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ACCELERATED COMMUNICATION

Nicotinic Acid-Induced Flushing Is Mediated by Activation of Epidermal Langerhans Cells

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ABSTRACT

The antidyslipidemic drug nicotinic acid (niacin) has been used for decades. One of the major problems of the therapeutical use of nicotinic acid is a strong cutaneous vasodilation called flushing, which develops in almost every patient taking nicotinic acid. Nicotinic acid-induced flushing has been shown to be mediated by the nicotinic acid receptor GPR109A and to involve the formation of vasodilatory prostanoids. However, the cellular mechanisms underlying this short-term effect are unknown. Here, we show that epidermal Langerhans cells are essential for the cutaneous flushing response induced by nicotinic acid. Langerhans cells respond with an increase in $[Ca^{2+}]_i$ to nicotinic acid and express prostanoid synthases required for the formation of the vasodilatory prostanoids prostaglandin E_2 and prostaglandin D_2. Depletion of epidermal Langerhans cells but not of macrophages or dendritic cells abrogates nicotinic acid-induced flushing. These data unexpectedly identify epidermal Langerhans cells as essential mediators of nicotinic acid-induced flushing and may help to generate new strategies to suppress the unwanted effects of nicotinic acid. In addition, our results suggest that Langerhans cells besides their immunological roles are also involved in the local regulation of dermal blood flow.

Nicotinic acid (niacin) is the oldest lipid-modifying drug and induces a unique spectrum of changes in lipid and lipoprotein levels (Carlson, 2005). Besides its ability to decrease triglyceride and low-density lipoprotein cholesterol levels, it has the strongest HDL cholesterol-elevating activity among the currently available lipid modifying drugs. Because a low HDL cholesterol level is an independent risk factor for cardiovascular diseases, the HDL cholesterol elevating effect of nicotinic acid has recently led to a renewed interest in this drug (Carlson, 2006; Kontush and Chapman, 2006; Offermanns, 2006), and there is good evidence indicating a beneficial effect of nicotinic acid alone or in combination with statins (Coronary Drug Project Research Group, 1975; Brown et al., 2001; Taylor et al., 2004).

The major problem of oral nicotinic acid treatment is the occurrence of a strong flushing phenomenon associated with cutaneous vasodilation, which occurs in virtually all patients and severely influences patients' compliance. It has been shown recently that the nicotinic acid receptor GPR109A (HM74A in humans, PUMA-G in mice) mediates not only the short-term metabolic effects of nicotinic acid but also the flushing response (Tunaru et al., 2003; Benyo et al., 2005). However, the cells and molecular mechanisms mediating nicotinic acid-induced flushing are unclear.

The flushing response of nicotinic acid can be inhibited by pretreatment with cyclooxygenase inhibitors (Andersson et al., 1977; Svedmyr et al., 1977; Eklund et al., 1979; Kaijser et al., 1979), and the levels of several vasodilatory prostanoids like prostaglandin E_2 (PGE_2) and prostaglandin D_2 (PGD_2) and their metabolites are elevated after administration of nicotinic acid (Eklund et al., 1979; Nozaki et al., 1987; Mor-

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ABBREVIATIONS: HDL, high density lipoprotein; DT, diphtheria toxin; DTR, diphtheria toxin receptor; LDF, laser-Doppler flow; PGE_2, prostaglandin E_2; PGD_2, prostaglandin D_2; mPGES-1 and mPGES-2, type 1 and type 2 PGE_2 synthases; MHC, major histocompatibility complex; PE, phosphatidylethanolamine; GFP, green fluorescent protein; FITC, fluorescein isothiocyanate; PBS, phosphate-buffered saline.

row et al., 1989; Stern et al., 1991). These observations have led to the hypothesis that prostanoids are involved in nicotinic acid-induced flushing. Pharmacological and genetic evidence has been provided recently that PGD_2 acting through the PGD_2 receptor and PGE_2 acting via type 2 PGE_2 receptor and type 4 PGE_2 receptor mediate the nicotinic acid-induced flushing response (Benyo et al., 2005; Cheng et al., 2006).

The cells required for nicotinic acid-induced and prostanoid-mediated flushing, however, remain elusive. The ability of topically applied nicotinic acid to induce locally restricted hyperemia (Wilkin et al., 1985; Morrow et al., 1992) and the fact that the nicotinic acid receptor GPR109A is expressed in macrophages and other immune cells (Schaub et al., 2001) suggest that immune cells of the skin are involved in the flushing response. This is supported by data demonstrating that MHC class II-positive skin cells express GPR109A and that the lack of nicotinic acid-induced flushing response in GPR109A-deficient mice can be restored by the transplantation of wild-type bone marrow (Benyo et al., 2005). We therefore systematically studied the potential involvement of various cell types in the cutaneous effects of nicotinic acid. By conditional ablation of defined subpopulations of immune cells and by the visualization of the local effects of nicotinic acid, we show in the present study that epidermal Langerhans cells respond to nicotinic acid and mediate the flushing response.

Materials and Methods

Mice. CD11b-DTR and CD11c-DTR mice were purchased (The Jackson Laboratory, Bar Harbor, ME), and Langerin-DTR transgenic mice have been described previously (Bennett et al., 2005). GPR109A-deficient mice were kindly provided by Klaus Pfeffer (Universität Düsseldorf, Düsseldorf, Germany). Mice were housed in temperature-controlled facilities on a 12-h light/dark cycle with ad libitum food and water access. All experimental procedures were performed in accordance with institutional guidelines of the University of Heidelberg (Heidelberg, Germany).

Measurement of Flush. Cutaneous blood flow was determined as described previously (Benyo et al., 2005). In brief, anesthetized mice were placed on their left side on a controlled heating pad, and blood flow in the ear was determined with a laser-Doppler probe (407; Perimed AB, Stockholm, Sweden). Original LDF recordings were averaged for 1-s intervals, and the baseline LDF was determined before injection of the tested compound. All data are presented as mean ± S.E.M., and n indicates the number of experimental animals. Statistical analysis of differences between flushing responses before and after diphtheria toxin (DT) treatment was performed by Student's paired t test, and $p < 0.05$ was considered significant. Nicotinic acid was prepared in 5% (2-hydroxypropyl)-β-cylodextrin (Sigma, St. Louis, MO), and the pH of the solutions was adjusted to 6.9 to 7.1 with 1 M NaOH. Prostaglandin D_2 (Cayman Chemical Co., Ann Arbor, MI) was dissolved in dimethyl sulfoxide and diluted 20 times with saline.

DT Treatment. After control experiments, the CD11b-DTR, CD11c-DTR, and Langerin-DTR transgenic animals were treated with 25, 4, and 16 ng/g diphtheria toxin (Sigma), respectively, as described previously (Jung et al., 2002; Bennett et al., 2005; Duffield et al., 2005). DT was injected intraperitoneally 24 and 48 h before retesting of the flushing responses. Wild-type littermate animals were treated with the same protocol and served as controls. Between two experiments the animals were allowed to recover for at least 1 week.

Isolation of Epidermal Sheets and Immunohistochemistry. Mouse ears were dissected, split into ventral and dorsal sheets, and incubated for 50 min in RPMI 1640 medium and 10 mM EDTA. The epidermis was removed from the dermis using fine forceps and was fixed on ice for 1 h in 4% paraformaldehyde/PBS. After permeabilization with 0.2% Triton/PBS for 10 min at 25°C and two washes with PBS for 10 min, the epidermal sheets were incubated with 10% goat serum for 30 min. Polyclonal rabbit anti-PGE synthase 1, polyclonal rabbit anti-PGE synthase 2 and monoclonal mouse PGD_2 synthase (all from Cayman Chemical) were each mixed with PE-labeled anti-MHC II-IA/IE (BD PharMingen, San Diego, CA) in 10% goat serum/PBS and incubated with epidermal sheets overnight at 4°C on a rotator. Secondary FITC-labeled anti-rabbit and anti-mouse antibodies were applied together with DAPI in 1.5% horse serum for 2 h on a rotator. After washing, epidermal sheets were mounted and analyzed by fluorescence microscopy.

Fluorescence Activated Cell Sorting. Splenocytes were isolated by collagenase digestion and passing through a 40-μm nylon mesh. Red blood cells were removed using Lympholyte-M (Cedarlane Laboratories, Burlington, NC). Splenocytes were stained with FITC-anti-CD11c and PE-labeled anti-F4/80 (BD PharMingen). Peritoneal macrophages were obtained by peritoneal lavage and stained with PE-labeled anti-F4/80 (BD PharMingen). All flow cytometric analyses were performed using the FACSCalibur and Cell Quest software (BD Biosciences, San Jose, CA).

Measurement of Intracellular [Ca^{2+}]. Epidermal sheets of Langerin-GFP-DTR or GPR109A-deficient animals were incubated in RPMI 1640 medium with 6 μM Fura-2/acetoxymethyl ester/pluronic acid (Invitrogen, Carlsbad, CA) and in the case of Puma-G knockout together with FITC-labeled anti MHC II-IA/IE (BD PharMingen) for 45 min. The epithelial sheets were placed dermal side up in a perfusion chamber and immobilized with thin silk threads tied to a steel ring. Epithelial sheets were superfused with 900 μl of RPMI 1640 medium at a flow rate of 3.5 ml/min, and stimulation was achieved by pipetting 100 μl of a 10× concentrated solution into the chamber. Excitation light was provided by a monochromator (TILL Photonics, Gräfelfing, Germany), and the fluorescence emission was captured by a cooled charge-coupled device camera (Image QE; TILL Photonics) on an upright microscope (Olympus BX51WI, Tokyo, Japan). The calcium concentration was visualized in Langerhans cells that were identified by GFP or FITC fluorescence, respectively. Ratio images were collected at intervals every 500 ms. Imaging was controlled and analyzed with Tillvision Software 4.0 (TILL Photonics).

Results

As reported previously, nicotinic acid-induced cutaneous vasodilation can be observed and quantified in the mouse ear using laser-Doppler flowmetry (Benyo et al., 2005; Cheng et al., 2006). Intraperitoneal injection of nicotinic acid results within a few minutes in a biphasic increase in the blood flow that lasts for approximately 40 min. Based on the fact that transplantation of wild-type bone marrow into GPR109A-deficient mice can restore the ability of nicotinic acid to induce flushing (Benyo et al., 2005), we tested the potential involvement of various cutaneous immune cells in the nicotinic acid-induced flushing response. Because nicotinic acid does not induce an increase in histamine levels (Morrow et al., 1989), and because mast cell-deficient mice still respond with flushing to nicotinic acid (Benyo et al., 2005), mast cells are obviously not required for the flushing phenomenon. Besides mast cells, dermal macrophages and dermal dendritic cells are the major immune cells present in the dermis. To examine their potential involvement in nicotinic acid-induced flushing, we conditionally depleted macrophages and dendritic cells using recently developed transgenic mouse lines in which either the CD11c promoter element drives the

expression of the human DT receptor in dendritic cells (Jung et al., 2002) or in which diphtheria toxin receptor (DTR) expression is restricted to macrophages by using the CD11b promoter element (Duffield et al., 2005). Murine cells are insensitive to DT because their DTR homolog does not bind DT. In both CD11b-DTR and CD11c-DTR mice we were able to show that the systemic administration of DT led to the depletion of macrophages and dendritic cells, respectively (Fig. 1A, B, F, and G). When DT-treated CD11b-DTR and CD11c-DTR mice were injected with nicotinic acid, a normal biphasic flushing response could be observed, which was indistinguishable from the flushing response induced by nicotinic acid before DT treatment (Fig. 1, C–E and H–J). This clearly indicates that neither macrophages nor dendritic cells in the dermis or elsewhere in the body are involved in the nicotinic acid-induced flushing response.

Another major immune cell type present in the skin is epidermal Langerhans cells, which densely populate the epidermal layer of the skin. By using a mouse line expressing DTR under the control of the Langerhans cell-specific langerin promoter (Bennett et al., 2005), we were able to study the potential role of Langerhans cells in nicotinic acid-induced flushing. DT treatment of Langerin-DTR mice resulted in ablation of the Langerhans cell population from the epidermis of mice, whereas dermal dendritic cells were not affected (Bennett et al., 2005) (Fig. 2, A and B). It is interesting that depletion of Langerhans cells was accompanied by abrogation of nicotinic acid-induced flushing, whereas Langerin-DTR animals before DT treatment showed normal distribution of epidermal Langerhans cells and normal flushing response to nicotinic acid (Fig. 2, C–E). Wild-type mice pretreated with DT under the same conditions as Langerin-DTR transgenic mice exhibited a normal flushing response (data not shown). Treatment of Langerin-DTR animals with DT did not principally affect the ability of these animals to respond with cutaneous vasodilation to other stimuli as, shown

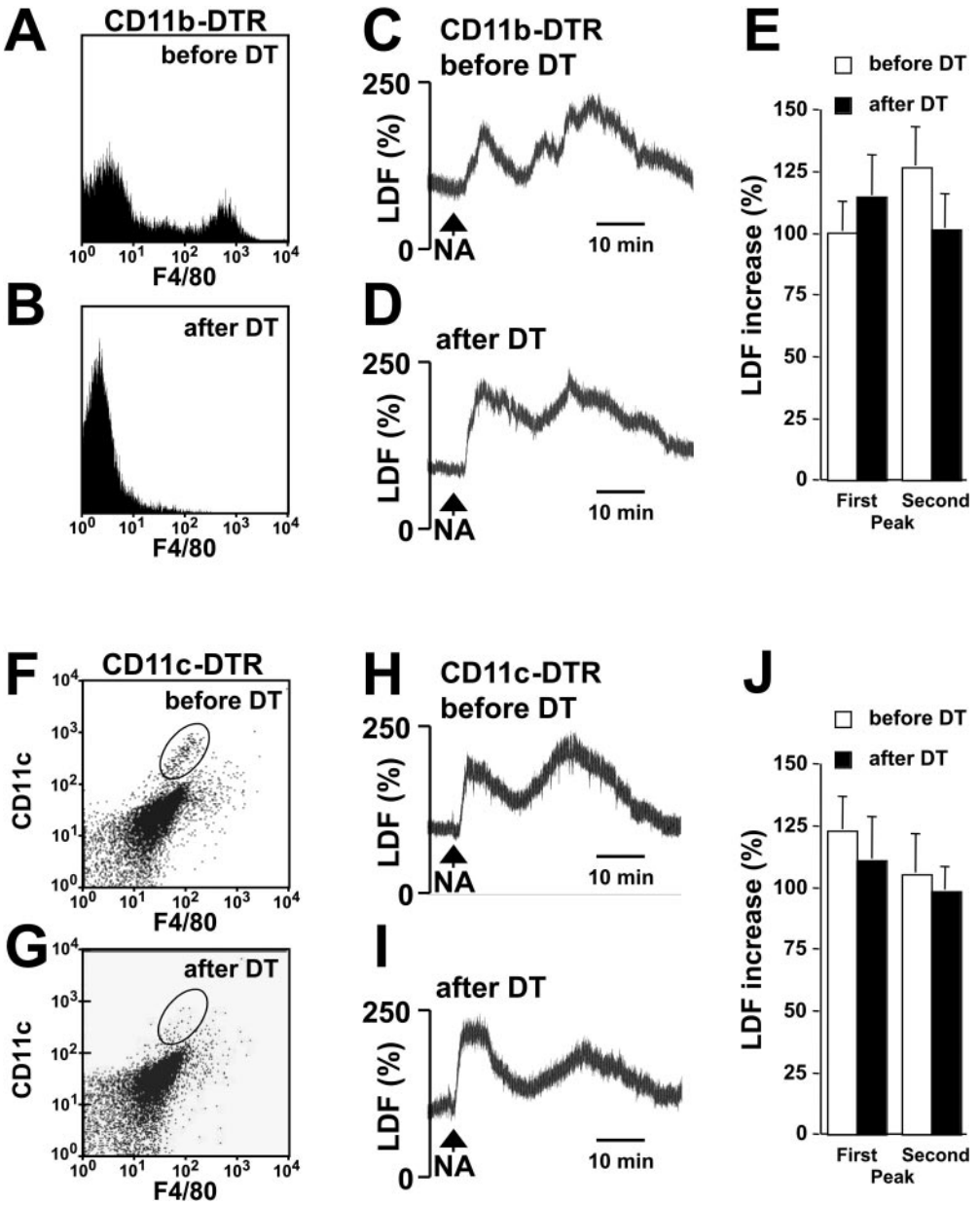

Fig. 1. Effect of macrophage and dendritic cell depletion on nicotinic acid-induced flushing. CD11b-DTR (A–E) and CD11c-DTR transgenic mice (F–J) were analyzed before or after intraperitoneal injection of DT. A, B, F, and G, verification of macrophage and dendritic cell depletion. Cells harvested by peritoneal lavage (A and B) or splenocytes (F and G) were analyzed by fluorescence-activated cell sorting. C–E and H–J, original laser-Doppler flow recordings and quantitative analysis of the percentage of LDF increase in response to intraperitoneal administration of 200 μg/g nicotinic acid in untreated or DT-treated CD11b-DTR (C–E) and CD11c-DTR mice (H–J).

by the normal flushing response to the intraperitoneal injection of PGD_2 (Fig. 2, F–H). Thus, epidermal Langerhans cells are specifically required for the nicotinic acid-induced cutaneous vasodilation and are positioned upstream of PGD_2 release.

To test whether Langerhans cells functionally respond to nicotinic acid, we prepared epidermal sheets from ears of Langerin-DTR mice, which express enhanced green fluorescent protein fused to DTR (Bennett et al., 2005), and loaded epidermal cells with the Ca^{2+} indicator Fura-2/acetoxymethyl ester. At the same time, Langerhans cells were visualized by fluorescence microscopy (Fig. 3A). Exposure of Fura-2-loaded epidermal sheets to 100 μM nicotinic acid resulted in a transient increase in $[Ca^{2+}]_i$ of Langerhans cells (Fig. 3, B and C). Fura-2-loaded Langerhans cells in epidermal sheets from GPR109A-deficient mice, which were identified by staining with an anti-MHCII antibody, did not respond with any increase in $[Ca^{2+}]_i$ to the application of nicotinic acid but still responded to the Ca^{2+} ionophore ionomycin (Fig. 3D).

Because PGD_2 and PGE_2 have been shown to be principal mediators of the nicotinic acid-induced flushing response, we tested whether epidermal Langerhans cells express prostaglandin D_2 and prostaglandin E_2 synthases. Staining of epidermal sheets from mouse ears with specific antibodies directed against murine PGD_2 synthase and types 1 and 2 PGE_2 synthases (mPGES-1 and mPGES-2) together with an antibody against mouse MHCII showed the presence of both PGD_2 synthase and type 2 PGE synthase, whereas we were unable to detect mPGES-1 (Fig. 4). The mPGES-2 enzyme seemed to be exclusively expressed in epidermal Langerhans cells, whereas prostaglandin D_2 synthase was also detected in other cells of the epidermis (Fig. 4).

Discussion

The nicotinic acid-induced flushing response is a phenomenon that was first described shortly after the discovery of nicotinic acid as a vitamin (Spies et al., 1938; Goldsmith and Cordill, 1943). The ability of nicotinic acid to induce a strong cutaneous vasodilation has always been an obstacle in the clinical use of nicotinic acid as a lipid-modifying drug. Despite the pharmacological importance of this phenomenon, the underlying mechanism is still not clear. Based on the recent observation that bone marrow-derived immune cells in the skin mediate the nicotinic acid-induced flushing response, we systematically studied the involvement of individual cell populations like dermal macrophages, dermal dendritic cells, and epidermal Langerhans cells, which are all present at relatively high numbers in human and mouse skin (Lenz et al., 1993; Dupasquier et al., 2004). Our data clearly indicate that the nicotinic acid-induced flushing response is mediated by epidermal Langerhans cells, whereas dermal dendritic cells and macrophages are not required. Depletion of Langerhans cells alone is able to prevent nicotinic acid-induced flushing.

Previous studies have shown that PGD_2 and PGE_2 are critically involved in the nicotinic acid-induced flushing response (Benyo et al., 2005; Cheng et al., 2006). To test

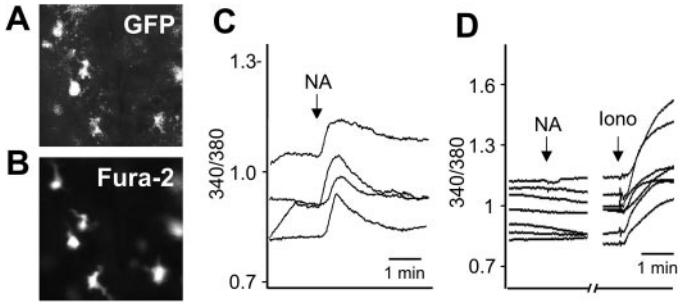

Fig. 3. Epidermal Langerhans cells respond to nicotinic acid. Langerhans cells were identified in epidermal sheets of untreated Langerin-DTR mice by enhanced green fluorescent protein fluorescence (A), and sheets were loaded with Fura-2 and exposed to 100 μM nicotinic acid (B and C). D, representative traces demonstrating the effect of nicotinic acid (100 μM) and ionomycin (Iono, 1 μM) on $[Ca^{2+}]_i$ on MHCII-positive cells of epidermal sheets prepared from GPR109A-deficient mice. Values on the *y*-axis indicate the measured 340/380-nm fluorescence ratio as an indicator of the free intracellular $[Ca^{2+}]$.

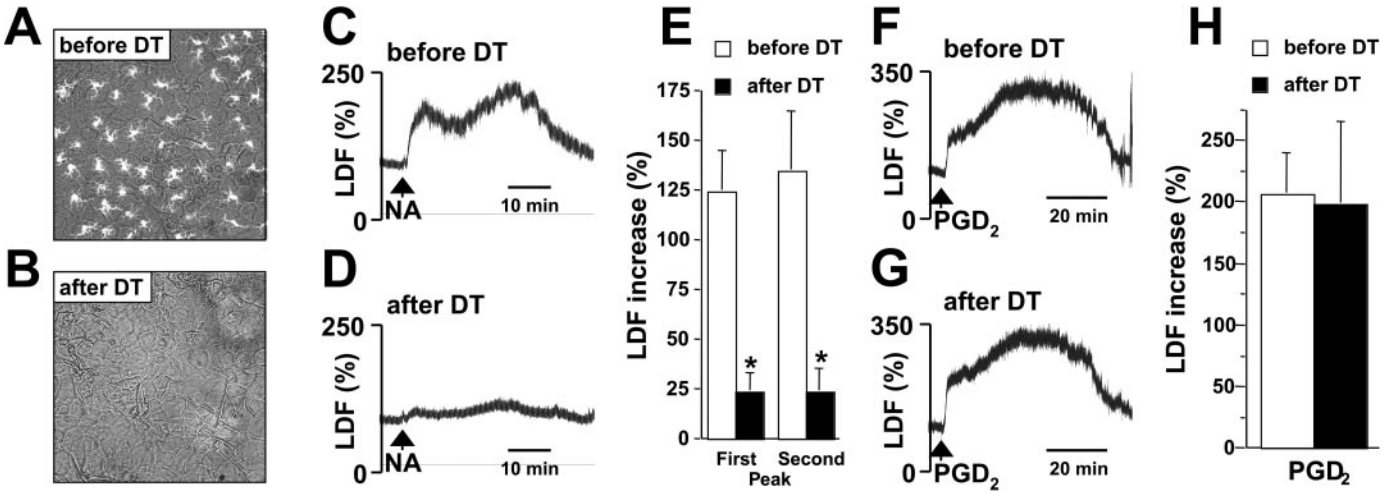

Fig. 2. Nicotinic acid-induced flushing requires the presence of epidermal Langerhans cells. Langerin-DTR transgenic mice were analyzed before or after intraperitoneal injection of DT. A and B, verification of Langerhans cell depletion. Shown is an overlay of the light microscopical image and the fluorescence image of epidermal sheets prepared from untreated (A) and DT-treated (B) Langerin-DTR mice, which were stained with PE-labeled anti-MHCII antibodies. C–E, original laser-Doppler flow recordings and quantitative analysis of the percentage of LDF increase in response to intraperitoneal administration of nicotinic acid in untreated or DT-treated Langerin-DTR mice. F–H, original laser-Doppler flow recordings and quantitative analysis of the percentage of LDF increase after intraperitoneal administration of 2 μg/g PGD_2 in untreated or DT-treated Langerin-DTR mice.

whether Langerhans cells are principally able to synthesize both prostanoids, we tested them for the expression of PGD_2 and PGE_2 synthases. We found both PGD_2 synthase and the constitutive type 2 PGE_2 synthase (mPGES-2) to be expressed in epidermal Langerhans cells. The inducible type 1 PGE synthase form (mPGES-1) (Kudo and Murakami, 2005) could, however, not be detected. This is consistent with earlier findings showing that Langerhans cells are a major source of prostanoids in the epidermis and that their main prostanoid product is PGD_2 whereas they are also able to synthesize PGE_2 (Ruzicka and Aubock, 1987; Rosenbach et al., 1990).

Our finding that Langerhans cells respond to nicotinic acid with a transient increase in the cytoplasmic Ca^{2+} concentration suggests that activation of G_i through the nicotinic acid receptor results in a G$\beta\gamma$-mediated phospholipase C activation, a classic response of immune cells to the activation of G_i-coupled receptors (Exton, 1996; Rhee, 2001). The transient increase in the cytoplasmic Ca^{2+} concentration is a major trigger of the activation of phospholipase A_2 and subsequent formation of arachidonic acid. Arachidonic acid is then further metabolized by the ubiquitously expressed type 1 cyclooxygenase and both PGD_2 and PGE_2 synthases, which are present in Langerhans cells. The release of PGD_2 and PGE_2 from nicotinic acid-activated Langerhans cells then results in vasodilation in the dermal papillae of the upper dermis layer, which are just adjacent to the epidermis-dermis junction close to the localization of Langerhans cells.

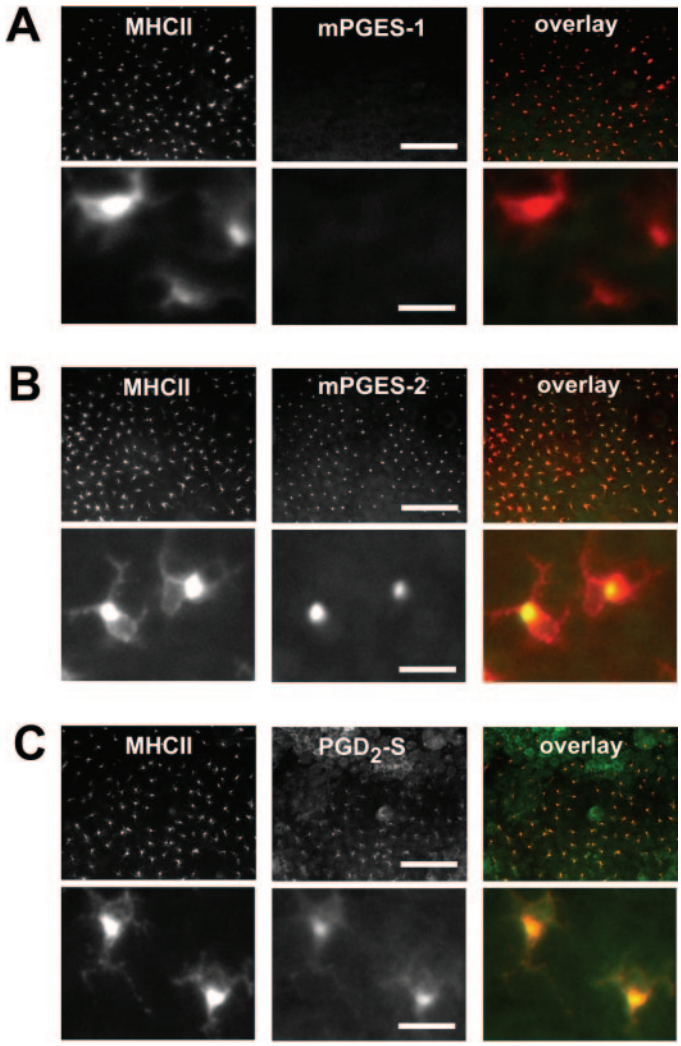

Fig. 4. Expression of prostanoid synthases in epidermal Langerhans cells. Epidermal sheets from wild-type mice were stained with antibodies against MHCII and mPGES-1 (A) or mPGES-2 (B) or PGD_2 synthase (C, PGD_2-S). Scale bars: top, 50 μm; bottom, 5 μm.

The nicotinic acid-induced flushing response is subject to a tolerance phenomenon that can be observed within days after repeated administration of nicotinic acid (Olsson, 1994). Tolerance is unlikely to develop on the basis of receptor desensitization because the metabolic effects are stable even after long-term administration of nicotinic acid (Olsson, 1994). It is more likely that the downstream mechanisms specific for the nicotinic acid-induced flushing response are involved. We could rule out the possibility that tolerance to nicotinic acid-induced flushing is due to any translocation of Langerhans cells, because repeated administration of nicotinic acid did not change the number of Langerhans cells per epidermal area, although the vasodilatory effect had seized (data not shown). It is therefore more likely that the nicotinic acid-induced prostanoid formation in Langerhans cells undergoes tachyphylaxis. This would be consistent with the observation that the development of tolerance to nicotinic acid-induced flushing is accompanied by a reduced formation of prostanoids (Stern et al., 1991). It has been described in the past that patients with atopic dermatitis show a severely reduced flushing response to topical application of nicotinic acid esters (Uehara and Ofuji, 1977; English et al., 1987). Thus, activation of Langerhans cells under certain pathological conditions like atopic dermatitis (Leung et al., 2004) may lead to a resistance of Langerhans cells to nicotinic acid-induced prostanoid formation.

The observed link between the activation of epidermal Langerhans cells and the regulation of blood vessel diameter in the upper dermis raises the question of whether this mechanism, in addition to its pharmacological significance, has any physiological or pathophysiological role. There are numerous transient and long-term forms of skin alterations that go along with erythema. It will be interesting to study the role of Langerhans cells not only in immunological responses of the skin but also in the local regulation of dermal blood flow.

Our data clearly show that epidermal Langerhans cells play a central role in the nicotinic acid-induced flushing response by mediating the formation of vasodilatory prostanoids in response to activation by nicotinic acid. This study provides new insight into the mechanism underlying the clinical problem of nicotinic acid-induced flushing and may provide the basis for new approaches aiming at the reduction of this unwanted side effect. In addition, our data point to an interesting new function of epidermal Langerhans cells in the regulation of the local blood flow in the dermis, whose potential physiological and pathophysiological role remains to be further characterized.

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References

Andersson RG, Aberg G, Brattsand R, Ericsson E, and Lundholm L (1977) Studies on the mechanism of flush induced by nicotinic acid. *Acta Pharmacol Toxicol (Copenh)* **41:**1–10.

Bennett CL, van Rijn E, Jung S, Inaba K, Steinman RM, Kapsenberg ML, and Clausen BE (2005) Inducible ablation of mouse Langerhans cells diminishes but fails to abrogate contact hypersensitivity. *J Cell Biol* **169:**569–576.

Benyo Z, Gille A, Kero J, Csiky M, Suchankova MC, Nusing RM, Moers A, Pfeffer K, and Offermanns S (2005) GPR109A (PUMA-G/HM74A) mediates nicotinic acid-induced flushing. *J Clin Investig* **115:**3634–3640.

Brown BG, Zhao XQ, Chait A, Fisher LD, Cheung MC, Morse JS, Dowdy AA, Marino EK, Bolson EL, Alaupovic P, et al. (2001) Simvastatin and niacin, antioxidant vitamins, or the combination for the prevention of coronary disease. *N Engl J Med* **345:**1583–1592.

Carlson LA (2005) Nicotinic acid: the broad-spectrum lipid drug. A 50th anniversary review. *J Intern Med* **258:**94–114.

Carlson LA (2006) Nicotinic acid and other therapies for raising high-density lipoprotein. *Curr Opin Cardiol* **21:**336–344.

Cheng K, Wu TJ, Wu KK, Sturino C, Metters K, Gottesdiener K, Wright SD, Wang Z, O'Neill G, Lai E, et al. (2006) Antagonism of the prostaglandin D2 receptor 1 suppresses nicotinic acid-induced vasodilation in mice and humans. *Proc Natl Acad Sci USA* **103:**6682–6687.

Coronary Drug Project Research Group (1975) Clofibrate and niacin in coronary heart disease. *J Am Med Assoc* **231:**360–381.

Duffield JS, Forbes SJ, Constandinou CM, Clay S, Partolina M, Vuthoori S, Wu S, Lang R, and Iredale JP (2005) Selective depletion of macrophages reveals distinct, opposing roles during liver injury and repair. *J Clin Investig* **115:**56–65.

Dupasquier M, Stoitzner P, van Oudenaren A, Romani N, and Leenen PJ (2004) Macrophages and dendritic cells constitute a major subpopulation of cells in the mouse dermis. *J Investig Dermatol* **123:**876–879.

Eklund B, Kaijser L, Nowak J, and Wennmalm A (1979) Prostaglandins contribute to the vasodilation induced by nicotinic acid. *Prostaglandins* **17:**821–830.

English JS, Winkelmann RK, Louback JB, Greaves MW, and MacDonald DM (1987) The cellular inflammatory response in nicotinate skin reactions. *Br J Dermatol* **116:**341–349.

Exton JH (1996) Regulation of phosphoinositide phospholipases by hormones, neurotransmitters, and other agonists linked to G proteins. *Annu Rev Pharmacol Toxicol* **36:**481–509.

Goldsmith GA and Cordill S (1943) The vasodilating effects of nicotinic acid (relation to metabolic rate and body temperature). *Am J Med Sci* **205:**204–208.

Jung S, Unutmaz D, Wong P, Sano G, De los Santos K, Sparwasser T, Wu S, Vuthoori S, Ko K, Zavala F, et al. (2002) In vivo depletion of $CD11c^+$ dendritic cells abrogates priming of $CD8^+$ T cells by exogenous cell-associated antigens. *Immunity* **17:**211–220.

Kaijser L, Eklund B, Olsson AG, and Carlson LA (1979) Dissociation of the effects of nicotinic acid on vasodilatation and lipolysis by a prostaglandin synthesis inhibitor, indomethacin, in man. *Med Biol* **57:**114–117.

Kontush A and Chapman MJ (2006) Antiatherogenic small, dense HDL–guardian angel of the arterial wall? *Nat Clin Pract Cardiovasc Med* **3:**144–153.

Kudo I and Murakami M (2005) Prostaglandin e synthase, a terminal enzyme for prostaglandin E2 biosynthesis. *J Biochem Mol Biol* **38:**633–638.

Lenz A, Heine M, Schuler G, and Romani N (1993) Human and murine dermis contain dendritic cells. Isolation by means of a novel method and phenotypical and functional characterization. *J Clin Investig* **92:**2587–2596.

Leung DY, Boguniewicz M, Howell MD, Nomura I, and Hamid QA (2004) New insights into atopic dermatitis. *J Clin Investig* **113:**651–657.

Morrow JD, Awad JA, Oates JA, and Roberts LJ 2nd (1992) Identification of skin as a major site of prostaglandin D2 release following oral administration of niacin in humans. *J Investig Dermatol* **98:**812–815.

Morrow JD, Parsons WG 3rd, and Roberts LJ 2nd (1989) Release of markedly increased quantities of prostaglandin D2 in vivo in humans following the administration of nicotinic acid. *Prostaglandins* **38:**263–274.

Nozaki S, Kihara S, Kubo M, Kameda K, Matsuzawa Y, and Tarui S (1987) Increased compliance of niceritrol treatment by addition of aspirin: relationship between changes in prostaglandins and skin flushing. *Int J Clin Pharmacol Ther Toxicol* **25:**643–647.

Offermanns S (2006) The nicotinic acid receptor GPR109A (HM74A or PUMA-G) as a new therapeutic target. *Trends Pharmacol Sci* **27:**384–390.

Olsson AG (1994) Nicotinic acid and derivatives, in *Principles and Treatment of Lipoprotein Disorders* (Schettler G and Habenicht AJR eds) pp 349–400, Springer Verlag, New York.

Rhee SG (2001) Regulation of phosphoinositide-specific phospholipase C. *Annu Rev Biochem* **70:**281–312.

Rosenbach T, Czernielewski J, Hecker M, and Czarnetzki B (1990) Comparison of eicosanoid generation by highly purified human Langerhans cells and keratinocytes. *J Investig Dermatol* **95:**104–107.

Ruzicka T and Aubock J (1987) Arachidonic acid metabolism in guinea pig Langerhans cells: studies on cyclooxygenase and lipoxygenase pathways. *J Immunol* **138:**539–543.

Schaub A, Futterer A, and Pfeffer K (2001) PUMA-G, an IFN-gamma-inducible gene in macrophages is a novel member of the seven transmembrane spanning receptor superfamily. *Eur J Immunol* **31:**3714–3725.

Spies TD, Cooper C, and Blankenhorn MA (1938) The use of nicotinic acid in the treatment of pellagra. *J Am Med Assoc* **110:**622–627.

Stern RH, Spence JD, Freeman DJ, and Parbtani A (1991) Tolerance to nicotinic acid flushing. *Clin Pharmacol Ther* **50:**66–70.

Svedmyr N, Heggelund A, and Aberg G (1977) Influence of indomethacin on flush induced by nicotinic acid in man. *Acta Pharmacol Toxicol (Copenh)* **41:**397–400.

Taylor AJ, Sullenberger LE, Lee HJ, Lee JK, and Grace KA (2004) Arterial Biology for the Investigation of the Treatment Effects of Reducing Cholesterol (ARBITER) 2: a double-blind, placebo-controlled study of extended-release niacin on atherosclerosis progression in secondary prevention patients treated with statins. *Circulation* **110:**3512–3517.

Tunaru S, Kero J, Schaub A, Wufka C, Blaukat A, Pfeffer K, and Offermanns S (2003) PUMA-G and HM74 are receptors for nicotinic acid and mediate its anti-lipolytic effect. *Nat Med* **9:**352–355.

Uehara M and Ofuji S (1977) Abnormal vascular reactions in atopic dermatitis. *Arch Dermatol* **113:**627–629.

Wilkin JK, Fortner G, Reinhardt LA, Flowers OV, Kilpatrick SJ, and Streeter WC (1985) Prostaglandins and nicotinate-provoked increase in cutaneous blood flow. *Clin Pharmacol Ther* **38:**273–277.

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