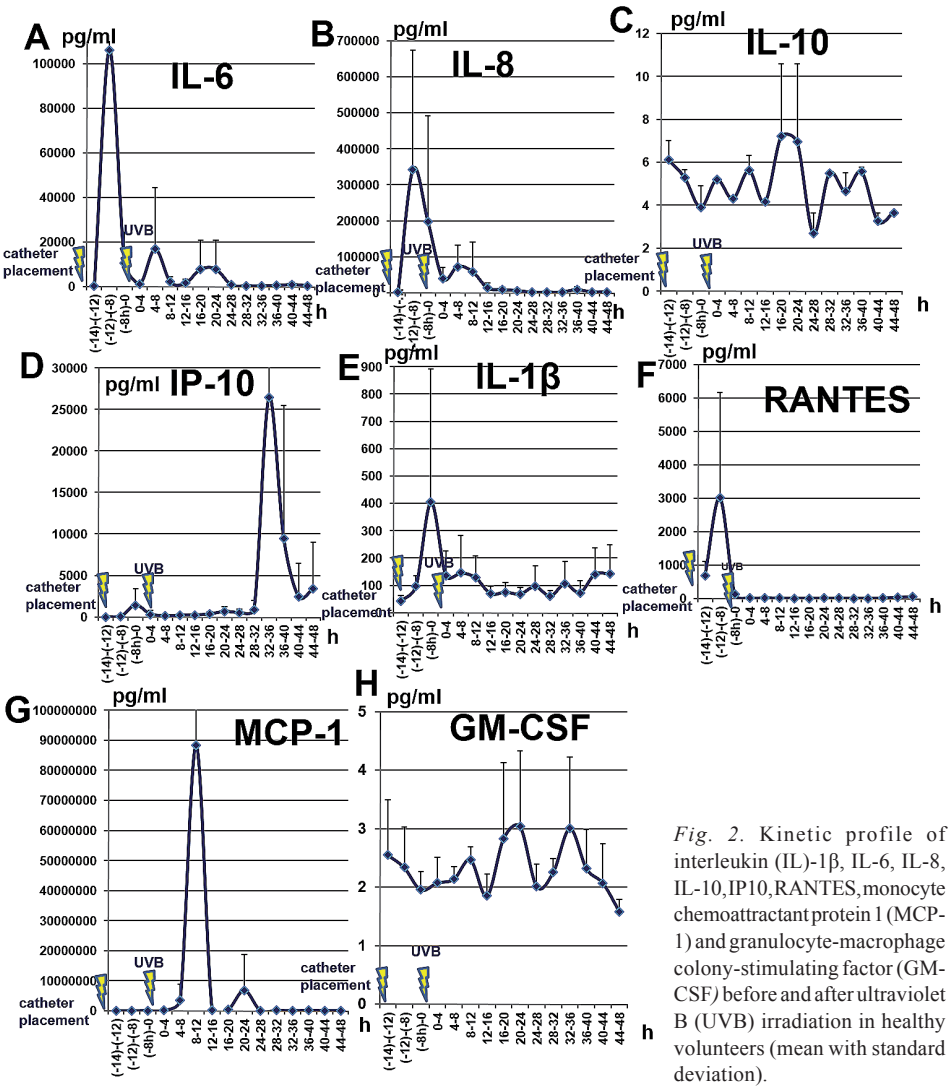

Fig. 2. Kinetic profile of interleukin (IL)-1β, IL-6, IL-8, IL-10, IP10, RANTES, monocyte chemoattractant protein 1 (MCP-1) and granulocyte-macrophage colony-stimulating factor (GM-CSF) before and after ultraviolet B (UVB) irradiation in healthy volunteers (mean with standard deviation).

prostaglandins is induced by inflammatory stimuli including UVB irradiation. Prostaglandins, such as 9α,11α-$PGF_{2\alpha}$ and PGE_2, are bioactive products that act as vasoregulators. However, the non-enzymatic pathway of arachidonic acid oxidation includes free radical-catalysed peroxidation of arachidonic acid and synthesis of F2-isoprostanes, which are mostly bound to the backbone of phospholipids and which have vascular, proinflammatory and nociceptive functions. These products can be used as an indicator of photo-oxidative cell damage, sunburn-associated pain, and inflammation; in a dose-response study, the generation of 8-isoprostane was detected by specific antibody staining in the epidermis after UVB exposure (3, 25). Microdialysis has only been used once to detect PGE2 in UVB-irradiated skin (4×MED) at 24 h after UVB irradiation. Microdialysis was performed for only 30 min and PGE2 levels were increased in UVB-irradiated skin erythema compared with non-irradiated skin (310 pg/ml vs. 237 pg/ml) (25). In the current study, we were able to elaborate a compete kinetic profile, following catheter placement and UVB irradiation up to 48 h post-irradiation and the PGE2 value average approximately 400 pg/ml 24 h after UVB irradiation.

In another single previous report (10), cytokines were collected and a time-dependent profile generated for 24 h after UVB irradiation by combining a multiplex cytokine array with cutaneous microdialysis. In this interesting approach, the time intervals were 8 h, and microdialysis was performed 24 h before and 24 h after UVB challenge. The authors concluded that comparing cytokine responses between traumatic tissue injuries due to either catheter placement or UVB irradiation revealed significant differences; catheter placement mainly induced an unspecific proinflammatory response driven by IL-6, IL-8, TNF-α, and IL-1 beta, as previously described for traumatic tissue injury, whereas the cytokine response to UVB challenge showed a mixed TH1/TH2-related cytokine profile, suggesting a late TH2-driven shift that ultimately could not be evaluated because the study was stopped 24 h after UVB irradiation. The authors concluded that the cytokine response to UVB irradiation is finally terminated by IL-4 and IL-10, but the levels of these mediators were still high 24 h post-irradiation, indicating that the UV stress-associated regulated immune response was ongoing. In addition, a negative control with catheter placement without UVB irradiation was lacking, and levels of many of the cytokines decreased 24 h after catheter trauma. Therefore, the authors could not fully exclude that the observed increases in cytokine levels may have been a result of repair processes after tissue trauma, and not related to UVB exposure. In a murine model (13), it was shown that release of PGE2 and TNF-α *in vivo* in response to UVB irradiation increased strongly after 17 h and continued until 72 h. Furthermore, a maximum level of leukocyte cell infiltration was still evident 72 h post-irradiation, indicating that even the repair process of the epidermis had been initiated. The epidermal structure seemed to have fully recovered at 72 h, but inflamma-

Table I. *Area under the curve (AUC) analysis comparing the ultraviolet B (UVB)-irradiated (AUC_{UV}) and non-irradiated (AUC_C) kinetic profiles of the cytokines and prostanoids analysed*

	AUC_{UV} pg×h/ml	AUC_C pg×h/ml	*p*-value (UV vs. control)
Cytokines			
IL-1β	5,383.8	5,336.5	0.58
IL-2	149.1	0	0.06
IL-3	1,207.8	38.3	<0.0001*
IL-4	108.2	19.6	0.003*
IL-6	152,803.6	19,321.5	0.27
IL-8	767,470.3	156,633.8	0.12
IL-10	244.5	33.2	<0.001*
IL-13	339	348.7	0.72
Fas-Ligand	634.5	29.6	<0.001*
TNF-α	344.2	118	<0.001*
Eotaxin	95.2	4.2	0.08
GM-CSF	101.2	8.4	<0.001*
RANTES	482.9	149.1	0.02*
IP-10	172,283.2	48,447.4	0.51
MCP-1	443,554,789	115,554.1	0.44
Prostanoids			
5-iso-$PGF_{2\alpha}$	15,924.1	6,430.5	0.015*
8-iso-$PGF_{2\alpha}$	25,316.2	5,229.5	<0.001*
9a,11a-$PGF_{2\alpha}$	26,733.1	11,924	0.048*
PGE_2	13,860.9	0	<0.001*

AUC shows mean values from all volunteers. AUC_{UV}: AUC 0–48 h after UV irradiation in pg×h/ml; AUC_C: AUC of control, 0–48h during the same time without UV irradiation in pg*h/ml. IL: interleukin; TNF-α: tumour necrosis factor alpha; IP-10: interferon-γ–inducible protein-10; MCP-1: monocyte chemoattractant protein 1; GM-CSF: granulocyte-macrophage colony-stimulating factor.
*$p<0.05$. *p*-values were determined via a paired 2-sample *t*-test.

tory mediators were still being released (13). In previous reports, it was demonstrated that exposure to UVB irradiation resulted in increased homogeneous expression of Fas on epidermal cells from suction blisters, with the greatest expression at 24 and 72 h after irradiation, as detected by flow cytometry. The authors, however, could not detect increased levels of soluble FasL in the suction blisters by ELISA, which seems unsurprising because the levels that we have detected were relatively low (up to 25 pg/ml) and probably would not have been detectable with a commercial ELISA at that time (26, 27). Furthermore, we observed a strong increase in MCP-1, which is known to be strongly released after UVB exposure of keratinocytes *in vitro*, together with IL-8, and which is also mediated by ROS (1).

In conclusion, cutaneous microdialysis, together with a cytometric bead array and GC/MS, allows us to elaborate a kinetic profile for inflammation markers after an immune challenge, such as UVB irradiation, in the dermal skin *in vivo*. Furthermore, we have evidence that release of cytokines and prostanoids is synchronized and that a slow TH1-to-TH2 shift occurs up to 40 h after UVB irradiation. Cutaneous microdialysis is possibly limited to a 58 h duration because an increase in the levels of some mediators, the cytokines, chemokine and prostanoid IL-6, IL-8, IP-10, MCP-1 and 9α,11α-$PGF_{2\alpha}$ were detected in non-UVB-irradiated skin at 58–62 h of the experiment. As volunteers were allowed free mobility throughout the experiment, methodological improvements for longer investigations might include a closer observation, possible hospitalization, and the use of smaller and shorter catheters (CMA66 catheters; 10 mm instead of 30 mm), which might reduce possible irritation induced by the catheter itself.

Long-term microdialysis could be utilized further, not only in studying skin physiology, such as response to heat and pain stimuli, but also in investigating other inflammatory skin diseases, such as psoriasis, atopic dermatitis, or chronic urticaria. It could also be used to study the pharmacodynamic effects of pharmacological intervention using new drugs, such as chemicals or biologicals, delivered via the microdialysis catheters, on the *in vivo* release of cytokines or prostanoids within the dermal skin in real time (18, 24, 28–32).

ACKNOWLEDGEMENTS

The authors would like to thank Ines Doering for excellent technical assistance. The study was supported by the German BMBF (funds number 01ZZ0407 (NBL3-2)) granted to SRQ.

The authors declare no conflicts of interest.

REFERENCES

1. Kang JS, Kim HN, Jung da J, Kim JE, Mun GH, Kim YS, et al. Regulation of UVB-induced IL-8 and MCP-1 production in skin keratinocytes by increasing vitamin C uptake via the redistribution of SVCT-1 from the cytosol to the membrane. J Invest Dermatol 2007; 127: 698–706.
2. Wiswedel I, Hirsch D, Kropf S, Gruening M, Pfister E, Schewe T, et al. Flavanol-rich cocoa drink lowers plasma F(2)-isoprostane concentrations in humans. Free Radic Biol Med 2004; 37: 411–421.
3. Schneider LA, Bloch W, Kopp K, Hainzl A, Rettberg P, Wlaschek M, et al. 8-Isoprostane is a dose-related biomarker for photo-oxidative ultraviolet (UV) B damage in vivo: a pilot study with personal UV dosimetry. Br J Dermatol 2006; 154: 1147–1154.
4. Wiswedel I, Keilhoff G, Dorner L, Navarro A, Bockelmann R, Bonnekoh B, et al. UVB irradiation-induced impairment of keratinocytes and adaptive responses to oxidative stress. Free Radic Res 2007; 41: 1017–1027.
5. Benveniste H, Hansen AJ, Ottosen NS. Determination of brain interstitial concentrations by microdialysis. J Neurochem 1989; 52: 1741–1750.
6. Chaurasia CS, Muller M, Bashaw ED, Benfeldt E, Bolinder J, Bullock R, et al. AAPS-FDA Workshop White Paper: microdialysis principles, application, and regulatory perspectives. J Clin Pharmacol 2007; 47: 589–603.
7. Benfeldt E, Hansen SH, Volund A, Menne T, Shah VP. Bioequivalence of topical formulations in humans: evaluation by dermal microdialysis sampling and the dermatopharmacokinetic method. J Invest Dermatol 2007; 127: 170–178.
8. Joukhadar C, Muller M. Microdialysis: current applications in clinical pharmacokinetic studies and its potential role in the future. Clin Pharmacokinet 2005; 44: 895–913.
9. Grundmann JU, Wiswedel I, Hirsch D, Gollnick HP. Detection of monohydroxyeicosatetraenoic acids and F2-isoprostanes in microdialysis samples of human UV-

irradiated skin by gas chromatography-mass spectrometry. Skin Pharmacol Physiol 2004; 17: 37–41.
10. Averbeck M, Beilharz S, Bauer M, Gebhardt C, Hartmann A, Hochleitner K, et al. In situ profiling and quantification of cytokines released during ultraviolet B-induced inflammation by combining dermal microdialysis and protein microarrays. Exp Dermatol 2006; 15: 447–454.
11. Averbeck M, Gebhardt CA, Voigt S, Beilharz S, Anderegg U, Termeer CC, et al. Differential regulation of hyaluronan metabolism in the epidermal and dermal compartments of human skin by UVB irradiation. J Invest Dermatol 2007; 127: 687–697.
12. Sjogren F, Svensson C, Anderson C. Technical prerequisites for in vivo microdialysis determination of interleukin-6 in human dermis. Br J Dermatol 2002; 146: 375–382.
13. Paz ML, Ferrari A, Weill FS, Leoni J, Maglio DH. Time-course evaluation and treatment of skin inflammatory immune response after ultraviolet B irradiation. Cytokine 2008; 44: 70–77.
14. Paz ML, Gonzalez Maglio DH, Weill FS, Bustamante J, Leoni J. Mitochondrial dysfunction and cellular stress progression after ultraviolet B irradiation in human keratinocytes. Photodermatol Photoimmunol Photomed 2008; 24: 115–122.
15. Kuhn M, Wolber R, Kolbe L, Schnorr O, Sies H. Solar-simulated radiation induces secretion of IL-6 and production of isoprostanes in human skin in vivo. Arch Dermatol Res 2006; 297: 477–479.
16. Yoshizumi M, Nakamura T, Kato M, Ishioka T, Kozawa K, Wakamatsu K, et al. Release of cytokines/chemokines and cell death in UVB-irradiated human keratinocytes, HaCaT. Cell Biol Int 2008; 32: 1405–1411.
17. Meyer W. Bemerkungen zur Eignung der Schweinehaut als biologisches Modell für die Haut des Menschen. Hautarzt 1996; 47: 178–182.
18. Quist SR, Wiswedel I, Doering I, Quist J, Gollnick HP. Effects of topical tacrolimus and polyunsaturated fatty acids (PUFA) on in vivo release of eicosanoids in atopic dermatitis (AD) during dermal microdialysis. Acta Derm Venereol 2016; 96: 905–909.
19. Stenken JA, Church MK, Gill CA, Clough GF. How minimally invasive is microdialysis sampling? A cautionary note for cytokine collection in human skin and other clinical studies. AAPS J 2010; 12: 73–78.
20. Clough GF. Microdialysis of large molecules. AAPS J 2005; 7: E686–92.
21. Ao X, Stenken JA. Microdialysis sampling of cytokines. Methods 2006; 38: 331–341.
22. Elshal MF, McCoy JP. Multiplex bead array assays: performance evaluation and comparison of sensitivity to ELISA. Methods 2006; 38: 317–323.
23. Wiswedel I, Grundmann JU, Boschmann M, Krautheim A, Bockelmann R, Peter DS, et al. Effects of UVB irradiation and diclofenac on F2-isoprostane/prostaglandin concentrations in keratinocytes and microdialysates of human skin. J Invest Dermatol 2007; 127: 1794–1797.
24. Angst MS, Clark JD, Carvalho B, Tingle M, Schmelz M, Yeomans DC. Cytokine profile in human skin in response to experimental inflammation, noxious stimulation, and administration of a COX-inhibitor: a microdialysis study. Pain 2008; 139: 15–27.
25. Rhodes LE, Belgi G, Parslew R, McLoughlin L, Clough GF, Friedmann PS. Ultraviolet-B-induced erythema is mediated by nitric oxide and prostaglandin E2 in combination. J Invest Dermatol 2001; 117: 880–885.
26. Bang B, Gniadecki R, Larsen JK, Baadsgaard O, Skov L. In vivo UVB irradiation induces clustering of Fas (CD95) on human epidermal cells. Exp Dermatol 2003; 12: 791–798.
27. Bang B, Rygaard J, Baadsgaard O, Skov L. Increased expression of Fas on human epidermal cells after in vivo exposure to single-dose ultraviolet (UV) B or long-wave UVA radiation. Br J Dermatol 2002; 147: 1199–1206.
28. Sjogren F, Davidsson K, Sjostrom M, Anderson CD. Cutaneous microdialysis: cytokine evidence for altered innate reactivity in the skin of psoriasis patients? AAPS J 2012; 14: 187–195.
29. Salgo R, Thaci D, Boehncke S, Diehl S, Hofmann M, Boehncke WH. Microdialysis documents changes in the micromilieu of psoriatic plaques under continuous systemic therapy. Exp Dermatol 2011; 20: 130–133.
30. Hersini KJ, Melgaard L, Gazerani P, Petersen LJ. Microdialysis of inflammatory mediators in the skin: a review. Acta Derm Venereol 2014; 94: 501–511.
31. Kring Tannert L, Stahl Skov P, Bjerremann Jensen L, Maurer M, Bindslev-Jensen C. Cold urticaria patients exhibit normal skin levels of functional mast cells and histamine after tolerance induction. Dermatology 2012; 224: 101–105.
32. Krause K, Spohr A, Zuberbier T, Church MK, Maurer M. Up-dosing with bilastine results in improved effectiveness in cold contact urticaria. Allergy 2013; 68: 921–928.