Suppression of AP1 Transcription Factor Function in Keratinocyte Suppresses Differentiation

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Abstract

Our previous study shows that inhibiting activator protein one (AP1) transcription factor function in murine epidermis, using dominant-negative c-jun (TAM67), increases cell proliferation and delays differentiation. To understand the mechanism of action, we compare TAM67 impact in mouse epidermis and in cultured normal human keratinocytes. We show that TAM67 localizes in the nucleus where it forms TAM67 homodimers that competitively interact with AP1 transcription factor DNA binding sites to reduce endogenous jun and fos factor binding. Involucrin is a marker of keratinocyte differentiation that is expressed in the suprabasal epidermis and this expression requires AP1 factor interaction at the AP1-5 site in the promoter. TAM67 interacts competitively at this site to reduce involucrin expression. TAM67 also reduces endogenous c-jun, junB and junD mRNA and protein level. Studies with c-jun promoter suggest that this is due to reduced transcription of the c-jun gene. We propose that TAM67 suppresses keratinocyte differentiation by interfering with endogenous AP1 factor binding to regulator elements in differentiation-associated target genes, and by reducing endogenous c-jun factor expression.

Introduction

Activator protein one (AP1) transcription factors are a family of jun and fos proteins that form jun-jun and jun-fos homo- and heterodimers, and these complexes interact with AP1 factor DNA binding sites to regulate gene expression [1–4]. The AP1 factor family includes c-jun, junB, junD, c-fos, FosB, Fra-1 and Fra-2. These proteins are implicated in control of keratinocyte proliferation [5–7], differentiation [8–10], apoptosis [11,12], and transformation [13–16]. The importance of these proteins is confirmed by in vivo studies [13,17–25]. Analysis of the role of these proteins in epidermis is complicated because AP1 proteins display context-dependent functions and because multiple family members are expressed.

An altered form of c-jun, which is truncated to remove the N-terminal transactivation domain, has been used to study AP1 factor function [26]. Deletion of the c-jun transactivation domain creates a dominant-negative form of the protein (TAM67) that inhibits AP1 factor function [26]. TAM67 has been used in a number of systems. TAM67 expression in lung cancer in mice [27,28] and in nasopharyngeal carcinoma inhibits cell growth by altering cell cycle protein expression [29]. TAM67 inhibits growth of MCF-7 breast cancer cells [30], and halts HT-1080 cell proliferation in G1 phase [31]. TAM67 has also been used to study the impact of AP1 factor signaling on cell differentiation. Inhibition of AP1 factor function in neuroblastoma cells suppresses nerve growth factor-dependent differentiation [32]. In melanoma cells, induction of the melanoma differentiation associated genes is increased by AP1 factors and inhibited by TAM67 [33], and TAM67 also inhibits differentiation in monocytic leukemia cells [34]. We [35,36] and others [37–43] have used TAM67 to study AP1 factor function in keratinocytes. These studies show that TAM67 inhibits keratinocyte differentiation [35,36]. Cell culture based studies in human primary foreskin keratinocytes show that AP1 factors are required for expression of markers of terminal differentiation and that inhibition of AP1 factor function with TAM67 suppresses these responses [10,36,44]. We have also recently shown that expression of TAM67 in vivo in suprabasal mouse epidermis results in delayed and incomplete epidermal differentiation [35]. However, the molecular mechanism of TAM67 action in these models is not fully understood. In the present study we examine the mechanism of TAM67 action on AP1 factor function in epidermal keratinocytes. These studies indicate that TAM67 homodimer binds to AP1 factor DNA binding sites in human keratinocytes to inhibit jun and fos factor binding, and also reduces the mRNA and protein level of endogenous jun family members. In the case of c-jun this is via inhibition of transcription. Moreover, TAM67 binding to the AP1-5 binding site of the involucrin (hINV) promoter reduces expression of involucrin, a keratinocyte differentiation marker, in cultured keratinocytes. We further show that TAM67 in murine epidermis reduces...
involucrin (and loricrin) gene expression and reduces binding of endogenous AP1 factors to AP1 factor binding elements.

**Results**

TAM67 is a truncated form of c-jun that lacks the amino terminal transactivation domain and is not transcriptionally active [26] (Fig. 1A). In the present study we utilize TAM67 as a tool to study AP1 factor function in normal human keratinocytes. To initiate these studies, we monitored TAM67-FLAG expression. Fig. 1B shows that TAM67-FLAG is expressed in keratinocytes and Fig. 1C shows that, as expected of a nuclear transcriptional regulator, TAM67-FLAG accumulates in the nucleus.

AP1 factors are key regulators of function in keratinocytes [45–47]. To understand the impact of TAM67 on AP1 factor function, we monitored endogenous AP1 factor level in TAM67-expressing cells. Fig. 2A shows a reduction in c-jun, junB and junD but no change in Fra-1, Fra-2 or c-fos level in TAM67 expressing cells, suggesting that TAM67 reduces the level of a subset of AP1 factors. To assess the mechanism causing c-jun, junB and junD reduction, we monitored mRNA level using quantitative RT-PCR. The level of c-jun, junB and junD encoding mRNA is reduced in TAM67 expressing cells, indicating that part of the reason for loss of these factors is a reduction in mRNA level (Fig. 2B). In contrast, the level of RNA encoding fos family members (Fra-1, Fra-2, c-fos) is not altered. We next examined the ability of TAM67-FLAG to interact with other AP1 factors by testing the ability of TAM67-FLAG to co-precipitate individual AP1 factors in keratinocytes. As shown in Fig. 2C, anti-FLAG precipitation of TAM67-FLAG co-precipitates Fra-1, Fra-2 and c-fos. In contrast, junB and junD did not co-precipitate, which is expected considering that these proteins are reduced in level in TAM67-expressing cells (Fig. 2A). In spite of the reduction in total c-jun level (Fig. 2A), sufficient c-jun appears to remain and interacts with TAM67-FLAG (Fig. 2C). We next monitored the impact on nuclear AP1 factor level. Fig. 2D shows that TAM67 expression is associated with reduced nuclear c-jun, junB and junD. In contrast, nuclear c-fos, Fra-1 and Fra-2 levels are not affected.

![Figure 1. TAM67-FLAG expression in keratinocytes. A Comparison of c-jun and TAM67 structure. The numbers are indicated in amino acids. The transactivation, DNA binding and leucine zipper domains are indicated. The TAM67 truncated protein is FLAG epitope tagged as indicated. B/C TAM67-FLAG is expressed in keratinocytes. Normal human keratinocytes were infected with 10 MOI of tAd5-EV or tAd5-TAM67-FLAG with 5 MOI of Ad5-TA. After 24 h the cells were fixed for immunostaining and extracts were prepared for immunoblot with anti-FLAG. Similar results were observed in each of three repeated experiments.](image-url)
As shown above, c-jun, junB and junD protein and mRNA levels are reduced in TAM67-expressing cells. To gain insight regarding the mechanism, we used c-jun as a model. We examined the impact of TAM67 on c-jun mRNA level and promoter activity in a side-by-side comparison. Fig. 3A shows that TAM67 reduces c-jun encoding mRNA by more than 50%. To gain insight into the mechanism, we monitored the impact of TAM67 on activity of a c-jun promoter construct in which nucleotides −1780/+731 is linked to luciferase (Fig. 3B). Our studies show that TAM67 reduces promoter activity by 50% in keratinocytes. In contrast, the same promoter in which the key API factor binding sites are mutated, −1780/+731(AP1m) [48], displays basal activity and is not regulated by TAM67. Fig. 3C shows the structure of the promoter constructs. These findings suggest that c-jun level is reduced by a transcriptional mechanism that requires AP1 factor binding sites in the c-jun promoter upstream regulatory region.

**TAM67-FLAG Inhibits AP1 Factor Binding to AP1 Consensus DNA Binding Element**

Gel mobility shift and supershift analysis, using a consensus AP1 binding probe, was performed to investigate the effect of...
The numbers are given in nucleotides.

in which the critical AP1 sites are eliminated by mutation [48]. LUC indicates the luciferase gene. The promoter region. The promoter constructs encode nucleotides (2218/+731) with the transcription start site at 1780/+731) is the wild-type intact promoter and c-jun(−1780/+731)-AP1m is a construct in which the critical AP1 sites are eliminated by mutation [46]. LUC indicates the luciferase gene. The numbers are given in nucleotides.

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TAM67-FLAG on AP1 factor interaction with DNA. Fig. 4A shows a gel shift using ³²P-labeled AP1 consensus binding site oligonucleotide and human foreskin keratinocyte nuclear extract. Shifted bands appear at increased intensity and free probe appears at reduced intensity in nuclear extracts prepared from TAM67-FLAG expressing cells (lanes 3, 5 and 9). This is caused by an increase in total cellular AP1 site binding capacity due to the presence of TAM67. As expected, addition of anti-AP1 results in appearance of a supershifted band only in extracts from TAM67-FLAG expressing cells (lane 5, asterisk). We next incubated nuclear extract from control and TAM67-expressing cells with anti-c-jun, junB, junD, Fra-1, Fra-2, c-fos or fosB. Supershifted bands are observed for each AP1 factor. The most obvious supershifts were observed for c-jun, junD, Fra-1, Fra-2 and c-fos [Fig. 4B]. The amount of supershifted DNA is reduced in TAM67-expressing cells, demonstrating that TAM67 competes for endogenous AP1 factor binding to the AP1c element (Fig. 4B).

TAM67-FLAG Binds to the AP1-5 Site of hINV Gene Promoter

API factors regulate transcription of hINV via binding to the proximal and distal AP1 sites in the hINV promoter [22–25]. In particular, the AP1-5 site in the distal promoter is absolutely required for involucrin gene expression in vivo [22–25]. We therefore examined the impact of TAM67 on AP1 factor interaction at the AP1-5 site. Fig. 6 shows gel mobility shift analysis of AP1 factor binding to the hINV promoter AP1-5 site. Fig. 6A shows that the presence of TAM67-FLAG markedly increases the intensity of the gel shifted band (compare lanes 2 and 3) and that incubation with anti-FLAG produces a strong supershifted band only in cells expressing TAM67-FLAG (compare lanes 4 and 5). Moreover, the binding is competed by incubation with a 50-fold molar excess of radioinert AP1-5 oligonucleotide (see lanes 6 and 7), but a 50-fold excess of AP1-5 m does not compete (lane 8). We next examined the impact of TAM67 on endogenous AP1 factor interaction with AP1-5. As shown in Fig. 6B, supershifted bands (asterisks) are observed when extracts are incubated with anti-c-jun, junB, junD, Fra-1, Fra-2 and c-fos, and this interaction is reduced in the presence of TAM67-FLAG. Fos-B was not detected. The low signal intensity of the shifted bands is consistent with previous reports [47].

To further assess the in vivo impact of TAM67 we used chromatin immunoprecipitation. Nuclear extracts from TAM67-FLAG positive and negative keratinocytes were prepared for ChIP analysis using a primer set that targets the AP1-5 binding site (−2218/+−2005) and a second primer set that targets a region of the promoter lacking an AP1 factor binding site (−1040/+−919).
Figure 4. TAM67-FLAG inhibits AP1 factor binding to AP1 consensus DNA binding element. Keratinocytes were infected with 10 MOI tAd5-EV or tAd5-TAM67-FLAG and after 24 h nuclear extracts were prepared. A AP1 factors interact with AP1 consensus DNA element. Nuclear extracts were incubated with AP1c-P32 without or with a 50-fold molar excess of Sp1c or AP1c oligonucleotides, or anti-FLAG antibody and electrophoresed on a 6% acrylamide non-denaturing gel. FP indicates free probe and NE is nuclear extract. The arrow indicates the major shifted band and asterisks indicate migration of supershifted complexes. AP1c and Sp1c encode consensus AP1 and Sp1 binding elements. B TAM67-FLAG
TAM67-FLAG and associated chromatin was precipitated with anti-FLAG. Fig. 6C shows that TAM67-FLAG is substantially enriched at the AP1-5 binding site (nucleotides −2218/−2055) as compared to the control DNA segment that lacks an AP1 binding site (nucleotides −1040/−919), suggesting TAM67 interaction at the hINV promoter AP1-5 site in vivo.

TAM67 Impact on AP1 Factors in vivo

We previously described TAM67-rTA mice in which TAM67-FLAG expression can be induced in the suprabasal epidermis by addition of doxycycline to the drinking water [35]. Expression of TAM67 in this tissue would be expected to reduce expression of AP1 factor-regulated genes. To assess this, we compared expression of two AP1-factor regulated genes, involucrin and loricrin [10,52,53]. TAM67-rTA mice were treated for three days with doxycycline and total epidermal extracts were prepared to detect involucrin and loricrin. Consistent with the finding that involucrin expression is reduced in TAM67-expressing cultured keratinocytes, we find that involucrin level is reduced in TAM67 expressing mouse epidermis (Fig. 7A). We also show that loricrin protein level is reduced. Loricrin expression is also AP1 factor signaling dependent [52].

We next examined the impact of TAM67 on endogenous AP1 factor DNA binding in mouse epidermis nuclear extracts. Fig. 7B shows an increase in the quantity of shifted AP1c-P32 probe in extract prepared from TAM67-expressing epidermis. This binding is specifically reduced by addition of excess radioinert AP1c, but is not competed by Sp1 consensus sequence. Moreover, TAM67-FLAG binding to AP1c-P32 is confirmed by anti-FLAG supershift (Fig. 7B). We also examined the impact of TAM67 on endogenous AP1 factor binding to DNA. The supershift analysis in Fig. 7C shows that TAM67 binding to the AP1 consensus element reduces c-jun, junB and junD interaction, with a strong reduction observed for junD. In contrast, Fra-2 and c-fos interaction is not altered by TAM67 and interaction of Fra-1 and FosB is below the limits of detection.

Discussion

We recently expressed dominant-negative c-jun in murine epidermis and observed significant changes in epidermal phenotype [35]. These changes included increased cell proliferation, delayed differentiation and reduced tumor formation [35]. We presume that TAM67 is impacting AP1 target genes in this tissue and so in the present study we examine the TAM67 mechanism of action in more detail. We studied the role of dominant-negative c-jun (TAM67) in human epidermal keratinocytes and in an in vivo murine keratinocyte model of differentiation.

In cultured human keratinocytes TAM67-FLAG was detected in punctate foci in the center of the nucleus. Expression of TAM67 produced profound changes in AP1 transcription factor function. The first change we observed was a reduction in c-jun, junB and junD protein and mRNA level. The decrease in mRNA encoding the jun factors could be due to a reduction in mRNA stability or to a reduction in transcription. Further study with the c-jun promoter upstream regulatory region revealed a TAM67-dependent reduction in promoter activity. This reduction required the presence of TAM67-FLAG and associated chromatin precipitated with anti-FLAG. Fig. 6C shows that TAM67-FLAG is substantially enriched at the AP1-5 binding site (nucleotides −2218/−2055) as compared to the control DNA segment that lacks an AP1 binding site (nucleotides −1040/−919), suggesting TAM67 interaction at the hINV promoter AP1-5 site in vivo.
of AP1 transcription factor binding sites within the c-jun promoter. These findings are consistent with previous reports indicating that AP1 factor auto-regulate via a feedback loop [48,54–57]. Our findings suggest that TAM67 binds to these elements, displacing other AP1 factors, and thereby suppresses c-jun transcription. In contrast, it is interesting that level of the fos family members (Fra-1, Fra-2, c-fos, or fosB specific antibodies, and electrophoresed on a 6% acrylamide non-denaturing gel. Arrows indicate major shifted band and asterisks indicate supershifted bands. FP is free probe. C ChIP analysis reveals TAM67 presence at the hINV upstream regulatory region AP1-5 site in vivo. Nuclear extracts were prepared for ChIP analysis and incubated with anti-IgG or anti-FLAG and the precipitated DNA was analyzed for AP1-5 site encoding sequences. The values are mean ± SD (n = 3, p<0.001) and the asterisk indicates a significant increase compared to all other groups. Nucleotides −2218/−2055 encodes the AP1-5 site and nucleotides −1040/−919 is a region of the hINV upstream regulatory region that lacks an AP1 site.

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Figure 6. TAM67 binds to the AP1-5 site of hINV gene promoter. Keratinocytes were infected with 10 MOI tAd5-EV or tAd5-TAM67-FLAG and after 24 h nuclear extracts were prepared for gel shift. A TAM67 interaction with hINV promoter AP1-5 site. Nuclear extracts were incubated with AP1-5-P32 with or without a 50-fold molar excess of AP1-5 or AP1-5 m oligonucleotide, or anti-FLAG antibody, and electrophoresed on a 6% acrylamide non-denaturing gel. FP indicates free probe and NE is nuclear extract. The arrow indicates the major shifted bands and asterisks indicate supershifted bands. AP1-5 is an oligonucleotide encoding the AP1-5 site of hINV promoter. AP1-5 m is an AP1-5 mutant that does not bind AP1 transcription factors [47]. B TAM67 inhibits AP1 factor interaction with AP1-5. Nuclear extracts were incubated with AP1-5-P32 in the absence or presence of c-jun, junB, junD, Fra-1, Fra-2, c-fos, or fosB specific antibodies, and electrophoresed on a 6% acrylamide non-denaturing gel. Arrows indicate major shifted band and asterisks indicate supershifted bands. FP is free probe. C ChIP analysis reveals TAM67 presence at the hINV upstream regulatory region AP1-5 site in vivo. Nuclear extracts were prepared for ChIP analysis and incubated with anti-IgG or anti-FLAG and the precipitated DNA was analyzed for AP1-5 site encoding sequences. The values are mean ± SD (n = 3, p<0.001) and the asterisk indicates a significant increase compared to all other groups. Nucleotides −2218/−2055 encodes the AP1-5 site and nucleotides −1040/−919 is a region of the hINV upstream regulatory region that lacks an AP1 site.

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Dimerization partners for Jun and Fos, the absence of Jun factors is expected to severely limit AP1 factor signaling. An equally interesting feature is that expression of Fos family members is not reduced. This suggests that Fos family proteins are not regulated by an AP1 factor-dependent feedback loop in this system.

Second, we examined the impact of TAM67 on AP1 factor interaction with DNA. DNA gel shift experiments indicate that TAM67-FLAG interacts with the AP1 consensus DNA sequence, and that TAM67, at the level we achieve in these experiments, substantially reduces interaction of endogenous AP1 factors with DNA binding sites. Previous studies suggest that TAM67 forms transcriptionally inactive heterodimers with Jun and Fos family members [26]. These factors bind to the promoter of target genes, but are not able to activate transcription. This mechanism, called transcriptional quenching, leads to reduced target gene expression [26]. Our findings also suggest an additional mechanism. Protein-

Figure 7. Impact of TAM67 on AP1 factors in vivo. TAM67-rTA mice were treated with (+) or without (−) 2 mg/ml doxycycline in drinking water for 3 days. A Murine epidermis was collected free of the dermis by high temperature separation as previously described [35]. Total extract was prepared for immunoblot to detect the indicated proteins. TAM67-FLAG was detected with anti-FLAG. B Interaction of TAM67 with AP1 site consensus element. Nuclear extracts were prepared from epidermis and incubated with AP1c-P\(^{32}\) and other probes as indicated. FP indicates free probe, NE indicates nuclear extract. Similar results were observed in each of three experiments. C Impact of TAM67 on interaction of endogenous AP1 factors with AP1 site element. Nuclear extracts were prepared from TAM67-negative and TAM67-expressing epidermis and incubated with the AP1c-P\(^{32}\) and antibodies as indicated. The complexes were then separated on a non-denaturing 6% polyacrylamide gel. FP indicates free probe and NE is nuclear extract. Note the reduction in Jun factor binding in the presence of TAM67-FLAG (left panel). We did not observe a significant reduction in Fos factor interaction in the presence of TAM67 (right panel).

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protein crosslinking and gel shift experiments strongly suggest that TAM67-FLAG homodimers are preferentially formed in these cells, and we suspect that this homodimer is a major AP1 factor complex that interacts with DNA. This would suggest that a major mechanism whereby TAM67 inhibits AP1 target gene expression in keratinocytes is TAM67 homodimer interaction with DNA to block endogenous AP1 factor access to these sites. It is also clear, as reported previously [26], that TAM67 forms heterodimers with jun and fos proteins, to form inactive complexes that quench activity of the complex. Thus, two mechanisms are possible: a blocking action wherein the TAM67 homodimer binds to DNA to block endogenous AP1 factor interaction with AP1 sites, and a quenching action wherein TAM67 inhibits the transactivation potential of endogenous AP1 factors by forming inhibitory TAM67:jun and TAM67:fos heterodimers (Fig. 8). Our studies favor the blocking mechanism involving TAM67 homodimers.

In addition, we examined the impact of TAM67 on an important AP1 transcription factor-regulated target, involucrin. Involucrin is a marker of suprabasal differentiation in epidermis that is regulated by a MAP kinase cascade [36,47]. Activation of this cascade leads to AP1 factor interaction with specific DNA binding elements on the hINV promoter to drive expression [23–25]. A key DNA binding site that is required for involucrin expression, both in cultured keratinocytes and in vivo, is the AP1-5 DNA binding site located in the distal regulatory region of the hINV gene promoter [26–28]. We show that TAM67 reduces hINV mRNA and protein level in cultured keratinocytes. Moreover, hINV promoter activity is also reduced, suggesting that TAM67 is inhibiting AP1 factor-dependent transcription. We confirmed TAM67 interaction with AP1-5 transcription factor binding site in the hINV promoter by gel mobility shift and chromatin IP. These findings confirm the important role of the AP1-3 binding site in driving hINV gene expression [22–25]. The fact that this is associated with reduced binding of AP1 factor at this site, as measured by gel mobility supershift assay, suggests that TAM67 is displacing these factors by competition.

We also examined the impact of TAM67 expression on involucrin protein level in TAM67-expressing murine epidermis. We compared control mice (lacking TAM67 expression) and TAM67-expressing mice. These studies reveal a substantial reduction in murine involucrin protein in TAM67-expressing epidermis. This is associated with a 2 to 3-fold increase in transcription factor binding to the AP1 site in extracts prepared from TAM67-expressing epidermis. This increase is directly associated with increased TAM67 level, suggesting that TAM67 is a major factor interacting with the AP1 binding elements in the epidermis of these mice. TAM67 appears to readily compete jun family factors off from this site, but appears less efficient at competing fos family factors. We suspect that this is due preferred interaction with jun factors and to the somewhat lower level of TAM67 expression in mouse epidermis as compared to cultured keratinocytes.

In summary, we describe several findings regarding the mechanism of TAM67 action in keratinocytes and in TAM67-expressing murine epidermis. First, our findings suggest that AP1 transcription factors regulate c-jun, junB, junD mRNA and protein level. Moreover, we show that TAM67 inhibits activity of the c-jun promoter, suggesting a transcriptional mechanism of regulation. Second, we show that blocking AP1 factor access to the hINV gene promoter AP1 factor binding site inhibits transcription, both in cultured human cells and in vivo in mouse epidermis. Third, this inhibition appears to be mediated by a “blocking” mechanism where a TAM67 homodimer interacts with the AP1 response element to suppress transcription by preventing endogenous jun and fos factor binding to the element (Fig. 8). Crosslinking experiments suggest the presence of TAM67 homodimers as the major species present in keratinocytes. We suspect that the balance of TAM67 homodimers versus TAM67 heterodimerization with endogenous jun and fos factors is depend upon the concentration of TAM67 expressed. At higher concentrations we would expect TAM67 homodimers to be the major species and that these factors will block endogenous AP1 factor interaction with DNA. An alternate mechanism, quenching, where TAM67 forms heterodimers with fos and jun proteins to produce a transcriptionally inactive complex at AP1 DNA binding sites, is also likely. Crosslinking and co-immunoprecipitation experiments suggest some formation of TAM67 heterodimers with endogenous AP1 factors. An additional mechanism, called squelching (not shown), is also possible [26,38,39]. In this mechanism an inhibitor protein interacts with endogenous factors involved in transcription regulation that are not bound to DNA [26,38,39]. Although this may also be a mechanism of TAM67 inhibition, wherein TAM67 sequesters co-activator proteins away from the AP1 binding sites, we suspect that the major mechanisms whereby TAM67...
suppresses gene expression in keratinocytes are AP1 site blocking and quenching [Fig. 8A] leading to suppression of jun factor and target gene (hINV, loricrin) expression [Fig. 8B]. Our results suggest that these mechanisms are active both in cultures keratinocytes and in TAM67-expressing murine epidermis.

Materials and Methods

Cell Culture and Virus Infection

Primary cultures of human newborn foreskin keratinocytes were cultured in keratinocyte serum-free medium (KSF, supplemented with epidermal growth factor and bovine pituitary extract (10724, Gibco, Invitrogen, Carlsbad, CA). These are obtained as discarded tissue samples and their use was reviewed and approved in writing by the University of Maryland Human Subjects Institutional Review Board. For virus infection, cells were plated at 40% confluence (0.5 million cells per 21 cm² dish) and infected with 0, 2 or 10 MOI of Ad5-EV or Ad5-TAM67-FLAG in the presence of 5 MOI of Ad5-TA virus in KSF containing 6 µg/ml polybrene (H9268, Sigma, St. Louis, MO). After 6 h the cells were washed and shifted to fresh virus-free medium.

Immunological Methods and Antibodies

For immunoblot, keratinocytes were washed twice with phosphate-buffered saline (PBS), drained, and 0.5 ml of lysis buffer (20 mM Tris-HCl, pH 7.5, 150 mM NaCl, 1 mM Na₂EDTA, 1 mM EGTA, 1% Triton X-100, 25 mM sodium pyrophosphate, 1 mM β-glycerophosphate, 1 mM Na₃VO₄ and 1 µg/ml leupeptin) supplemented with protease inhibitors was added to each 21 cm² (60 mm) dish. After 5 min on ice, the cells were collected by scraping, and pelleted and sonicated. After centrifugation at 4°C and 15,000 x g for 10 min, protein aliquots containing 30 µg of protein were separated on denaturing and reducing Laemmli [60] 8% polyacrylamide gels and transferred to nitrocellulose. The membrane was blocked in PBS containing 5% milk powder and 0.1% Tween 20 and incubated at 4°C overnight with primary antibody and for 1 h at 23°C with horseradish peroxidase-conjugated secondary antibody. Antibody binding was visualized using chemiluminescence detection reagent [61].

For anti-FLAG immunoprecipitation, keratinocytes were infected with 10 MOI of Ad5-EV or Ad5-TAM67-FLAG with 10 MOI of Ad5-TA. At 24 h, 200 µg of total cell extract was diluted to final volume of 500 µl in lysis buffer and pre-cleared by addition of 25 µl of protein A/G-agarose for 1 h at 4°C. The samples were then incubated with 20 µl of anti-FLAG M2 affinity gel (Sigma, A2220) overnight, and the antibody complex was washed three times with lysis buffer and boiled in 40 µl of Laemmli sample buffer for electrophoresis.

Immunofluorescence

Keratinocytes, growing on coverslips, were rinsed with PBS and fixed with 1:1 acetic:methanol for 10 min at −20°C. Cells were washed three times in PBS for 5 min, and the coverslips were blocked in 3% bovine serum albumin in PBS for 1 h at room temperature and then incubated with monoclonal anti-FLAG M2 antibody (F3163, Sigma, diluted 1:1000) for 1 h at room temperature. Coverslips were washed three times in PBS for 5 min each and incubated with Alexa Fluor 488-conjugated goat anti-mouse IgG (A11029, Invitrogen, Eugene, OR, diluted 1:1000) for 45 min at room temperature. Coverslips were further co-stained with 2 µg/ml Hoechst 33258 (H3569, Invitrogen) for 5 min, rinsed in PBS and place in mounting medium (M1289, Sigma). Fluorescence was visualized using an Olympus OX81 spinning-disc confocal microscope. No signaling was detected in the absence of primary antibody.

Antibodies

Rabbit polyclonal antibodies including anti-c-jun (sc-16941, diluted 1:1000), anti-c-jun D (sc-74 x, diluted 1:500), anti-Fra-1 (sc-603 x, diluted 1:1000) and anti-Fra-2 (sc-604 x, diluted 1:1000), and mouse anti-junB (sc-8051, diluted 1:300) and goat anti-fosB (sc-482, diluted 1:300) were obtained from Santa Cruz Biotechnology (Santa Cruz, CA). Rabbit polyclonal anti-c-fos (ab7963, diluted 1:300) was from Abcam (Cambridge, UK). Monoclonal anti-FLAG M2-Peroxidase (A9552, diluted 1:3000) and monoclonal anti-f-actin (A1978, diluted 1:1000) were purchased from Sigma. St. Louis, MO. Rabbit anti-human involucrin (hINV) serum (diluted 1:2000) was produced in our laboratory [62]. Donkey anti-rabbit (NA934, diluted 1:3000) and sheep anti-mouse HRP-conjugated secondary antibody (NA931, diluted 1:3000) were from GE Healthcare (GE Healthcare, Piscataway, NJ). Donkey anti-goat HRP-conjugated secondary antibody (sc-2033, diluted 1:3000) was from Santa Cruz Biotechnology (Santa Cruz, CA). Rabbit anti-loricin (PRB-145P, diluted 1:1000) was obtained from Covance (Princeton, NJ).

Nuclear Extract Preparation

Keratinocytes (5 × 10⁶ cells) were harvested with trypsin-EDTA, collected by centrifugation at 500 x g and washed several times with PBS. Nuclear pellet and cytoplasmic fractions were prepared using Nuclear and Cytoplasmic Extraction Kit (78833, Pierce Biotechnology, Rockford IL) and stored at −80°C. For protein crosslinking, the pellet (nuclear fraction, 5 × 10⁶ cell equivalents) was suspended in 100 µl of PBS (pH 8.0) containing 1 mM disuccinimidyl suberate (DSS, 21555, Pierce, Rockford, IL) and incubated for 10 min at room temperature. Tris-HCl (1 M, pH 7) was added to a final concentration of 10 mM to stop the reaction, and the protein samples were used for gel electrophoresis and immunoblot.

To prepare nuclear extract from mouse epidermis, skin was removed and placed on ice and the epidermis was removed by scraping with a razor blade. Nuclear extract was prepared from the epidermal tissue using the nuclear and cytoplasmic extraction kit (78833, Pierce Biotechnology, Rockford, IL) and stored at −80°C.

Chromatin Immunoprecipitation Assay (ChIP)

ChIP assay was performed as described [63] with minor modification. Keratinocytes (5 × 10⁶ cells) from a 35 mm dish were crosslinked with 1.42% formaldehyde at room temperature for 15 min followed by quenching with 125 mM glycine and then washed with ice cold PBS containing histone deacetylase inhibitors. The cells were then lysed in 150 µl of lysis buffer (50 mM Tris-HCl, pH 8, 10 mM EDTA, 1% SDS, 1 mM PMSF, 20 mM sodium butyrate, and protease inhibitors). Samples were chilled on ice and DNA was sheared using a Branson Sonifier (three 30-sec pulses on ice at 40% amplitude with 30 seconds between pulses to produce fragments of 1,000 bp). Four hundred microliters of RIPA buffer containing protease inhibitors and histone deacetylase inhibitors was added followed by a centrifugation of 12,000×g for 10 min. Aliquots of supernatant containing sheared chromatin were used for immunoprecipitation. Mouse monoclonal anti-FLAG (2 µg, F3163, Sigma, St. Louis, MO) was added to Dynabeads Protein A and incubated for 2 h at 4°C with rotation at 40 rpm. Sheared chromatin was added and mixture was incubated at 4°C overnight with rotation. The chromatin-
antibody complex was washed twice with RIPA buffer and 40 μl of Chelex 100 slurry (10% wt/vol) was added to the washed beads prior to boiling for 10 min. The samples were then treated with proteinase K for 30 min at 55°C and boiled for 10 min. Enrichment of TAM67-FLAG-associated DNA sequences in immunoprecipitated samples and input samples were detected by quantitative RT-PCR using sequence specific primers and LightCycler 480 SYBR Green Master mix. CdpK primers included hINV promoter AP1-5 probe (nucleotides −2118/−2055) forward: 5'-TCAGCTGATAGTCGCGCCAGGA-3' (E320A, Promega, Madison, WI, AP site in bold) and hINV promoter control (nucleotides −1040/−919) forward: 5'-CCTCTCAGGGAGAGAGATGA-3' and reverse: 5'-CAACAGTGCAAGGCAGACCTTGA-3' primers [23].

Gel Mobility Shift Assays
Cells were washed with PBS for preparation of nuclear extract using NE-PER Nuclear and Cytoplasmic Extraction Reagent (78833, Pierce Biotechnology, Rockford, IL). Binding of transcription factors to double-stranded AP1 consensus (AP1 site in bold) oligonucleotide 5'-CGCTTATGAGTCGCCAGGAAAG-3' (E320A, Promega, Madison, WI, AP site in bold) or hINV probe which encodes the AP1-5 binding site in upstream regulatory region of human involucrin promoter, 5'-CTTAAGGCTCTTATTATGCCG-3' (AP site in bold, Sp1 site underlined) was monitored by gel mobility shift assay. Three micrograms of nuclear extract was incubated for 30 min at room temperature in a volume of 20 μl containing 20 mM HEPES, pH 7.5, 10% glycerol, 0.5 mM EDTA, 0.5 mM DTT, 10% glycerol, 50 mM KCl, 2 mM MgCl2, 5 mM HEPES, pH 7.5, 10% glycerol, 0.5 mM EDTA, 0.5 mM DTT, 10% glycerol, 50 mM KCl, 2 mM MgCl2, and 40,000 cpm radioactive double-stranded AP1-5 probe which encodes the AP1-5 binding site in upstream regulatory region of human involucrin promoter, 5'-CTTAAGGCTCTTATTATGCCG-3' (AP site in bold, Sp1 site underlined), AP1c and AP1-5 m/Sp1 m, 5'-CTTAAGGCTCTTATTATGCCG-3' (AP site in bold) or hINV promoter AP1-5 (nucleotides 2321-2334) forward: 5'-TGTCGTGGCTCCCTTGATCTGA-3'/5'-TGGA-TGCTGGAACAGAAGTGTT-3' [54], and reverse: 5'-GCCGAGGAGGAGGAAAGTGTGA-3' [54], was added to the reaction mixture and incubated 30 min at 25°C. The samples were then treated with proteinase K for 30 min at 55°C and boiled for 10 min. This mixture was then added to 1 μg of hINV plasmid and incubated at 25°C for 20 min followed by direct addition to cultures containing 2 μl of KSF. The final DNA concentration in all groups was maintained constant by addition of empty control vector. At 24 h after transfection, 2 ml of fresh medium was added containing 0 or 50 ng/ml TPA. After an additional 24 h, the cells were washed with PBS and scraped into 200 μl of cell lysis buffer, and luciferase activity was assayed immediately. All assays were performed in triplicate, and each experiment was repeated a minimum of three times. Luciferase activity was normalized per microgram of protein. Promoter activity experiments were also performed in keratinocytes using c-jun promoter luciferase reporter constructs c-jun−1780/+731 and c-jun−1780/+731-AP1 m which encode nucleotides −1780/+731 of the human c-jun promoter and upstream regulatory region [48]. The latter construct is identical except that the AP1 sites in the c-jun upstream regulatory region are mutated [48].

hINV and c-jun Promoter Activity
Human involucrin hINV reporter plasmids, encoding various lengths of hINV promoter upstream regulatory region fused to the luciferase reporter gene have been described [36,47]. We used hINV promoter constructs, pINV-2473, pINV-241, and pINV-41, which include nucleotides −2473/−7, −241/−7 and −41/−7, respectively, of the hINV promoter linked to the luciferase reporter gene [47]. TAM67 expression plasmid was pcDNA3-TAM67-FLAG. 12-O-Tetradecanoylphorbol-13-acetate (TPA) was obtained from Sigma (St. Louis, MO). For experiments, 2×10⁶ cells were seeded into 35 mm dishes 24 h before transfection. For transfection, 6 μl of Fugene-6 reagent (11 814 443 00, Roche, Indianapolis, IN) was mixed with 94 μl of KSF, and incubated at 25°C for 10 min. This mixture was then added to 1 μg of hINV plasmid and 1 μg of TAM67-FLAG expression plasmid and incubated and incubated for 20 min followed by direct addition to cultures containing 2 μl of KSF. The final DNA concentration in all groups was maintained constant by addition of empty expression vector. At 24 h after transfection, 2 ml of fresh medium was added containing 0 or 50 ng/ml TPA. After an additional 24 h, the cells were washed with PBS and scraped into 200 μl of cell lysis buffer, and luciferase activity was assayed immediately. All assays were performed in triplicate, and each experiment was repeated a minimum of three times. Luciferase activity was normalized per microgram of protein. Promoter activity experiments were also performed in keratinocytes using c-jun promoter luciferase reporter constructs c-jun−1780/+731 and c-jun−1780/+731-AP1 m which encode nucleotides −1780/+731 of the human c-jun promoter and upstream regulatory region [48]. The latter construct is identical except that the AP1 sites in the c-jun upstream regulatory region are mutated [48].

TAM67-TRA Transgenic Mice
The TAM67-TRA mice are maintained in the genetic background as previously described [35]. These mice harbor a transgene that encodes TAM67-FLAG linked to a tetracycline-inducible promoter. Endermis-specific TAM67-FLAG expression is induced by addition of 2 mg/ml doxycycline in drinking water and expression is maximal within two days [35]. A FLAG epitope is included at the carboxyl terminus of TAM67 so that expression can be easily monitored. For the experiments outlined in the present study we utilize 20 wk old female mice from TAM67-44 strain [35]. Epidermal extracts were prepared for gel mobility shift or immunoblot after a three day treatment with doxycycline. Mice were maintained in the University of Maryland School of Medicine animal facility in compliance with NIH regulations with laboratory chow and water accessible ad libitum. The study was approved by the University of Maryland.
School of Medicine Institutional Animal Care and Use Committee.

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References
1. Angel P, Szabowski A, Schorpp-Kistner M (2001) Function and regulation of AP-1 subunits in skin physiology and pathology. Oncogene 20: 2413-2423.
2. Karin M, Liu Z, Zandi E (1997) AP-1 function and regulation. Curr Opin Cell Biol 9: 240-246.
3. Shaulian E, Karin M (2002) AP-1 as a regulator of cell death and life. Nat Cell Biol 4: E131-E136.
4. Shaulian E, Karin M (2001) AP-1 in cell proliferation and survival. Oncogene 20: 2390-2400.
5. Mizuno H, Cho YY, Ma WY, Bode AM, Dong Z (2006) Effects of MAP kinase inhibitors on epidermal growth factor-induced neoplastic transformation of human keratinocytes. Mol Carcinog 45: 1-9.
6. Shi B, Isseroff RR (2005) Epidermal growth factor (EGF)-mediated DNA-binding activity of AP-1 is attenuated in senescent human epidermal keratinocytes. Exp Dermatol 14: 519-527.
7. Takahashi H, Ibe M, Nakamura S, Ishida-Yamamoto A, Hashimoto Y, et al. (2005) Extracellular regulated kinase and c-Jun N-terminal kinase are activated in psoriatic epidermis. J Dermatol Sci 39: 94-99.
8. Adhikary G, Jon G, Zaim TM, Eckert RL (2008) Regulation of involucrin expression in normal human corneal epithelial cells: a role for activator protein 1. Invest Ophthalmol Vis Sci 49: 1080-1097.
9. Eckert RL, Efimova T, Balasubramanian S, Crish JF, Bone F, et al. (2003) p38 Mitogen-Activated Protein Kinases on the Body Surface - A Function for p38delta. J Invest Dermatol 120: 823-826.
10. Eckert RL, Crish JF, Efimova T, Bone F, Dorough A, et al. (2004) Regulation of involucrin gene expression. J Invest Dermatol 123: 13-22.
11. Efimova T, Bounounce AM, Eckert RL (2004) Protein kinase Cdelta regulates human involucrin promoter activity in psoriatic epidermis. J Invest Dermatol 123: 821-732.
12. Kahn CR, Young E, Lee IH, Rhim JS (1993) Human corneal epithelial primary cells and cultures with extended life span. in vitro model for ocular studies. Invest Ophthalmol Vis Sci 34: 3429-3441.
13. She QB, Chen N, Bode AM, Flavell RA, Dong Z (2002) Deficiency of c-jun(NH2)-terminal kinase-1 in mice enhances skin tumor development by 12-O-tetradecanoylphorbol-13-acetate. Cancer Res 62: 1343-1348.
14. Rutberg SE, Muller E, Oppenheim H, Snolok J, et al. (1995) c-fos is required for malignant progression of skin tumors. Cell 83: 271-284.
15. Sun K, Young MR, Lee IH, Rhim JS (1993) Human corneal epithelial primary cells and cultures with extended life span. in vitro model for ocular studies. Invest Ophthalmol Vis Sci 34: 3429-3441.
16. Liu Y, Lu C, Shon Q, Munoz-Medellin D, Kim JH, et al. (2004) AP-1 blockade in breast cancer cells causes cell cycle arrest by suppressing G1 cyclin expression and reducing cyclin-dependent kinase activity. Oncogene 23: 8230-8246.
17. Herminga RF, Stammler JP (2001) Dominant negative c-jun inhibits activation of cyclin D1 and cyclin kinase complexes. Mol Biol Cell 12: 2552-2563.
18. Fong Z, Li L, Ng PY, Porter AG (2002) Neuronal differentiation and protection from nitric oxide-induced apoptosis requires c-jun-dependent expression of NCAM140. Mol Cell Biol 22: 3397-3396.
19. Madireddi MT, Dent P, Fehnel PB (2000) AP-1 and G/ERK transcription factors contribute to mdr-7 gene promoter activity during human melanoma differentiation. J Cell Physiol 185: 46-56.
20. Grant S, Freedenmar AJ, Bjerre MR, Martin HA, Turner AJ, et al. (1996) Effect of 1-beta-D-arabinofuranosylcytosine on apoptosis and differentiation in human nonmelanocytic keratinocytes (Cl37) expressing a c-Jun dominant-negative-mutant protein (TAM67). Cell Growth Differ 7: 603-613.
21. Leit F, Adhikary G, Jon G, Crish JF, Eckert RL (2010) AP-1 factor activation in the suprabasal epidermis causes increased epidermal hyperplasia and hyperkeratosis but reduced carcinogen-dependent tumor formation. Oncogene 29: 5873-5882.
22. Efimova T, LaCelle P, Welter JF, Eckert RL (1998) Regulation of human keratin promoter activity by protein kinase C, Ras, MEK1, MEK3, p38/ERK, AP1 signal transduction pathway. J Biol Chem 273: 24197-24199.
23. Cooper SJ, MacGowan J, Ranger-Mooore J, Young MR, Colburn NH, et al. (2003) Expression of dominant negative c-jun inhibits ultraviolet-B-induced squamous cell carcinoma number and size in an SKH-1 hairless mouse model. Cancer Res 63: 8400-8408.
24. Dong Z, Crawford HC, Lavrovsky V, Taub D, Watts R, et al. (1997) A dominant negative mutant of jun block 12-O-tetradecanoylphorbol-13-ace late-induced invasion in mouse keratinocytes. Mol Carcinog 19: 204-212.
25. Li Y, Chowdhury KH, Colburn NH (1998) Expression of dominant negative Jun inhibits elevated AP-1 and NF-kappaB transactivation and suppresses anchorage independent growth of HPV immortalized human keratinocytes. Oncogene 17: 2711-2721.
26. Shen Q, Zhang Y, Uray IF, Hill JS, Kim HT, et al. (2006) The AP-1 transcription factor regulates postnatal mammary gland development. Dev Biol 295: 589-603.
27. Thompson EJ, MacGowan J, Young MR, Colburn N, Bowden GT (2002) A dominant negative c-jun specifically blocks okadaic acid-induced skin tumor promotion. Cancer Res 62: 3044-3047.
28. Young MR, Farrell L, Lambert P, Avasthi P, Colburn NH (2002) Protection against human papillomavirus type 16-E7 oncogene-induced tumorgenesis by in vivo expression of dominant-negative c-jun. Mol Carcinog 34: 72-77.
29. Young MR, Li JJ, Rincon M, Flavell RA, Sathyanarayana BK, et al. (1999) Transgenic mice demonstrate AP-1 (activator protein-1) transactivation is required for tumor promotion. Proc Natl Acad Sci U S A 96: 9027-9032.
30. Efimova T, Eckert RL (2000) Regulation of human involucrin promoter activity by novel protein kinase C, Ras, MEK1, MEK3, p38/ERK, AP1 signal transduction pathway. J Biol Chem 273: 24197-24199.
31. Cooper SJ, MacGowan J, Ranger-Mooore J, Young MR, Colburn NH, et al. (2003) Expression of dominant negative c-jun inhibits ultraviolet-B-induced squamous cell carcinoma number and size in an SKH-1 hairless mouse model. Cancer Res 63: 8400-8408.
32. Thompson EJ, MacGowan J, Young MR, Colburn N, Bowden GT (2002) A dominant negative c-jun specifically blocks okadaic acid-induced skin tumor promotion. Cancer Res 62: 3044-3047.
33. Young MR, Farrell L, Lambert P, Avasthi P, Colburn NH (2002) Protection against human papillomavirus type 16-E7 oncogene-induced tumorgenesis by in vivo expression of dominant-negative c-jun. Mol Carcinog 34: 72-77.
34. Young MR, Li JJ, Rincon M, Flavell RA, Sathyanarayana BK, et al. (1999) Transgenic mice demonstrate AP-1 (activator protein-1) transactivation is required for tumor promotion. Proc Natl Acad Sci U S A 96: 9027-9032.
35. Efimova T, Eckert RL (2000) Regulation of human involucrin promoter activity by novel protein kinase C, Ras, MEK1, MEK3, p38/ERK, AP1 signal transduction pathway. J Biol Chem 273: 24197-24199.
36. Eckert RL, Welter JF (1996) Transcription factor regulation of epidermal growth factor induction of human involucrin promoter transcription. Mol Endocrinol 12: 1322-1334.
49. Adhikary G, Crish JF, Bone F, Gopalakrishnan R, Lass J, et al. (2005) An involucrin promoter AP1 transcription factor binding site is required for expression of involucrin in the corneal epithelium in vivo. Invest Ophthalmol Vis Sci 46: 1219–1227.

50. Banks EB, Crish JF, Welser JF, Eckert RL (1998) Characterization of human involucrin promoter distal regulatory region transcriptional activator elements—a role for Sp1 and AP1 binding sites. Biochem J 331 (Pt 1): 61–68.

51. Balasubramanian S, Eckert RL (2007) Curcumin suppresses AP1 transcription factor-dependent differentiation and activates apoptosis in human epidermal keratinocytes. J Biol Chem 282: 6707–6715.

52. Jang SI, Steinert PM (2002) Loricrin expression in cultured human keratinocytes is controlled by a complex interplay between transcription factors of the Sp1, CREB, AP1, and AP2 families. J Biol Chem 277: 42768–42779.

53. Yoneda K, Hohl D, McBride OW, Wang M, Celrux K, et al. (1992) The human loricrin gene. J Biol Chem 267: 18060–18066.

54. Angel P, Hattori K, Smeal T, Karin M (1988) The jun proto-oncogene is positively autoregulated by its product, Jun/AP-1. Cell 55: 875–885.

55. Devary Y, Gottlieb RA, Lau LF, Karin M (1991) Rapid and preferential activation of the c-jun gene during the mammalian UV response. Mol Cell Biol 11: 2004–2011.

56. Stein B, Angel P, van Dam H, Ponta H, Herrlich P, et al. (1992) Ultraviolet-radiation induced c-jun gene transcription: two AP-1 like binding sites mediate the response. Photochem Photobiol 55: 409–415.

57. Berger I, Shaul Y (1994) The human junD gene is positively and selectively autoregulated. DNA Cell Biol 13: 249–255.

58. Brown PH, Kim SH, Wise SC, Sabichi AL, Birrer MJ (1996) Dominant-negative mutants of cJun inhibit AP-1 activity through multiple mechanisms and with different potencies. Cell Growth Differ 7: 1013–1021.

59. Thompson EJ, Gupta A, Stratton MS, Bowden GT (2002) Mechanism of action of a dominant negative c-jun mutant in inhibiting activator protein-1 activation. Mol Carcinog 35: 157–162.

60. Laemmli UK (1970) Cleavage of structural proteins during the assembly of the head of the bacteriophage T4. Nature 227: 680–685.

61. Adhikary G, Crish JF, Gopalakrishnan R, Bone F, Eckert RL (2005) Involucrin expression in the corneal epithelium: an essential role for Sp1 transcription factors. Invest Ophthalmol Vis Sci 46: 3170–3179.

62. Robinson NA, LaCelle PT, Eckert RL (1996) Involucrin is a covalently crosslinked constituent of highly purified epidermal corneocytes: evidence for a common pattern of involucrin crosslinking in vivo and in vitro. J Invest Dermatol 107: 101–107.

63. Chew YC, Adhikary G, Wilson GM, Rees E, Eckert RL (2011) PKCdelta suppresses keratinocyte proliferation by increasing p21CIP1 level by a KLF4-dependent mechanism. J Biol Chem 286: 28771–28772.

64. Ramos-Nino ME, Blumen SR, Pass H, Mossman BT (2007) Fra-1 governs cell migration via modulation of CD44 expression in human mesotheliomas. Mol Cancer 6: 81.

65. Diegmann J, Junker K, Gerstmayr B, Bosio A, Hindermann W, et al. (2005) Identification of CD70 as a diagnostic biomarker for clear cell renal cell carcinoma by gene expression profiling, real-time RT-PCR and immunohistochemistry. Eur J Cancer 41: 1794–1801.

66. Kamioka N, Akahane T, Kohno Y, Kuroki T, Iijima M, et al. (2010) Protein kinase C delta and eta differently regulate the expression of loricrin and Jun family proteins in human keratinocytes. Biochem Biophys Res Commun 394: 106–111.