

Regulation of Retinoid-Mediated Signaling Involved in Skin Homeostasis by RAR and RXR Agonists/Antagonists in Mouse Skin

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Abstract

Endogenous retinoids like all-*trans* retinoic acid (ATRA) play important roles in skin homeostasis and skin-based immune responses. Moreover, retinoid signaling was found to be dysregulated in various skin diseases. The present study used topical application of selective agonists and antagonists for retinoic acid receptors (RARs) α and γ and retinoid-X receptors (RXRs) for two weeks on mouse skin in order to determine the role of retinoid receptor subtypes in the gene regulation in skin. We observed pronounced epidermal hyperproliferation upon application of ATRA and synthetic agonists for RAR γ and RXR. ATRA and the RAR γ agonist further increased retinoid target gene expression (Rbp1, Crabp2, Krt4, Cyp26a1, Cyp26b1) and the chemokines Ccl17 and Ccl22. In contrast, a RAR α agonist strongly decreased the expression of ATRA-synthesis enzymes, of retinoid target genes, markers of skin homeostasis, and various cytokines in the skin, thereby markedly resembling the expression profile induced by RXR and RAR antagonists. Our results indicate that RAR α and RAR γ subtypes possess different roles in the skin and may be of relevance for the auto-regulation of endogenous retinoid signaling in skin. We suggest that dysregulated retinoid signaling in the skin mediated by RXR, RAR α and/or RAR γ may promote skin-based inflammation and dysregulation of skin barrier properties.

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Introduction

The nuclear hormone receptors retinoic acid receptors (RAR) α , β , and γ and retinoid X receptors (RXR) α , β , and γ are ligand-dependent transcription factors that can be activated by retinoids. RAR-RXR heterodimers regulate the expression of multiple genes in skin and various other tissues [1], while their transcriptional activity is dependent on the RAR-activating ligand [2–4]. The most abundant RAR and RXR subtypes in skin are RXR α and RAR γ , followed by lower quantities of RAR α [5]. Since retinoid receptors exhibit tissue and cell type-specific distribution patterns, functional specificity of each subtype is suggested [6–12]. Moreover, RAR and RXR subtypes differ in ligand specificity and/or affinity [9,11–14], therefore, it can be assumed that their contribution to gene expression patterns in skin differs, depending on quantitative receptor distribution, on the nature and level of co-regulators, as well as on available retinoid receptor-selective agonists and antagonists.

RAR-RXR-mediated signaling pathways induced by retinoids are essentially involved in immune-modulatory events [15–17], and skin physiology [18] through their role in the regulation of

several aspects of skin cell proliferation, differentiation, apoptosis, and epidermal barrier function [19,20]. Retinoid metabolism and concentrations in skin are tightly regulated ensuring sufficient levels of the endogenous pan-RAR activator all-*trans* retinoic acid (ATRA) [2,21,22]. However, alterations in retinoid metabolism, signaling and concentrations have been observed in various dermatoses, such as psoriasis [23], ichthyosis [24], and recently in a study by our group in atopic dermatitis [25]. Altered retinoid-mediated signaling in skin of these patients may also be a result of activation or antagonism of specific retinoid receptor subtypes under disease conditions.

In order to dissect retinoid-mediated signaling in skin, mice were treated topically for two weeks with selective RAR and RXR agonists or antagonists. Our aim was to determine the effect of RAR subtype-selective and RXR activation or antagonism on the expression of genes involved in retinoid metabolism and signaling, as well as epidermal barrier homeostasis and skin-based immune regulation. The outcome of the present study will help to identify pathways and genes that are selectively regulated by RAR α , RAR γ , or RXR in the skin of mice. This might allow for conclusions regarding the involvement of subtype-specific retinoid



Figure 1. Back skin of mice after treatment with retinoid receptor-specific agonists and antagonists. Representative photographs of dorsal skin areas from mice topically treated with vehicle control (acetone), or various retinoid receptor-selective agonists or antagonists for 14 days. Note the scaly skin of mice treated with the synthetic RXR agonist or the synthetic RAR γ agonist, and appearing most pronounced in the RAR agonist (ATRA) treated group. ¹all-trans retinoic acid/ATRA.

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receptor-mediated signaling in various skin diseases and may suggest alternative therapeutic strategies.

Materials and Methods

Retinoid Receptor-specific Agonists and Antagonists

ATRA was a gift from BASF (Ludwigshafen, D) and the synthetic RXR activator LG268 was kindly provided by Ligand Pharmaceuticals (San Diego, CA). Synthetic agonists selective for RAR α (BMS753) and RAR γ (BMS189961) were prepared in our laboratories as described in the original patents [26,27] with the yields indicated as supporting information (Figure S1 and S2). The RAR α -specific antagonist (BMS614) was made following the patented procedure developed at BMS [28,29] as detailed in the supporting information section (Figure S3). The RAR γ -selective antagonist (UVI2041) was prepared by the condensation of the ester **15** derived from chalcone **14** [30] with hydroxylamine [31,32] followed by hydrolysis as described in supplements (Figure S4). The RAR pan-antagonist/inverse agonist (BMS493) and the RXR pan-antagonist (UVI3003) were synthesized according to reported procedures [33,34]. The purity of the synthesized compounds was determined to be greater than 95% by HPLC after crystallization. We have confirmed that these retinoids are stable when stored as solids or in solution at -78°C , and during the time frame of biological experiments.

Sensitization of Mice

8–12 weeks old female C57BL6 mice were obtained from and housed within the animal facility of the University of Debrecen, Hungary. Animals were maintained in single cages on standard animal chow and water *ad libitum*. All experimental procedures were approved by the Committee of Animal Research of the University of Debrecen, Hungary (Approval number: 25/2006 DEMÁB).

Mice were anesthetized and subsequently shaved on dorsal skin sites using an electric razor. Retinoid receptor-specific agonists and antagonists were applied topically each other day in 25 μl acetone (vehicle/control; Merck, Darmstadt, D) per treatment for two weeks. According to previous studies by other groups [2,35] agonists and antagonist were applied in the following concentrations: ATRA, 40 nmol; LG268, 100 nmol; BMS753, 40 nmol; BMS189961, 40 nmol; BMS614, 100 nmol; UVI2041, 100 nmol; BMS493, 100 nmol; UVI3003, 100 nmol. On day 14, four hours after the last treatment, mice were sacrificed, sera and full thickness skin biopsies were collected, skin specimen were shock frozen in liquid nitrogen and all samples were kept at -80°C until analyses. Skin samples were obtained from equal body sites by means of the same procedure for each mouse in order to control for variability among specimen. Samples were visibly controlled to ensure no excessive adipose tissue remained, though some contamination with remaining adipose tissue cannot be excluded.

RNA Preparation and Reverse Transcription

Total RNA was isolated from frozen full thickness skin biopsies using Tri[®] reagent (Molecular Research Center Inc., Cincinnati,

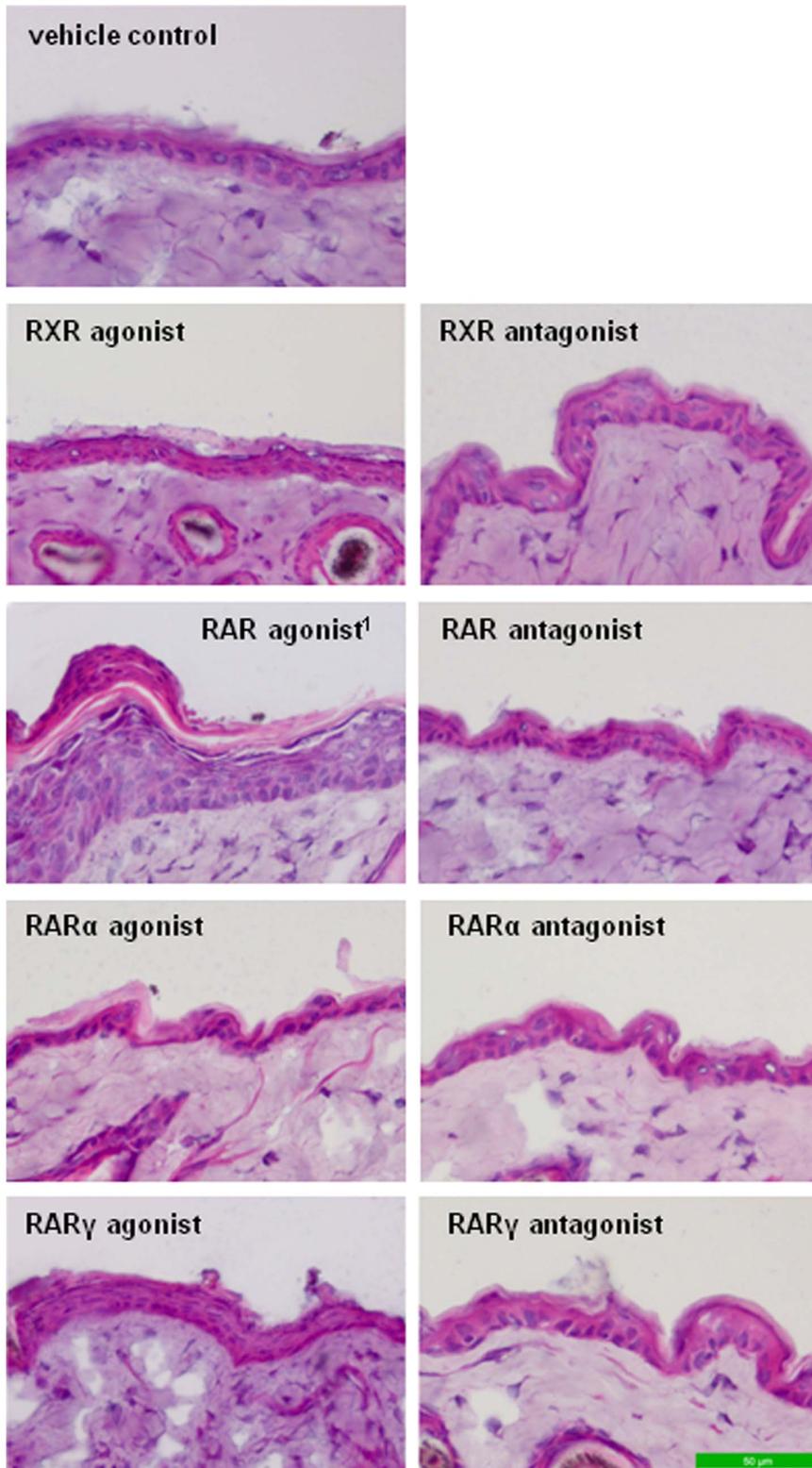


Figure 2. H+E stained skin sections of mice after treatment with retinoid receptor-specific agonists and antagonists. Representative photographs of H+E stained skin sections from mice topically treated with vehicle control (acetone), or various retinoid receptor-selective agonists or antagonists for 14 days. Note the epidermal thickness of mice treated with synthetic agonists for RXR or RAR γ , and appearing most pronounced in the RAR agonist (ATRA) treated group. Epidermal thickness seemed comparable to vehicle control in mice treated with RAR α agonist, RXR antagonist, RAR antagonist, and selective antagonists of RAR α or RAR γ . Original magnification ($\times 20$) was digitally magnified. ¹all-trans retinoic acid/ATRA. doi:10.1371/journal.pone.0062643.g002

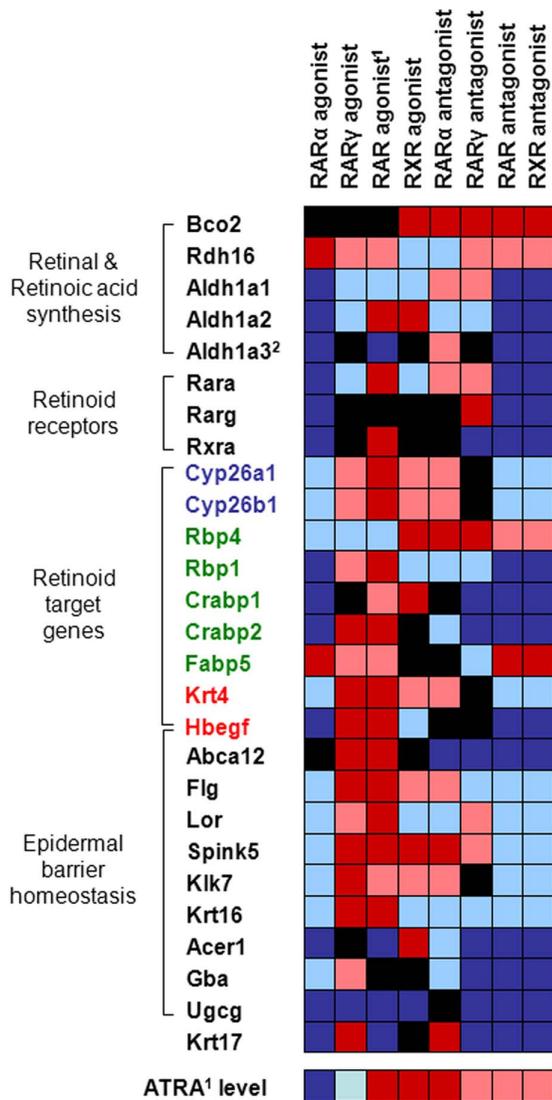


Figure 3. Altered gene expression after treatment with retinoid receptor-specific agonists and antagonists. Heat map displaying fold change of gene expression in mouse skin ($n \geq 5$ /group) after treatment with retinoid receptor-specific agonists and antagonists compared to control mice (acetone). Genes are differentiated according to roles in retinoid metabolism or epidermal homeostasis. Retinoid target genes are further distinguished by specific function, i.e. retinoic acid synthesis (blue), retinoid transport (green), and genes unrelated to retinoid signaling (red). Color codes: dark red – significantly up-regulated; light red – non-significantly up-regulated; black – not regulated ($\pm 20\%$); light blue – non-significantly down-regulated; dark blue – significantly down-regulated. Statistical significance (p) is based on one-way ANOVA followed by Dunnett's post test. A p -value < 0.05 was considered significant. ¹all-*trans* retinoic acid; ²also relevant as retinoid target gene.
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OH) following the manufacturer's instructions. Concentration and purity of RNA samples were determined with NanoDrop spectrophotometer (Thermo Scientific, Budapest, H). 750 ng of total RNA were reverse transcribed into cDNA in a 30 μ L reaction mix using the High Capacity cDNA Reverse Transcription Kit (Life Technologies, Budapest, H) according to the manufacturer's protocol.

Analysis of mRNA Expression

mRNA expression in total skin was determined by means of quantitative real time-PCR (qRT-PCR) on an ABI Prism 7900. Measurements were performed in triplicate using pre-designed TaqMan[®] Gene Expression Assays and reagents (Applied Biosystems Applied Biosystems, Budapest, H). Relative quantification of mRNA expression was achieved using the comparative C_T method and values were normalized to cyclophilin A mRNA. Additionally, Gapdh gene expression was determined to confirm that house keeping gene expression was not affected by the various treatment regimens (not shown). Gene expression values below detection limit were assumed to be zero for the purpose of statistical analysis.

Histological Analysis

Skin biopsies were taken from similar dorsal body sites and kept at -80°C until analysis. Frozen specimens were sectioned (4 μ m) and stained with hematoxylin and eosin (H&E).

Determination of All-*trans* retinoic Acid Levels in Skin

Concentrations of ATRA were determined in mouse skin samples by our high performance liquid chromatography mass spectrometry - mass spectrometry (HPLC MS-MS) method as described previously [36]. In summary, 100 mg of skin biopsy (if samples were under 100 mg, water was added up to the used standard weight: 100 mg) were diluted with a threefold volume of isopropanol, tissues were minced by scissors, vortexed for 10 seconds, put in an ultra sonic bath for 5 minutes, shaken for 6 minutes and centrifuged at 13000 rpm in a Heraeus BIOFUGE Fresco at 4°C . After centrifugation, the supernatants were dried in an Eppendorf concentrator 5301 (Eppendorf, Germany) at 30°C . The dried extracts were resuspended with 60 μ L of methanol, vortexed, shaken, diluted with 40 μ L of 60 mM aqueous ammonium acetate solution and transferred into the autosampler for subsequent analysis.

Statistical Analysis

Data are indicated as mean \pm SEM. Statistical analysis of qRT-PCR data was performed using one-way ANOVA followed by Dunnett's post-test. Significance of HPLC MS-MS results was determined using Student's t -test. Differences were considered significant at $p < 0.05$.

Results

ATRA and a Synthetic RAR γ agonist Induce Epidermal Hyperproliferation

After two weeks topical treatment of mice with various retinoid receptor-specific agonists or antagonists, obvious signs of dryness (scales) could be observed in some groups compared to control mice. Representative images of the treated skin area at day 14 (end of treatment) are shown in Figure 1. Control animals were treated with acetone (vehicle) and their skin appeared normal without scales at the end of two weeks. Similar observations were made in the group treated with the RAR α agonist showing only a very few scattered white scales on the back skin. In contrast, application of synthetic agonists for RXR or RAR γ and the natural RAR ligand ATRA resulted in visibly dry and scaly skin. Compared to rather mild effects induced by the RXR agonist we could detect small scales already after the third treatment with the synthetic RAR γ agonist. During the following days, number and size of scales increased and the skin appeared red and slightly shiny compared to control mice (Figure 1). Application of ATRA (same concen-

Table 1. Fold change of mRNA expression of genes involved in epidermal barrier homeostasis and chemotaxis in murine skin after two weeks of topical treatment with retinoid receptor-specific agonists or antagonists.

Gene name	Symbol	Agonists (Fold change)				Antagonists (Fold change)			
		RAR α ¹	RAR γ ²	ATRA ³	RXR ⁴	RAR α ⁵	RAR γ ⁶	RAR ⁷	RXR ⁸
Epidermal barrier homeostasis									
ATP-binding cassette A12	Abca12	1±0.1	1.6±0.2 [§]	1.5±0.1 [§]	1±0.1	0.6±0.1*	0.5±0.1**	0.001±0.0003 [§]	0.04±0.02 [§]
Filaggrin	Flg	0.2±0.1	11.4±1.3 [#]	32±4.4 [§]	4.1±0.1	1.4±0.1	2.2±0.8	0.0003±0.0003	0.004±0.003
Involucrin	Ivl	0.9±0.1	1.6±0.1 [§]	1.3±0.1	0.9±0.1	1±0.1	1.2±0.1	1.3±0.1	0.8±0.2
Loricrin	Lor	0.04±0.003	1.8±0.3	7.3±0.8 [§]	0.6±0.1	0.7±0.2	1.3±0.3	0.002±0.0005	0.008±0.004
Transglutaminase 1	Tgm1	UDL [§]	0.7±0.2	2.5±0.2 [§]	0.1±0.02 [§]	0.4±0.1 [#]	UDL [§]	UDL [§]	UDL [§]
Serine peptidase inhibitor, Kazal-type 5	Spink5	0.01±0.01	5.1±1 [§]	2.8±0.4*	2.8±0.3*	5.1±0.6 [§]	2.3±0.3	0.003±0.001	0.03±0.01
Kallikrein-related peptidase 5	Klk5	UDL	4.9±1.5 [§]	2.8±0.4	1±0.1	2.4±0.5	3.4±0.7*	UDL	UDL
Kallikrein-related peptidase 7	Klk7	0.0008±0.0005	5.6±1.8 [§]	2.7±0.3	3.2±0.6	2.1±0.3	1.2±0.1	0.005±0.001	0.02±0.008
Matrix metalloproteinase 9	Mmp9	0.4±0	2.7±0.5	2±1.1	0.8±0.1	4.7±0.8 [§]	UDL	0.3±0.1	0.9±0.3
S100 calcium binding protein A7A	S100a7a	0.2±0.1	1.4±0.1	3.4±0.6 [§]	0.8±0.1	0.02±0.002*	UDL [#]	UDL*	0.002±0.001*
Keratin 16	Krt16	0.02±0.004	3.8±0.4 [§]	2.8±0.9*	0.6±0.1	0.5±0.1	UDL	0.03±0.006	0.03±0.01
Heparin-binding EGF-like growth factor ⁹	Hbegf	0.03±0.01*	2.7±0.6 [§]	2±0.2*	0.3±0.2	0.8±0.1	0.8±0.1	UDL*	UDL*
3-Hydroxy-3-methylglutaryl-CoA synthase 2	Hmgcs2	0.01±0.004 [§]	0.5±0.1*	0.1±0.02 [§]	1.3±0.3	0.6±0.1	UDL [§]	0.0006±0.0006 [§]	0.1±0.02 [§]
UDP-glucose ceramide glucosyltransferase	Ugcg	0.1±0.02 [§]	0.4±0.1 [§]	0.1±0.03 [§]	0.2±0.02 [§]	0.9±0.1	UDL [§]	0.002±0.002 [§]	0.001±0.001 [§]
Glucocerebrosidase	Gba	0.4±0.2	1.4±0.3	0.9±0.2	0.9±0.1	0.5±0.2	UDL [§]	UDL [§]	0.003±0.003 [§]
Alkaline ceramidase 1	Acer1	UDL*	1.2±0.1	0.02±0.007 [§]	1.5±0.2*	0.7±0.1	0.1±0.02 [§]	UDL [§]	0.2±0.03 [§]
Immune response									
Chemokine ligand 11/eotaxin-1	Ccl11	UDL [§]	0.6±0.1*	0.6±0.1*	0.5±0.1*	2±0.2 [§]	UDL [§]	UDL [§]	UDL [§]
Chemokine ligand 24/eotaxin-2	Ccl24	UDL [§]	0.1±0.1 [§]	0.009±0.009 [§]	0.5±0.1*	1.9±0.2 [§]	UDL [§]	UDL [§]	UDL [§]
Chemokine ligand 17/Tarc	Ccl17	2±0.6	2.7±0.4	9.6±1.5 [§]	0.6±0.1	0.2±0.1	13.9±2.8 [§]	UDL	0.1±0.1
Chemokine ligand 22/Mdc	Ccl22	UDL	4.3±1 [§]	1.9±0.3	0.8±0.1	0.5±0.2	UDL	UDL	UDL
Keratin 17	Krt17	0.03±0.006 [§]	1.5±0.1 [§]	0.2±0.02 [§]	1±0.1	1.3±0.1*	0.03±0.01 [§]	0.04±0.004 [§]	0.03±0.01 [§]

¹BMS753; ²BMS961; ³all-trans retinoic acid; ⁴LG268; ⁵BMS614; ⁶UVI2041; ⁷BMS493; ⁸UVI3003; ⁹gene also relevant as retinoid target gene; UDL, under detection limit. Fold change data are expressed as mean ± SEM (n≥5) and were determined in skin specimens of topically treated mice by qRT-PCR. Statistical significance (p) was tested using one-way ANOVA followed by Dunnett's post test. *p<0.05, #p<0.01, §p<0.001, versus control (acetone). doi:10.1371/journal.pone.0062643.t001

tration as the synthetic RAR γ agonist) showed the strongest effects resulting in apparently very dry skin with big white scales already shortly after initiating the treatment (not shown). Skin of these mice also seemed shiny compared to controls. Skin regions treated with receptor antagonists appeared mostly normal at day 14. A few small scales could be observed only after application of the RAR α and RXR antagonists. In order to verify these visual impressions we also performed histological analysis (Figure 2). In accordance, epidermal thickness seemed comparable to control mice in all treatment groups except for mice treated with the synthetic RAR γ agonist, RXR agonist or ATRA. Epidermal thickness was markedly increased in all three groups but appeared stronger in mice treated with the RAR γ agonist and was most pronounced in ATRA-treated mice. Additionally, the epidermal surface seemed notably scaly after application of the synthetic RAR γ agonist and ATRA (Figure 2).

RAR-RXR Signaling Pathways Modify Epidermal Barrier Homeostasis

We next investigated the expression of various genes with significant functions in epidermal barrier homeostasis upon

treatment with receptor-specific agonists and antagonists. As shown in Table 1 and Figure 3, application of the synthetic RAR γ agonist and ATRA both induced genes involved in barrier function (Abca12, Flg, Lor, Spink5, Krt16, Hbegf). On the other hand, mRNA levels of genes implicated in ceramide metabolism (Acer1, Gba, Ugcg) or cholesterol synthesis (Hmgcs2) were mainly decreased or unaffected by the treatment. Compared to RAR γ ligand application, expression of these genes was markedly down-regulated (several times below detection limit) when mice were treated with the synthetic RAR α agonist (Table 1, Figure 3). Noticeably, the same expression profile was observed after application of RAR or RXR antagonists. Treatment with the RXR agonist and RAR α - and RAR γ -specific antagonists resulted in inconsistent gene expressions with an increase of some genes (Spink5, Flg, Klk7) and decrease of other genes (Abca12, Krt16, Ugcg) involved in epidermal function (Table 1, Figure 3). Krt6b expression was below the limit of detection in all groups (not shown).

Table 2. Fold change of retinoid metabolism-related gene expression in skin of mice after two weeks topical treatment with retinoid receptor-specific agonists.

Gene name	Symbol	Agonists (Fold change)			
		RAR α ¹	RAR γ ²	ATRA ³	RXR ⁴
Retinal synthesis					
Beta-carotene oxygenase	Bco2	UDL	UDL	UDL	3305 \pm 192 ⁵
Short chain dehydrogenase/reductase 16C5	Sdr16c5	UDL	0.6 \pm 0.1	9.4 \pm 1.3 ⁵	0.9 \pm 0.1
Retinol dehydrogenase 10	Rdh10	0.01 \pm 0.003 ⁵	1.5 \pm 0.1 ⁵	0.7 \pm 0.1*	0.6 \pm 0.1 [#]
Retinol dehydrogenase 16	Rdh16	493 \pm 128 ⁵	1.3 \pm 0.3	2.5 \pm 0.3	0.5 \pm 0.1
Alcohol dehydrogenase 7	Adh7	0.2 \pm 0.1	1.8 \pm 0.3	2.8 \pm 0.5 ⁵	2 \pm 0.1*
Retinoic acid synthesis					
Aldehyde dehydrogenase 1A1	Aldh1a1	UDL [#]	0.7 \pm 0.1	0.6 \pm 0.1	0.3 \pm 0.1
Aldehyde dehydrogenase 1A2	Aldh1a2	0.04 \pm 0.009*	0.7 \pm 0.2	3.4 \pm 0.5 ⁵	2.4 \pm 0.3 [#]
Aldehyde dehydrogenase 1A3 ⁵	Aldh1a3	UDL ⁵	1 \pm 0.04	0.02 \pm 0.008 ⁵	0.9 \pm 0.2
Retinoid receptor					
Retinoic acid receptor α	Rara	UDL*	0.3 \pm 0.1	5.8 \pm 0.4 ⁵	0.7 \pm 0.1
Retinoic acid receptor β ⁵	Rarb	UDL ⁵	1.1 \pm 0.2	1.4 \pm 0.1*	0.6 \pm 0.1*
Retinoic acid receptor γ	Rarg	UDL ⁵	1.1 \pm 0.1	0.9 \pm 0.3	0.9 \pm 0.1
Retinoid X receptor α	Rxra	0.002 \pm 0.0006 ⁵	0.9 \pm 0.1	1.4 \pm 0.1 ⁵	1 \pm 0.1
Retinoid target genes					
<i>Retinoic acid degradation</i>					
Cytochrome P450 26A1	Cyp26a1	UDL	19 \pm 5.4	1410 \pm 161 ⁵	1.5 \pm 0.3
Cytochrome P450 26B1	Cyp26b1	0.003 \pm 0.003	13 \pm 0.5	299 \pm 54 ⁵	1.6 \pm 0.2
Cytochrome P450 251	Cyp251	UDL [#]	0.9 \pm 0.1	0.6 \pm 0.1	0.9 \pm 0.1
<i>Retinoid transport proteins</i>					
Retinol binding protein 4	Rbp4	UDL	UDL	UDL	2816 \pm 244 ⁵
Cellular retinol binding protein 1	Rbp1	0.02 \pm 0.004 ⁵	1.4 \pm 0.2	2.8 \pm 0.2 ⁵	0.7 \pm 0.1
Cellular retinoic acid binding protein 1	Crabp1	0.02 \pm 0.01 [#]	1 \pm 0.2	1.7 \pm 0.3	1.8 \pm 0.2*
Cellular retinoic acid binding protein 2	Crabp2	0.0007 \pm 0.0003 ⁵	1.5 \pm 0.2*	2 \pm 0.2 ⁵	0.8 \pm 0.04
Fatty acid binding protein 5	Fabp5	10 \pm 0.8 ⁵	1.9 \pm 0.4	2.2 \pm 0.1	1.2 \pm 0.1
<i>Retinol esterification</i>					
Lecithin-retinol acyltransferase	Lrat	0.02 \pm 0.007 ⁵	2.3 \pm 0.2 ⁵	2 \pm 0.1 ⁵	1 \pm 0.1
Diacylglycerol O-acyltransferase	Dgat	UDL ⁵	1.5 \pm 0.2 ⁵	0.4 \pm 0.1 ⁵	0.2 \pm 0.03 ⁵
<i>Further retinoid target genes⁶</i>					
Keratin 4	Krt4	UDL	6470 \pm 646 ⁵	3167 \pm 679 ⁵	7.7 \pm 3
Retinoic acid receptor responder 2	Rarres2	UDL	1.8 \pm 0.2	1.3 \pm 0.3	1.6 \pm 0.2
Heparin-binding EGF-like growth factor ⁷	Hbegf	0.03 \pm 0.01*	2.7 \pm 0.6 ⁵	2 \pm 0.2*	0.3 \pm 0.2

¹BMS753; ²BMS961; ³all-trans retinoic acid; ⁴LG268; ⁵retinoid target genes; ⁶target genes not involved in retinoid signaling; ⁷gene also relevant in epidermal homeostasis; UDL, under detection limit. Fold change data are expressed as mean \pm SEM (n \geq 5) and were determined in skin specimens of topically treated mice by qRT-PCR. Statistical significance (p) was tested using one-way ANOVA followed by Dunnett's post-test. *p<0.05, #p<0.01, ⁵p<0.001, versus control (acetone). doi:10.1371/journal.pone.0062643.t002

RAR-RXR Signaling Pathways Modify Skin-based Immune Responses

Retinoid-mediated signaling is known to play an important role in the immune system and a dysregulated retinoid metabolism was found in skin of atopic dermatitis patients (Mihály et al. 2011). Therefore, we investigated whether topical application of receptor-specific retinoids is sufficient to alter the expression of genes implicated in the immune response in skin, such as the chemokines Ccl11 (eotaxin-1), Ccl17 (Tarc), Ccl22 (Mdc), Ccl24 (eotaxin-2), Ccr3 and the inflammatory marker Krt17 (Table 1). The synthetic RXR activator exerted only a slight effect on gene expression in skin, while levels of chemokines and Krt17 were markedly

decreased in response to the RAR α agonist (except for Ccl17). Again, this result strongly resembled to those found after application of RAR or RXR antagonists. Topical treatment with the synthetic RAR γ agonist and ATRA, as well as the RAR γ antagonist decreased mRNA levels of Ccl11 and Ccl24 but induced Ccl17 and partly Ccl22, while it was the opposite in mouse skin treated with the RAR α antagonist. Moreover, the chemokine receptor Ccr3 was below detection level regardless of which agonist or antagonist was applied (not shown). Expression of Krt17 was increased only in response to the RAR γ agonist or RAR α antagonist while it was decreased or unaltered in all other groups (Table 1).

Table 3. Fold change of retinoid metabolism-related gene expression in skin of mice after two weeks topical treatment with retinoid receptor-specific antagonists.

Gene name	Symbol	Antagonists (Fold change)			
		RAR α ¹	RAR γ ²	RAR ³	RXR ⁴
Retinal synthesis					
Beta-carotene oxygenase	Bco2	443±84 [§]	124±78	90±41	117±14
Short chain dehydrogenase/reductase 16C5	Sdr16c5	0.7±0.04	0.3±0.04	UDL	UDL
Retinol dehydrogenase 10	Rdh10	0.8±0.1	0.1±0.03 [§]	0.003±0.003 [§]	0.1±0.04 [§]
Retinol dehydrogenase 16	Rdh16	0.02±0.01	3.5±0.7	6.5±1.2	1.3±0.5
Alcohol dehydrogenase 7	Adh7	0.01±0.001*	1±0.1	0.002±0.0004 [#]	0.006±0.002*
Retinoic acid synthesis					
Aldehyde dehydrogenase 1A1	Aldh1a1	1.3±0.3	1.5±0.3	UDL [#]	UDL [#]
Aldehyde dehydrogenase 1A2	Aldh1a2	0.5±0.1	0.2±0.03	0.1±0.1*	0.03±0.02*
Aldehyde dehydrogenase 1A3 ⁵	Aldh1a3	1.3±0.2	1±0.2	0.003±0.001 [§]	0.004±0.003 [§]
Retinoid receptor					
Retinoic acid receptor α	Rara	1.5±0.3	1.3±0.1	UDL*	UDL*
Retinoic acid receptor β ⁵	Rarb	0.6±0.03	0.7±0.1	UDL [§]	UDL [§]
Retinoic acid receptor γ	Rarg	0.8±0.1	1.7±0.2 [#]	UDL [§]	UDL [§]
Retinoid X receptor α	Rxra	0.9±0.1	0.8±0.1*	0.0004±0.0002 [§]	0.01±0.005 [§]
Retinoid target genes					
<i>Retinoic acid degradation</i>					
Cytochrome P450 26A1	Cyp26a1	1.6±0.6	0.9±0.3	UDL	UDL
Cytochrome P450 26B1	Cyp26b1	1.3±0.2	1.1±0.2	0.001±0.001	0.02±0.009
Cytochrome P450 251	Cyp2s1	0.9±0.1	1.6±0.1*	UDL [§]	0.006±0.004 [#]
<i>Retinoid transport proteins</i>					
Retinol binding protein 4	Rbp4	448±18 [§]	1710±505 [§]	12±12	30±30
Cellular retinol binding protein 1	Rbp1	0.6±0.1	0.7±0.04	0.003±0.002 [§]	0.02±0.003 [§]
Cellular retinoic acid binding protein 1	Crabp1	1.1±0.3	UDL [§]	0.02±0.01 [#]	0.1±0.03 [#]
Cellular retinoic acid binding protein 2	Crabp2	0.7±0.1	0.5±0.04 [#]	UDL [§]	0.04±0.01 [§]
Fatty acid binding protein 5	Fabp5	0.9±0.1	0.2±0.02	13±0.6 [§]	8±1 [§]
<i>Retinol esterification</i>					
Lecithin-retinol acyltransferase	Lrat	1.2±0.1	0.6±0.1	0.003±0.002 [§]	0.01±0.007 [§]
Diacylglycerol O-acyltransferase	Dgat	0.2±0.02 [§]	0.1±0.008 [§]	UDL [§]	0.003±0.003 [§]
<i>Further retinoid target genes⁶</i>					
Keratin 4	Krt4	154±37	UDL	UDL	UDL
Retinoic acid receptor responder 2	Rarres2	3.4±0.6 [§]	1±0.3	UDL	0.005±0.005
Heparin-binding EGF-like growth factor ⁷	Hbegf	0.8±0.1	0.8±0.1	UDL	UDL*

¹BMS614; ²UVI2041; ³BMS493; ⁴UVI3003; ⁵retinoid target genes; ⁶target genes not involved in retinoid signaling; ⁷gene also relevant in epidermal homeostasis; UDL, under detection limit. Fold change data are expressed as mean ± SEM (n≥5) and were determined in skin specimens of topically treated mice by qRT-PCR. Statistical significance (p) was tested using one-way ANOVA followed by Dunnett's post-test. *p<0.05, #p<0.01, §p<0.001, versus control (acetone). doi:10.1371/journal.pone.0062643.t003

RAR α and RAR γ Differentially Regulate Retinoid-mediated Signaling

Moreover, we were interested in the effect of RAR subtype-selective agonists on retinoid metabolism. Interestingly, we found that treatment with the synthetic RAR α agonist down-regulated the expression of all investigated genes with a role in retinoid metabolism that is RA synthesis, retinoid receptors and target genes (Table 2, Figure 3). Only mRNA levels of the lipid transporter Fabp5 and an enzyme involved in retinal synthesis (Rdh16) were significantly increased by the agonist. In contrast, the synthetic agonist for RAR γ and ATRA, which is a natural RAR agonist, induced the expression of nearly all retinoid target

genes in the skin of mice, e.g. Cyp26a1, Cyp26b1, Rbp1, Crabp1, Hbegf and Krt4 as a marker for retinoid activity (Table 2, Figure 3). Similarly, topical application of the RXR-selective agonist induced the expression of some retinoid target genes (Cyp26a1, Cyp26b1, Rbp4, Crabp1, Krt4), but the treatment did not affect or slightly decrease the expression of other targets (Crabp2, Fabp5, Rbp1, Hbegf). Repetitive treatment with the RAR γ -selective agonist showed no significant effect on retinal and RA-synthesis enzymes, and retinoid receptor gene expression in skin. However, the endogenous RAR ligand ATRA and the RXR agonist markedly increased mRNA levels of Aldh1a2 and ATRA

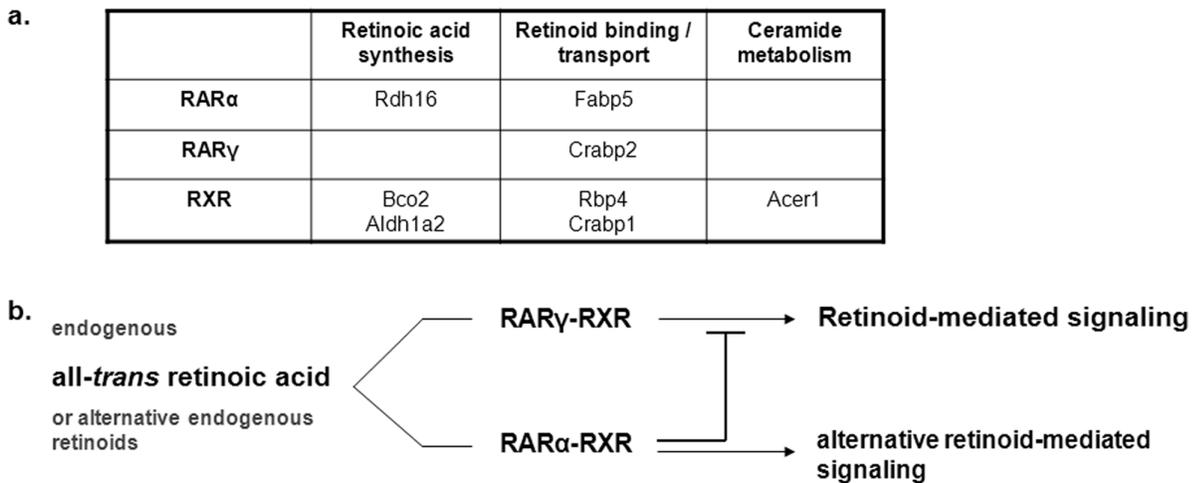


Figure 4. Retinoid receptor-selective gene regulation. (a) Retinoid receptor-selective induction of genes with specific roles in retinoid signaling or epidermal barrier homeostasis in skin of mice treated topically with selective agonists for RAR α , RAR γ or RXR for 14 days. (b) Proposed outcome of selective signaling via RAR α -RXR or RAR γ -RXR in skin of mice induced by endogenous retinoids, such as all-*trans* retinoic acid. doi:10.1371/journal.pone.0062643.g004

further induced *Rara* and *Rxra* gene expression, while it decreased *Aldh1a3* expression in skin (Table 2, Figure 3).

RAR and RXR Antagonists Decrease the Expression of Genes Involved in Retinoid Signaling in Skin

Topical application of antagonists for RAR α and RAR γ resulted in non-significantly reduced or unaltered expression of several genes involved in retinoid signaling in skin. However, some genes seemed to be slightly induced by both antagonists, such as *Bco2*, *Rbp4*, *Aldh1a1* which is responsible for RA synthesis, *Rara*, *Rarg* and some target genes like *Cyp26a1*, *Cyp26b1* and *Krt4* (Figure 3, Table 3). In contrast, antagonists for RAR and RXR decreased the expression of nearly all of these genes below detection limit. Only mRNA levels of *Bco2*, *Rdh16*, *Rbp4* and *Fabp5* were found to be elevated by the antagonists. Surprisingly, this expression pattern strongly resembled to that which we observed in skin of mice treated with the synthetic RAR α agonist (Figure 3, Table 3).

RXR Agonist and RAR α Antagonist Increase ATRA Levels in Skin via Induced Synthesis

ATRA levels in skin were found to be differentially affected depending on the applied receptor-selective agonist or antagonist (Figure 3, Table S1). Concentrations of ATRA were significantly decreased in the skin of mice treated with the synthetic RAR α agonist and non-significantly by the RAR γ agonist. Furthermore, treatments with antagonists for RAR γ , RARs, or RXRs resulted in elevated ATRA concentrations, while only RAR α antagonist treatment induced a significant increase. As expected, we found ATRA levels markedly elevated upon treatment with this RAR agonist itself (highest level among all groups). Noticeably, however, was the pronounced elevation of ATRA in mouse skin after application of the synthetic RXR agonist (Figure 3, Table S1).

Discussion

In the present study we repetitively treated mice topically with various retinoid receptor-specific agonists or antagonists in order to determine the effect of selective retinoid-mediated signaling in skin on epidermal barrier homeostasis, immune regulation and

retinoid metabolism. The main finding of this study was the strong difference between the positive retinoid-mediated signaling via RAR γ pathways in contrast to the negative retinoid-mediated signaling via RAR α in the skin.

Epidermal hyperproliferation is a well established effect of RAR-activation in skin [2,37,38] and was induced in this study by ATRA and the synthetic RAR γ agonist (Figure 1 and 2), which was further supported by an induced expression of regulators of desquamation such as *Spink5*, *Klk5* and *Klk7* [39–41]. Moreover, elevated mRNA levels of *Hbegf* and *Krt16*, which were already related previously with induced keratinocyte proliferation [2,42–44], also contributed to the result (Table 1, Figure 3). Somewhat surprising, however, was the mild induction of epidermal proliferation by the synthetic RXR agonist since no such observation was reported in a previous study using another synthetic RXR agonist [2]. Retinoid effects in skin are most likely mediated by RAR γ -RXR heterodimers while their transcriptional activity is dependent on the RAR-activating ligand [2,3]. Upon treatment with the RXR agonist we observed increased *Aldh1a2* gene expression and elevated ATRA levels in skin (Table 2 and S1), indicating induced ATRA synthesis which might account for the mild epidermal hyperproliferation, most probably mediated by the RAR partner. However, another RXR heterodimer partner, PPAR δ , was previously found to be implicated in the regulation of keratinocyte hyperproliferation [45–47]. Compared to RAR-RXR, this heterodimer is permissive which means an RXR ligand is sufficient to activate transcription of respective target genes [48]. This might suggest alternative pathways to be involved in RXR agonist-induced hyperproliferation.

Moreover, retinoid application affected various other processes in skin, as indicated by altered expression levels of genes involved in epidermal barrier homeostasis such as *Abca12*, *Flg*, and *Lor* [49,50] and of genes with roles in lipid barrier formation and ceramide metabolism, e.g. *Hmgcs2*, *Ugcg*, *Gba*, *Acer1* [51–54]. Consistently, such retinoid-mediated effects have already been reported by Lee et al. (2009) in epidermal keratinocytes [42].

These results strongly suggest that retinoid-mediated signaling is required for normal barrier homeostasis and that retinoid-induced dysregulation may be a predisposing factor for dermatological diseases. Thereby both, antagonism and induction of RAR- and/or RXR-mediated signaling in skin appear to be able to disturb

barrier homeostasis as shown in our study and previous works [55–59]. However, no further functional analysis, such as determination of trans-epidermal water loss, was performed in order to prove barrier disturbance.

It is well established that retinoids play important roles in the immune system [16,60], especially in Th2-type cell differentiation [61–63]. Interestingly, the expression of various chemokines which are preferentially attracting Th2-type lymphocytes during inflammatory processes [64–66] was differently altered by the retinoids applied in the present study (Table 1). However, undetectable mRNA levels of the corresponding chemokine receptor (CCR3) which is expressed by infiltrating immune competent cells such as eosinophils [67–69] might suggest the absence of inflammatory cells in the skin upon retinoid treatments. These results indicate that topical retinoids can modify potential immune responses by altering chemokine expression of resident skin cells and that the outcome of immune alterations seems to differ depending on the RAR subtype activated.

Retinoid receptor agonist treatment affected the expression of all genes investigated in the skin and involved in retinoid-mediated signaling (retinoid metabolism, transport, target genes) in general oppositely to antagonists. Likewise, target genes were mainly induced after treatment with ATRA or the RAR γ agonist (Figure 3 and Table 2), as previously reported [38,42,70,71]. Moreover, both agonists induced very similar gene expression patterns and given the fact that RAR γ is the predominant RAR subtype in skin [5] it is indicated that ATRA mediates its activity in skin through RAR γ rather than RAR α [2,5,72]. Most interesting, however, was a consequent down-regulation of gene expression by the synthetic RAR α agonist which is in line with reduced ATRA levels in mouse skin, possibly due to decreased ATRA synthesis via Aldh enzymes (Table 2). Only Fabp5 and Rdh16 expressions were increased in response to the agonist. This expression pattern strongly resembled to that in response to RAR or RXR antagonists while both antagonists further seemed to induce Bco2 and Rbp4 expression (Figure 3, Tables 2 and 3). The proteins encoded by those genes are implicated in retinoid metabolism and transport [73–76]. Thus, it seems plausible that ATRA or retinoid derivatives different from ATRA, like oxo-retinoids or still unknown endogenous RAR ligands could be generated upon retinoid receptor antagonism and shuttled to nuclear receptors different from RARs, as it was already proposed for Fabp5-mediated ATRA-induced PPAR δ activation [73,77,78]. Additionally, also NR4A1/NUR77 and RXR were shown to form heterodimers which respond to RXR activators *in vivo* and *in vitro* [79] and might thereby participate in retinoid-mediated signaling when RARs are antagonized. Moreover, Volakakis et al. [80] demonstrated that NR4A1/NUR77 can induce the expression of Fabp5 in HEK293 cells which potentially enhances RA-mediated PPAR δ signaling. Interestingly, we found Nr4a1/Nur77 and Ppard expression in skin significantly decreased or below detection limit in response to those ligands which markedly induced Fabp5 expression, namely the RAR α agonist, RAR and RXR antagonists (Tables 2 and 3, Table S2). This may be indicative of (late) negative feedback regulations on the gene expression level in response to induced Fabp5 expression. Whether FABP5-mediated PPAR δ signaling and/or a novel, as yet undetermined retinoid(s) might mediate such an alternative retinoid pathway in skin is currently under investigation in our laboratory. Moreover, since mRNA levels of ATRA-synthesizing enzymes (Aldhs) following RAR and RXR antagonist application were not in accord with elevated ATRA levels in the skin of those mice, we suggest that ATRA synthesis upon antagonist treatment may be mediated by Bco2, Rdh16, RBP4 and/or other pathways, from precursors

present in the skin and/or via transporter-mediated pathways delivering retinoids to the skin [74].

Altogether, our observations indicate different roles of RXR-, RAR α - and RAR γ -mediated signaling pathways in skin (Figure 4a) and suggest that induction of RAR α signaling might result in the suppression of RAR γ -mediated pathways in the skin of mice. Considering the induced RAR α gene expression after topical ATRA treatment, this appears to be an efficient physiological switch to different retinoid-mediated signaling pathways. However, it is unknown how RAR α mediates its suppressive action on RAR γ signaling. High RAR α expression was found in inflammatory cells infiltrating the skin in several dermatoses [81], however, in normal skin its expression level is fairly low compared to RAR γ molecules [5]. Thus it seems unlikely that a competition between both receptors for RXR α as heterodimer partner could be the explanation. Instead, RAR α apparently regulates the expression of different sets of genes, possibly also in different skin cell types, than does RAR γ and might also induce the transcription of co-repressor molecules upon activation.

In summary, this study lets us emphasize that there must be yet unidentified alternative retinoid signaling pathways or a broader range of endogenous retinoids present in skin for selective RAR α , RAR γ , or RXR activation as outlined in Figure 4b. Moreover, our data indicate that unbalanced retinoid signaling in the skin mediated by RAR α , RAR γ and/or RXR signaling pathways as well as potential unidentified pathways, affects epidermal barrier homeostasis and skin-based immune responses in mice. This retinoid dysregulation may play a central role in various skin diseases and the obtained data from this study might help to identify appropriate treatment strategies for diseased skin with dysregulated retinoid signaling using selective RAR and RXR agonists or antagonists, alone or in combination.

Supporting Information

Figure S1 Synthesis of BMS753. Reagents and conditions: a. AlCl₃, C₆H₆, 100°C, 4 h (65%). b. KMnO₄, H₂O, NaOH, 100°C, 3 h (78%). c. CrO₃, AcOH, 25°C, 4 h (93%). d. AlCl₃, ClCOCO₂Et, CH₂Cl₂, 25°C, 2 h (43%). e. NaOH (1 N, aq), MeOH, 25°C, 1 h (99%). f. NaOH, MeOH, H₂O₂, 25°C, 16 h (96%). g. i) Oxalyl chloride, CH₂Cl₂, DMF, 5 min. ii) Methyl 4-aminobenzoate, pyridine, 25°C, 16 h (45%). h. NaOH (1 N, aq), MeOH, 70°C, 4 h (89%). (TIF)

Figure S2 Synthesis of BMS189961. Reagents and conditions: a. i) *t*-Butyllithium, THF, –78°C, 30 min. ii) (COCO₂Me)₂, THF, 25°C, 16 h (88%). b. LiOH·H₂O, 4 h, 25°C (76%). c. i) Oxalyl chloride, DMF. ii) Ethyl 4-amino-3-fluorobenzoate, Et₃N, EtOAc, 16 h, 25°C (65%). d. NaBH₄, MeOH, 5 min, (79%) e. LiOH·H₂O, 25°C, 4 h (64%). (TIF)

Figure S3 Synthesis of BMS614. Reagents and conditions: a) HBF₄, NaNO₂, H₂O, 10°C, 89%. b) H₂SO₄, H₂O, reflux, 1 h, 88%. c) Tf₂O, Py, 25°C, 16 h, 100%. d) Pd(OAc)₂, dppp, CO, Et₃N, MeOH, DMSO, 70°C, 3 h, 93%. e) i. 3-bromoquinoline, *n*-BuLi, THF, –78°C. ii. THF, 25°C, 2 h, 32%. f) *p*-TsOH, toluene, 90°C, 2.5 h, 83%. g) NaOH (10 M), EtOH/H₂O (1:1), 25°C, 24 h, 88%. h) i. (ClCO)₂, CH₂Cl₂, DMF, 25°C, 2 h; ii. methyl 4-aminobenzoate, Py, 25°C, 2 h, 26%. i) NaOH (10 M), EtOH/H₂O (1:1), 25°C, 24 h, 28%. (TIF)

Figure S4 Synthesis of UVI2041. Reagents and conditions: a) EDC (1.1 equiv), DMAP (0.01 equiv), Trimethylsilylethanol (1.1

equiv), CH₂Cl₂, 18 h, 23°C, 65%. b) NH₂OH (2 equiv), pyridine (2.2 equiv), EtOH, 70°C, 20 h, 66% (*E/Z* isomer mixture at the oxime). c) TBAF (2 equiv), DMSO, 30 min, 63%. (TIF)

Table S1 ATRA concentrations (ng/g) in murine skin after two weeks topical treatment with retinoid receptor-selective agonists or antagonists. (DOCX)

Table S2 Fold change of mRNA expression of Nr4a1 and Ppard in skin of mice after two weeks of topical treatment with retinoid receptor-specific agonists or antagonists.

References

- Mangelsdorf DJ, Thummel C, Beato M, Herrlich P, Schutz G, et al. (1995) The nuclear receptor superfamily: the second decade. *Cell* 83: 835–839.
- Chapellier B, Mark M, Messaddeq N, Calleja C, Warot X, et al. (2002) Physiological and retinoid-induced proliferations of epidermis basal keratinocytes are differently controlled. *Embo J* 21: 3402–3413.
- Feng X, Peng ZH, Di W, Li XY, Rochette-Egly C, et al. (1997) Suprabasal expression of a dominant-negative RXR alpha mutant in transgenic mouse epidermis impairs regulation of gene transcription and basal keratinocyte proliferation by RAR-selective retinoids. *Genes Dev* 11: 59–71.
- Pérez E, Bourguet W, Gronemeyer H, de Lera AR (2012) Modulation of RXR function through ligand design. *Biochim Biophys Acta* 1821: 57–69.
- Fisher GJ, Talwar HS, Xiao JH, Datta SC, Reddy AP, et al. (1994) Immunological identification and functional quantitation of retinoic acid and retinoid X receptor proteins in human skin. *J Biol Chem* 269: 20629–20635.
- Elder JT, Astrom A, Pettersson U, Tavakkol A, Krust A, et al. (1992) Retinoic acid receptors and binding proteins in human skin. *J Invest Dermatol* 98: 36S–41S.
- Elder JT, Fisher GJ, Zhang QY, Eisen D, Krust A, et al. (1991) Retinoic acid receptor gene expression in human skin. *J Invest Dermatol* 96: 425–433.
- Dolle P, Ruberte E, Leroy P, Morriss-Kay G, Chambon P (1990) Retinoic acid receptors and cellular retinoid binding proteins. I. A systematic study of their differential pattern of transcription during mouse organogenesis. *Development* 110: 1133–1151.
- Germain P, Chambon P, Eichele G, Evans RM, Lazar MA, et al. (2006) International Union of Pharmacology. LX. Retinoic acid receptors. *Pharmacol Rev* 58: 712–725.
- Redfern CP, Todd C (1992) Retinoic acid receptor expression in human skin keratinocytes and dermal fibroblasts in vitro. *J Cell Sci* 102 (Pt 1): 113–121.
- Altucci L, Leibowitz MD, Ogilvie KM, de Lera AR, Gronemeyer H (2007) RAR and RXR modulation in cancer and metabolic disease. *Nat Rev Drug Discov* 6: 793–810.
- de Lera AR, Bourguet W, Altucci L, Gronemeyer H (2007) Design of selective nuclear receptor modulators: RAR and RXR as a case study. *Nat Rev Drug Discov* 6: 811–820.
- Allenby G, Bocquel MT, Saunders M, Kazmer S, Speck J, et al. (1993) Retinoic acid receptors and retinoid X receptors: interactions with endogenous retinoic acids. *Proc Natl Acad Sci U S A* 90: 30–34.
- Allenby G, Janocha R, Kazmer S, Speck J, Grippo JF, et al. (1994) Binding of 9-*cis*-retinoic acid and all-*trans*-retinoic acid to retinoic acid receptors alpha, beta, and gamma. Retinoic acid receptor gamma binds all-*trans*-retinoic acid preferentially over 9-*cis*-retinoic acid. *J Biol Chem* 269: 16689–16695.
- Rühl R, Garcia A, Schweigert EJ, Worm M (2004) Modulation of cytokine production by low and high retinoid diets in ovalbumin-sensitized mice. *Int J Vitam Nutr Res* 74: 279–284.
- Rühl R (2007) Effects of dietary retinoids and carotenoids on immune development. *Proc Nutr Soc* 66: 458–469.
- Rühl R, Hanel A, Garcia AL, Dahten A, Herz U, et al. (2007) Role of vitamin A elimination or supplementation diets during postnatal development on the allergic sensitization in mice. *Mol Nutr Food Res* 51: 1173–1181.
- Roos TC, Jugert FK, Merk HF, Bickers DR (1998) Retinoid metabolism in the skin. *Pharmacol Rev* 50: 315–333.
- Elias PM (1987) Retinoid effects on the epidermis. *Dermatologica* 175 Suppl 1: 28–36.
- Elias PM, Fritsch PO, Lampe M, Williams ML, Brown BE, et al. (1981) Retinoid effects on epidermal structure, differentiation, and permeability. *Lab Invest* 44: 531–540.
- Everts HB, King LE, Jr., Sundberg JP, Ong DE (2004) Hair cycle-specific immunolocalization of retinoic acid synthesizing enzymes Aldh1a2 and Aldh1a3 indicate complex regulation. *J Invest Dermatol* 123: 258–263.
- Everts HB, Sundberg JP, King LE, Jr., Ong DE (2007) Immunolocalization of enzymes, binding proteins, and receptors sufficient for retinoic acid synthesis and signaling during the hair cycle. *J Invest Dermatol* 127: 1593–1604.
- Saurat JH (1999) Retinoids and psoriasis: novel issues in retinoid pharmacology and implications for psoriasis treatment. *J Am Acad Dermatol* 41: S2–6.
- Mevorah B, Salomon D, Siegenthaler G, Hohl D, Meier ML, et al. (1996) Ichthyosiform dermatosis with superficial blister formation and peeling: evidence for a desmosomal anomaly and altered epidermal vitamin A metabolism. *J Am Acad Dermatol* 34: 379–385.
- Mihály J, Gamlieli A, Worm M, Rühl R (2011) Decreased retinoid concentration and retinoid signalling pathways in human atopic dermatitis. *Exp Dermatol* 20: 326–330.
- Swann RT, Smith DE, Tramposch KM, Zusi FC (1996) Preparation and RAR-specific retinoid receptor transactivation of retinobenzoic acid derivatives. *Eur Pat Appl EP* 747347.
- Zusi FC, Reczek PR, Ostrowski J (1998) Preparation of 5-substituted-1,1,3,3-tetramethyl-2-ketoindanes as retinoid-like compounds. *PCT Int Appl WO* 9847861.
- Starrett JE, Tortolani DR, Mansuri MM, Meanwell NA (1996) Retinoid-like heterocycles: US5559248. US patents.
- Starrett JE, Tortolani DR, Mansuri MM, Meanwell NA (1998) Heterocyclic-substituted naphthalenyl retinobenzoic acid derivatives: US5849923. US patents.
- Alvarez S, Alvarez R, Khanwalkar H, Germain P, Lemaire G, et al. (2009) Retinoid receptor subtype-selective modulators through synthetic modifications of RARgamma agonists. *Bioorg Med Chem* 17: 4345–4359.
- Tsang KY, Sinha S, Liu X, Bhat S, Chandarardna RAS (2007) Disubstituted chalcone oximes having RARg retinoid receptor antagonist activities. *US* 7,253,319 B2.
- Tsang KY, Sinha S, Liu XB, Bath S, Chandraratna RAS (2005) Disubstituted chalcone oximes having RARg retinoid receptor antagonist activity. *US* 2005/0165095.
- Bourguet W, de Lera AR, Gronemeyer H (2010) Inverse agonists and antagonists of retinoid receptors. *Methods Enzymol* 485: 161–195.
- Nahoum V, Perez E, Germain P, Rodriguez-Barrios F, Manzo F, et al. (2007) Modulators of the structural dynamics of the retinoid X receptor to reveal receptor function. *Proc Natl Acad Sci U S A* 104: 17323–17328.
- Calleja C, Messaddeq N, Chapellier B, Yang H, Krezel W, et al. (2006) Genetic and pharmacological evidence that a retinoic acid cannot be the RXR-activating ligand in mouse epidermis keratinocytes. *Genes Dev* 20: 1525–1538.
- Rühl R (2006) Method to determine 4-oxo-retinoic acids, retinoic acids and retinol in serum and cell extracts by liquid chromatography/diode-array detection atmospheric pressure chemical ionisation tandem mass spectrometry. *Rapid Commun Mass Spectrom* 20: 2497–2504.
- Cheepala SB, Syed Z, Trutschl M, Cvek U, Clifford JL (2007) Retinoids and skin: microarrays shed new light on chemopreventive action of all-*trans* retinoic acid. *Mol Carcinog* 46: 634–639.
- Fisher GJ, Voorhees JJ (1996) Molecular mechanisms of retinoid actions in skin. *Faseb J* 10: 1002–1013.
- Roelandt T, Thys B, Heughebaert C, De Vroede A, De Paepe K, et al. (2009) LEKTI-1 in sickness and in health. *Int J Cosmet Sci* 31: 247–254.
- Brattsand M, Stefansson K, Lundh C, Haasum Y, Egelrud T (2005) A proteolytic cascade of kallikreins in the stratum corneum. *J Invest Dermatol* 124: 198–203.
- Caubet C, Jonca N, Brattsand M, Guerrin M, Bernard D, et al. (2004) Degradation of corneodesmosome proteins by two serine proteases of the kallikrein family, SCTE/KLK5/hK5 and SCCE/KLK7/hK7. *J Invest Dermatol* 122: 1235–1244.
- Lee DD, Stojadinovic O, Krzyzanowska A, Vouthounis C, Blumenberg M, et al. (2009) Retinoid-responsive transcriptional changes in epidermal keratinocytes. *J Cell Physiol* 220: 427–439.
- Yoshimura K, Uchida G, Okazaki M, Kitano Y, Harii K (2003) Differential expression of heparin-binding EGF-like growth factor (HB-EGF) mRNA in normal human keratinocytes induced by a variety of natural and synthetic retinoids. *Exp Dermatol* 12 Suppl 2: 28–34.
- Weiss RA, Eichner R, Sun TT (1984) Monoclonal antibody analysis of keratin expression in epidermal diseases: a 48- and 56-kdalton keratin as molecular markers for hyperproliferative keratinocytes. *J Cell Biol* 98: 1397–1406.

(DOCX)

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Author Contributions

Conceived and designed the experiments: JG RR. Performed the experiments: JG JI JM DT. Analyzed the data: JG DT. Contributed reagents/materials/analysis tools: RA SA DT ADL RR. Wrote the paper: JG.

45. Romanowska M, al Yacoub N, Seidel H, Donandt S, Gerken H, et al. (2008) PPARdelta enhances keratinocyte proliferation in psoriasis and induces heparin-binding EGF-like growth factor. *J Invest Dermatol* 128: 110–124.
46. Romanowska M, Reilly L, Palmer CN, Gustafsson MC, Foerster J (2010) Activation of PPARbeta/delta causes a psoriasis-like skin disease in vivo. *PLoS One* 5: e9701.
47. Michalik L, Desvergne B, Tan NS, Basu-Modak S, Escher P, et al. (2001) Impaired skin wound healing in peroxisome proliferator-activated receptor (PPAR)alpha and PPARbeta mutant mice. *J Cell Biol* 154: 799–814.
48. Tan NS, Michalik L, Desvergne B, Wahli W (2005) Multiple expression control mechanisms of peroxisome proliferator-activated receptors and their target genes. *J Steroid Biochem Mol Biol* 93: 99–105.
49. Proksch E, Brandner JM, Jensen JM (2008) The skin: an indispensable barrier. *Exp Dermatol* 17: 1063–1072.
50. Akiyama M (2011) The roles of ABCA12 in keratinocyte differentiation and lipid barrier formation in the epidermis. *Dermatoendocrinol* 3: 107–112.
51. Jennemann R, Sandhoff R, Langbein L, Kaden S, Rothermel U, et al. (2007) Integrity and barrier function of the epidermis critically depend on glucosylceramide synthesis. *J Biol Chem* 282: 3083–3094.
52. Holleran WM, Takagi Y, Uchida Y (2006) Epidermal sphingolipids: metabolism, function, and roles in skin disorders. *FEBS Lett* 580: 5456–5466.
53. Harris IR, Farrell AM, Grunfeld C, Holleran WM, Elias PM, et al. (1997) Permeability barrier disruption coordinately regulates mRNA levels for key enzymes of cholesterol, fatty acid, and ceramide synthesis in the epidermis. *J Invest Dermatol* 109: 783–787.
54. Mao C, Xu R, Szulc ZM, Bielawski J, Becker KP, et al. (2003) Cloning and characterization of a mouse endoplasmic reticulum alkaline ceramidase: an enzyme that preferentially regulates metabolism of very long chain ceramides. *J Biol Chem* 278: 31184–31191.
55. Fullerton A, Serup J (1997) Characterization of irritant patch test reactions to topical D vitamins and all-*trans* retinoic acid in comparison with sodium lauryl sulphate. Evaluation by clinical scoring and multiparametric non-invasive measuring techniques. *Br J Dermatol* 137: 234–240.
56. Attar PS, Wertz PW, McArthur M, Imakado S, Bickenbach JR, et al. (1997) Inhibition of retinoid signaling in transgenic mice alters lipid processing and disrupts epidermal barrier function. *Mol Endocrinol* 11: 792–800.
57. Li M, Chiba H, Warot X, Messaddeq N, Gerard C, et al. (2001) RXR-alpha ablation in skin keratinocytes results in alopecia and epidermal alterations. *Development* 128: 675–688.
58. Li M, Indra AK, Warot X, Brocard J, Messaddeq N, et al. (2000) Skin abnormalities generated by temporally controlled RXRalpha mutations in mouse epidermis. *Nature* 407: 633–636.
59. Stücker M, Hoffmann M, Altmeyer P (2002) Instrumental evaluation of retinoid-induced skin irritation. *Skin Res Technol* 8: 133–140.
60. Stephensen CB (2001) Vitamin A, infection, and immune function. *Annu Rev Nutr* 21: 167–192.
61. Stephensen CB, Rasooly R, Jiang X, Ceddia MA, Weaver CT, et al. (2002) Vitamin A enhances in vitro Th2 development via retinoid X receptor pathway. *J Immunol* 168: 4495–4503.
62. Dawson HD, Collins G, Pyle R, Key M, Taub DD (2008) The Retinoic Acid Receptor-alpha mediates human T-cell activation and Th2 cytokine and chemokine production. *BMC Immunol* 9: 16.
63. Iwata M, Eshima Y, Kagechika H (2003) Retinoic acids exert direct effects on T cells to suppress Th1 development and enhance Th2 development via retinoic acid receptors. *Int Immunol* 15: 1017–1025.
64. Imai T, Nagira M, Takagi S, Kakizaki M, Nishimura M, et al. (1999) Selective recruitment of CCR4-bearing Th2 cells toward antigen-presenting cells by the CC chemokines thymus and activation-regulated chemokine and macrophage-derived chemokine. *Int Immunol* 11: 81–88.
65. Bonecchi R, Bianchi G, Bordignon PP, D'Ambrosio D, Lang R, et al. (1998) Differential expression of chemokine receptors and chemotactic responsiveness of type 1 T helper cells (Th1s) and Th2s. *J Exp Med* 187: 129–134.
66. Sallusto F, Mackay CR, Lanzavecchia A (1997) Selective expression of the cotaxin receptor CCR3 by human T helper 2 cells. *Science* 277: 2005–2007.
67. Dulky Y, Schramm G, Kimmig D, Knoss S, Weyergraf A, et al. (2001) Detection of mRNA for cotaxin-2 and cotaxin-3 in human dermal fibroblasts and their distinct activation profile on human eosinophils. *J Invest Dermatol* 116: 498–505.
68. Menzies-Gow A, Ying S, Sabroe I, Stubbs VL, Soler D, et al. (2002) Eotaxin (CCL11) and eotaxin-2 (CCL24) induce recruitment of eosinophils, basophils, neutrophils, and macrophages as well as features of early- and late-phase allergic reactions following cutaneous injection in human atopic and nonatopic volunteers. *J Immunol* 169: 2712–2718.
69. Sabroe I, Hartnell A, Jopling LA, Bel S, Ponath PD, et al. (1999) Differential regulation of eosinophil chemokine signaling via CCR3 and non-CCR3 pathways. *J Immunol* 162: 2946–2955.
70. Balmer JE, Blomhoff R (2002) Gene expression regulation by retinoic acid. *J Lipid Res* 43: 1773–1808.
71. Virtanen M, Torma H, Vahlquist A (2000) Keratin 4 upregulation by retinoic acid in vivo: a sensitive marker for retinoid bioactivity in human epidermis. *J Invest Dermatol* 114: 487–493.
72. Goyette P, Feng Chen C, Wang W, Seguin F, Lohnes D (2000) Characterization of retinoic acid receptor-deficient keratinocytes. *J Biol Chem* 275: 16497–16505.
73. Schug TT, Berry DC, Shaw NS, Travis SN, Noy N (2007) Opposing effects of retinoic acid on cell growth result from alternate activation of two different nuclear receptors. *Cell* 129: 723–733.
74. Goodman DS (1984) Overview of current knowledge of metabolism of vitamin A and carotenoids. *J Natl Cancer Inst* 73: 1375–1379.
75. Chai X, Zhai Y, Napoli JL (1997) cDNA cloning and characterization of a *cis*-retinol/3alpha-hydroxysterol short-chain dehydrogenase. *J Biol Chem* 272: 33125–33131.
76. Kiefer C, Hessel S, Lampert JM, Vogt K, Lederer MO, et al. (2001) Identification and characterization of a mammalian enzyme catalyzing the asymmetric oxidative cleavage of provitamin A. *J Biol Chem* 276: 14110–14116.
77. Tan NS, Michalik L, Noy N, Yasmin R, Pacot C, et al. (2001) Critical roles of PPAR beta/delta in keratinocyte response to inflammation. *Genes Dev* 15: 3263–3277.
78. Shaw N, Elholm M, Noy N (2003) Retinoic acid is a high affinity selective ligand for the peroxisome proliferator-activated receptor beta/delta. *J Biol Chem* 278: 41589–41592.
79. Perlmann T, Jansson L (1995) A novel pathway for vitamin A signaling mediated by RXR heterodimerization with NGFI-B and NURR1. *Genes Dev* 9: 769–782.
80. Volakakis N, Joodmardi E, Perlmann T (2009) NR4A orphan nuclear receptors influence retinoic acid and docosahexaenoic acid signaling via up-regulation of fatty acid binding protein 5. *Biochem Biophys Res Commun* 390: 1186–1191.
81. Haider AS, Lowes MA, Suarez-Farinas M, Zaba LC, Cardinale I, et al. (2008) Cellular genomic maps help dissect pathology in human skin disease. *J Invest Dermatol* 128: 606–615.