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Stereo-specific Induction of NF-κB Activation by Isochamaejasmin[*]

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Running title: Induction of NF-κB by isochamaejasmin

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Number of text pages: 22

Number of tables: 1

Number of figures: 8

Number of References: 35

Number of words in Abstract: 226

Number of words in Introduction: 478

Number of words in Discussion: 1027

Abbreviations

FPRL1, formyl peptide receptor-like 1; ERK, extracellular signal-regulated kinase; DMEM, Dulbecco's modified Eagle's medium; FBS, fetal bovine serum; HBSS, Hanks's balanced saline solution; BSA, bovine serum albumin; PBS, phosphate-buffered saline; AM, acetoxymethl ester; NF-κB, nuclear factor-κB; PKC, protein kinase C; GPCR, G protein-coupled receptor; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5diphenyl tetrazolium bromide; EtOAc, ethyl acetate; EtOH, ethanol; WKYMVm, Trp-Lys-Tyr-Met-Val-D-Met-NH$_2$; DMSO, dimethyl sulfoxide.

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ABSTRACT

The root of *Stellera chamaejasme* L. is a traditional Chinese herb termed Rui Xiang Lang Du and has been used to treat solid tumors, tuberculosis and psoriasis. Exactly how *Stellera chamaejasme* L. regulates cellular responses remains unclear. We examined four biflavonoids isolated from *Stellera chamaejasme* L., including isochamaejasmin, two of its stereo-isomers and a methyl derivative, in functional assays originally designed to screen ligands for the G protein-coupled formyl peptide receptor-like 1 (FPRL1). Isochamaejasmin was found to induce the expression of a NF-κB-directed reporter gene in transfected HeLa cells with an EC_{50} of 3.23 μM, independently of FPRL1. The isochamaejasmin-stimulated NF-κB reporter activity was accompanied by nuclear translocation of NF-κB proteins and was blocked by a dominant negative construct of IκBα. Isochamaejasmin also induced time-dependent phosphorylation of the mitogen-activated protein kinases ERK1/2 and p38, and a novel protein kinase C, PKCδ. Likewise, inhibition of these kinases with the respective pharmacological inhibitors significantly reduced the isochamaejasmin-stimulated NF-κB activation. Interestingly, the two stereoisomers and the methyl derivative did not induce detectable activation of NF-κB and were more cytotoxic than isochamaejasmin, which could partially rescue cycloheximide-induced apoptosis. Inhibition of NF-κB activation reversed the anti-apoptotic effect of isochamaejasmin. These results provide the first evidence for a potential mechanism of action by *Stellera chamaejasme* L., and indicate that structurally similar compounds derived from *Stellera chamaejasme* L. may have different pharmacological properties.

In ancient China, medicines were called 'Ben Cao' (Chinese materia medica). The root of
Stellera chamaejasme L. (Thymelaeaceae) was first described, among 365 types of herbs, in the
oldest herbal medicine book ('Shen Nong Ben Cao') written in the late Han Dynasty (25-220
A.D.) (Lin and Zhu, 1992). Named Rui Xiang Lang Du in traditional Chinese medicine, this herb
was shown to possess both toxic and therapeutic effects (Zhou et al., 1997), and has been used to
treat solid tumors (e.g., liver and lung cancer) (Yang and Lu, 1989), tuberculosis (Yang, 1956)
and certain skin diseases (e.g., psoriasis and acariasis) (Guo, 1986; Si, 1989) for many years. The
clinical applications of this plant were supported by its pharmacological properties such as tumor
suppression and bactericidal action as demonstrated by a large number of experimental studies
conducted in the past decade (Jian et al., 2003). Despite a long history of clinical use in China,
very little is known about the mechanisms underlying its therapeutic effects. There have been
continued efforts in isolating individual compounds from *Stellera chamaejasme* L. and its water
and methanol extracts include biflavonoids, lignans, and diterpenes (Pei et al., 2001). Although
similar biflavonoids were found in *Euphorbia fischeriana* and *Euphorbia ebracteolata*
(Euphorbiaceae), the contents varied considerably among the three different plant families (Gong,
1982; Xing et al., 1992). Whether these chemical constituents (biflavonoids in particular) alone
or in combination are responsible for the bioactivities of *Stellera chamaejasme* L. remains to be
determined.

Formyl peptide receptor-like 1 (FPRL1) is a G protein-coupled receptor (GPCR) that binds
natural and synthetic peptides as well as lipoxin A4, and mediates important biological functions
such as inflammation (Chiang et al., 2000). Among more than 10 ligands identified for FPRL1,
WKYMVm (Baek et al., 1996; Le et al., 1999) has been widely employed in *in vitro* and *ex vivo*
studies of this GPCR. In an attempt to discover novel small molecule ligands for FPRL1, a high
throughput, highly sensitive, cell-based, NF-κB-dependent luciferase reporter system was
developed recently to screen both natural and synthetic compound libraries (Nanamori et al.,
2004). Isochamaejasmin isolated from *Stellera chamaejasme* L. was one of the compounds
initially discovered to display a potent NF-κB activation activity using this system.

In the present study, we examined 4 biflavonoids derived from ethanol extracts of *Stellera
chamaejasme* L. for their biological effects at the cellular level. We found that stereo-isomers

have drastically different functional properties, such that only isochamaejasmin (S/R/R/S at C2/C3/C2"/C3") possesses the ability to stimulate NF-κB activation. The all S as well as the S/S/R/S configurations were ineffective. Functional characterization suggests that isochamaejasmin-induced NF-κB stimulation in HeLa cells is accompanied by the activation of several protein kinases including ERK1/2 and p38, and the novel protein kinase C isoform, PKCδ. The activation of these kinases may contribute to the IκB kinase β (IKKβ)-mediated NF-κB activation and nuclear translocation of the NF-κB proteins.

Materials and Methods

Materials. W-peptide (WKYMVm) was synthesized at GL Biochem (Shanghai) Ltd. (Shanghai, China). Phorbol 12-myristate 13-acetate (PMA) was purchased from Sigma-Aldrich (St. Louis, MO). Steady-Glo[TM] Luciferase Assay solutions were obtained from Promega Corporation (Madison, WI). Other reagents were bought from Sigma-Aldrich.

Isochamaejasmin and analogues. Dried and powdered root of *Stellera chamaejasme* L. (2 kg), collected from Sichuan Province, China, was extracted with EtOH (8 liters×3) at room temperature. The concentrated extract obtained under reduced pressure was partitioned with EtOAc and H_2O. The EtOAc layer (41 g) was subjected to D-101 macroporous resin (Shanghai Chemical Reagent Factory, Shanghai, China), and eluted with EtOH-H_2O (50:50, 70:30 and 95:5). After sequential chromatography on silica gel (CHCl$_3$-MeOH-H_2O, 7:3:0.5), MCI gel CHP 20P (40% MeOH), Chromatorex ODS (50% MeOH) and Sephadex LH-20 (100% MeOH), four biflavonoids were isolated by liquid chromatography on a Waters 2690/996 HPLC-PDA system, with a solvent gradient of 50% methanol/50% water (0.5% HCOOH) to 100% methanol at 25°C, at a flow rate of 1 ml/min for 15 min. They were identified based on spectral properties: Isochamaejasmin (Niwa et al., 1984; 1986), neochamaejasmin A (Niwa et al., 1984), neochamaejasmin B (Niwa et al., 1984) and chamaejasmin B (Liu et al., 1984). The chromatograms (with analysis wavelength set at 300 nm) are shown in Figure 1 and the purity of each biflavonoid is summarized in Table 1. These compounds were deposited into the natural compound library at the National Center for Drug Screening for random screening with different bioassay systems.

Cell Culture. The human cervical carcinoma cell line HeLa was transfected with pNF-κB-Luc reporter plasmid that contains 5 copies of NF-κB binding sequence (Stratagene, La Jolla, CA), with or without a human FPRL1 cDNA expression vector in pSFFV.neo vector. The transfected cells were maintained in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% fetal bovine serum (FBS). Rat basophilic leukemia cell line RBL-2H3 expressing the human FPRL1 was described previously and maintained in DMEM supplemented with 20% FBS (He et al., 2000).

Whole cell-based compound screening. HeLa cells expressing NF-κB-Luc/ FPRL1 (HeLa/NF-κB/FPRL1) were seeded in 96-well plates at a density of 1.5×10^4 cells per well. After cells became adherent, they were serum-starved in DMEM without phenol red for 16 h prior to screening assay. A total of 320 pure compounds derived from natural products at a concentration of approximately 10 µg/ml were screened. After incubation with the compounds for 5 h, the expressed luciferase activity was determined in a Wallac 1420 multilabel counter (VICTOR^2, PerkinElmer, Boston, MA) using the Steady-Glo^{TM} Luciferase Assay solutions. Seven hits, that produced more than 5-fold induction of luciferase activity, were initially discovered. Secondary screening with the same assay confirmed that one compound (NPLC0169), namely isochamaejasmin, has an EC_{50} of 3.23 µM. It was further evaluated with HeLa cells expressing pNF-κB-Luc but not FPRL1 (HeLa/NF-κB) along with the three analogues of isochamaejasmin.

Chemotaxis. WKYMVm (W-peptide)-induced migration of cells was assessed in a 48-well micro-chemotaxis chamber (Neuro Probe, Cabin John, MA) and compared with that of isochamaejasmin. Briefly, different concentrations of isochamaejasmin (between 0 and 100 µM) were placed in the lower chamber (30 µl) and RBL-FPRL1 cells (50 µl at 1×10^6 cells/ml) were loaded in the upper chamber, which was separated from the lower chamber by a polycarbonate filter (pore size 10 µm). After incubation at 37°C for 4 h, the filter was removed, fixed and stained with Diff-Quick staining solutions (IMEB Inc., San Marcos, CA). The numbers of migrated cells were determined by counting in a high power field (×400). Results were presented as chemotaxis index that represents the ratio of the density of the area where cells migrated

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towards W-peptide or isochamaejasmin over the density of the area where cells migrated towards medium.

Cytotoxicity measurement. HeLa cells (ATCC, Manassas, VA) were seeded in a 96-well plate at a density of 3×10^3 per well in the presence of serial dilutions of isochamaejasmin and its analogues. After incubation at 37°C for 48 h, 3-(4,5-dimethylthiazol-2-yl)-2,5diphenyl tetrazolium bromide (MTT) was added to the cells and incubated for an additional 2 h at 37°C. The reaction product, formazan, was extracted with DMSO and absorbance at 560 nm was determined in a VERSAmax tunable microplate reader (Molecular Devices, Sunnyvale, CA) (Liu et al., 2002). For rescue experiment, cycloheximide (5 μg/ml; Supelco, Bellefonte, PA) and various concentrations of isochamaejasmin were introduced to the cells 24 h before the MTT assay. NF-κB SN50, a cell-permeable inhibitory peptide (Lin et al., 1995; Calbiochem, San Diego, CA), or a negative control peptide (SN50M), were added 30 min prior to the above reagents to determine if the rescue effect is associated with NF-κB activation.

NF-κB nuclear translocation. The NF-κB translocation assay was conducted according to the manufacturer's instructions using a NF-κB Activation Kit for High Content Screening (Cellomics Inc., Pittsburgh, PA). Briefly, HeLa cells were seeded in the μ Clear-plates (Kaminform, Greiner Bio-One, Kremsmuenster, Austria) at a density of 5×10^3 cells per well, and incubated for 24 h at 37°C. Following stimulation with various concentrations of IL-1α, PMA, isochamaejasmin or neochamaejasmin A at 37°C for 40 min, cells were fixed with pre-warmed 3.7% formalin in PBS for 10 min at room temperature. After washing, the cells were permeabilized and incubated with the rabbit anti-NF-κB antibody supplied with the kit for 1 h, followed by a 15 min wash with detergent buffer (once) and PBS (twice). The cells were then stained with the staining solution containing goat anti-rabbit IgG conjugated to Alexa Fluor 488 and Hoechst dye for 1 h before a 10 min wash with the detergent buffer and two additional washes with PBS. The cells were soaked in PBS at 4°C until imaging procedure using the ArrayScan™ HCS system (Cellomics).

Western blot analysis. Cells grown in six-well plates were stimulated with selected compounds for indicated times. The reaction was stopped by addition of 1 ml ice-cold PBS, and the cells were collected. After centrifugation, the cell pellet was resuspended in 1 ml ice-cold lysis buffer (50 mM Tris-HCl, pH 8.0, 1 mM EDTA, 1% Nonidet P-40, 150 mM NaCl, 1 mM Na_3VO_4, 5 mM NaF, and protease inhibitors). The contents were incubated on ice for 15 min, centrifuged, and the supernatant was transferred to fresh Eppendorf tubes. Samples were analyzed by SDS-PAGE and Western blotting with antibodies against either phospho-extracellular signal-related kinase (ERK) 1/2 or p38 (Cell Signaling Technologies, Beverly, MA) at 1:1000 dilution for 18 h. A similar experiment was performed with an anti-phospho-PKCδ antibody (Thr505), from the same vendor. The membrane was washed and incubated with 1:5000 dilution of horseradish peroxidase (HRP)-conjugated anti-mouse secondary antibody for 1 h. Excess antibody was removed by washing, and immunocomplexes were visualized using enhanced chemiluminescence detection (Pierce, Rockford, IL) according to the manufacturer's instructions.

Calcium mobilization assay. RBL-FPRL1 cells were harvested with the enzyme-free cell dissociation buffer (Invitrogen, Carlsbad, CA). The cells (5×10^5) were incubated with 4 μM Fluo-3/AM in HBSS/BSA at 37°C for 1 h, and examined for calcium mobilization in response to the compounds using a PTI Spectrofluorometer (Photon Technology International, Lawrenceville, NJ) with excitation wavelength at 488 nm and emission wavelength at 525 nm.

Results

Isochamaejasmin induces NF-κB activation in transfected HeLa cells. The human cervical carcinoma cell line HeLa has been used extensively in studies of the transcription factor NF-κB. The HeLa/NF-κB/FPRL1 cell line, that contains a 5×NF-κB binding sequence and expresses the human FPRL1, was initially generated for screening of small molecular weight ligands for FPRL1 (Nanamori, et al., 2004). Isochamaejasmin (Figure 1) was identified as one of the hits that stimulated NF-κB activation in this screening assay and was further analyzed in the current study. Quantitative analysis demonstrated that stimulation of HeLa/NF-κB/FPRL1 with isochamaejasmin resulted in a dose-dependent increase in NF-κB-directed luciferase reporter

expression that peaked at 10-15 μM with an EC_{50} of 3.23 μM (Figure 2). At higher concentrations of isochamaejasmin (≥ 10 μM), there was a progressive decrease in the NF-κB luciferase activities, most likely due to its cytotoxicity (Lin and Zhu, 1992).

Isochamaejasmin stereo-specifically induces NF-κB activation. We examined the two isochamaejasmin stereo-isoforms, neochamaejasmin A and chamaejasmin B, as well as a methyl derivative of neochamaejasmin A (Figure 1 and Table 1), for their abilities to stimulate NF-κB activation in HeLa/NF-κB/FPRL1 cells. Interestingly, none of these compounds was able to induce NF-κB luciferase reporter at concentrations up to 100 μM (Figure 2 and data not shown). Given the purity of the compounds used in this study (Table 1), this result suggests that the isochamaejasmin-induced NF-κB activation is a stereo-specific effect not shared by the isomers and the structurally similar derivative.

The effect of isochamaejasmin is independent of FPRL1. Since the cell line used in the initial study expresses FPRL1, it was necessary to determine whether isochamaejasmin is an agonist of this chemoattractant receptor (Su et al., 1999). HeLa cells were transfected to express the NF-κB luciferase reporter with or without FPRL1. The cells were stimulated with isochamaejasmin (1 μM) and the induced NF-κB luciferase activity over a 5-hour period was determined. As shown in Figure 3A, the presence of FPRL1 had no effect on the induced NF-κB luciferase reporter activity. Independent experiments were conducted with a RBL-2H3 cell line expressing FPRL1 (RBL-FPRL1) which functionally responds to FPRL1 agonists (Nanamori et al., 2004). Isochamaejasmin was unable to stimulate calcium mobilization in the RBL-FPRL1 cell line (Figure 3B), a response typically induced by FPRL1 agonists such as WKYMVm. Likewise, isochamaejasmin failed to induce chemotaxis at concentrations up to 100 μM; in contrast, the control peptide (WKYMVm) induced a 13.4-fold increase in cell migration with a typical bell-shaped chemotaxis dose curve (Figure 3C). Based on these results, we concluded that isochamaejasmin induces NF-κB activation independently of FPRL1.

Isochamaejasmin-stimulated NF-κB activation involves IKKβ and requires degradation of IκBα. The NF-κB activation pathway has been well established through studies in recent years.

The majority of NF-κB stimuli induce activation of IKKβ while others use an alternative pathway involving IKKα. Phosphorylation of IκBα by IKKβ causes subsequent ubiquitination and degradation of this inhibitory subunit, leading to nuclear translocation of the NF-κB proteins (Karin et al., 2004). We examined whether isochamaejasmin could induce nuclear translocation of the NF-κB protein p65/RelA. As shown in Figure 4A, isochamaejasmin (169), but not buffer (Ctl) or neochamaejasmin A (168), caused enrichment of p65/RelA in the nucleus suggesting nuclear translocation of this NF-κB protein. We next examined the potential involvement of IKKs and IκBα in isochamaejasmin-induced NF-κB activation by co-transfection of dominant negative constructs of IKKα and IKKβ (Lys44→Met44 mutation) (Mercurio et al., 1997). Expression of the IKKβ dominant negative construct, but not that of IKKα, resulted in a significant (p ≤ 0.01) reduction of the isochamaejasmin-induced NF-κB luciferase reporter activity (Figure 4B). Likewise, expression of a dominant negative IκBα with mutated serines at positions 32 and 36 (S32/36A) (Van Antwerp et al., 1996) completely blocked the isochamaejasmin-induced NF-κB activation in luciferase reporter assays. Taken together, these results indicate that isochamaejasmin stimulates the canonical NF-κB activation pathway.

Potential involvement of selected protein kinases in isochamaejasmin-stimulated NF-κB activation. To identify the signaling pathways leading to isochamaejasmin-induced NF-κB activation, we used pharmacological inhibitors for selected protein kinases in addition to the IKKs. Three different PKC inhibitors were used: Gö6976, an inhibitor for conventional PKC, GF109203X, an inhibitor for both conventional and novel PKCs, and rottlerin, an inhibitor that selectively blocks the novel PKC isoform, PKCδ. While all 3 inhibitors produced statistically significant (p ≤ 0.01) inhibition of the isochamaejasmin-stimulated NF-κB luciferase reporter activity, the effects of GF109203X and rottlerin were more prominent than that of Gö6976 (Figure 5A). To extend this finding, we examined isochamaejasmin-stimulated PKCδ activation using an antibody against phosphorylated PKCδ (Figure 5B). Isochamaejasmin (1 μM) induced a time-dependent phosphorylation that symbolizes activation of the kinase (Stahelin et al., 2004). Collectively, these results indicate that isochamaejasmin stimulates both the conventional PKCs and PKCδ, which are involved in the induced NF-κB activation.

We next examined several other protein kinases that have been implicated as upstream stimuli of NF-κB activation. Using anti-phospho-specific antibodies, we found that isochamaejasmin could induce phosphorylation of ERK1/2 (p44 and p42 MAPK; Figure 6A) and p38 (Figure 6B). The phosphorylation of these kinases increased with time up to 20 minutes, suggesting persistent activation by isochamaejasmin. The roles played by these kinases in isochamaejasmin-induced NF-κB activation were evidenced by a partial blockade of the induction of NF-κB luciferase reporter in cells pretreated with the p38 inhibitor, SB203580, or with the MEK inhibitor, U0126. When the cells were treated with both SB203580 and U0126 prior to isochamaejasmin stimulation, a more pronounced inhibitory effect was observed (Figure 6C), suggesting that the two kinase pathways work together in the isochamaejasmin-induced response.

Comparison of the different compounds for cytotoxicity. Since *Stellera chamaejasme* L. is known for its cytotoxicity at higher concentrations (Zhang et al., 2000), we examined whether the 4 compounds could all exhibit this property. Interestingly, at low micromolar concentrations, all compounds exhibited stimulatory effect in cell proliferation. At concentrations above 25 μM, there was a dramatic increase in cytotoxicity for all compounds except isochamaejasmin, which is much less toxic for the HeLa cell line (Figure 7). At 100 μM, all compounds except isochamaejasmin reduced cell viability to less than 25%. In isochamaejasmin-treated samples, however, ~90% of the cells were still viable. This finding provides additional evidence that isochamaejasmin differs from the other structurally similar compounds. To determine if the reduced cytotoxicity of isochamaejasmin was related to its ability to activate NF-κB, a rescue study was conducted using cells treated with cycloheximide. As shown in Figure 8A, the cycloheximide-induced apoptosis was partially reversed by isochamaejasmin in concentrations ranging from 10 to 40 μM. Although the reversal effect was small (an increase of cell viability from 42% to 48%), the difference was statistically significant. We further determined whether this effect was related to NF-κB activation, by using a cell-permeable peptide that inhibits NF-κB. Our results showed that the NF-κB-inhibitory peptide (SN50), but not the control peptide (SN50M), ablated the reversal effect of isochamaejasmin (Figure 8B).

Discussion

The therapeutic values of herbal medicine have drawn increasing attention in recent years. Yet the widespread use of herbal medicine is often hampered by a lack of understanding of the effective ingredients. Although clinical efficacy of *Stellera chamaejasme* L. has been long documented, it was not until the early 1980s that major chemistry efforts were made to isolate bioactive constituents. Apart from pharmacological analyses of the water or methanol extracts *in vitro* and *in vivo*, potential molecular targets for diterpenes purified from *Stellera chamaejasme* L. were identified near the end of the last century. For instance, daphnetin, a coumarin derivative, was implicated as an inhibitor of several protein kinases including EGF receptor (Yang et al., 1999), and gnidimacrin was shown to suppress cancer cell proliferation via an inhibition of cdk2 mediated by protein kinase C (particularly βII subtype) (Yoshida et al., 1996; 1998). However, information pertaining to the biological activities of biflavonoids from *Stellera chamaejasme* L. is very limited. In this study, we compared 4 of these biflavonoids for their cellular effects and found that these structurally similar compounds have different pharmacological properties.

NF-κB proteins are nuclear transcription factors that regulate different physiological actions. Malfunction in related signal transduction pathways may result in inflammatory and autoimmune diseases, as well as different types of cancer (Karin et al., 2004; Caramori and Adcock, 2004). To search for small molecules that may modulate this pivotal mechanism, an assay system was developed for our initial assessment of the functional properties of isochamaejasmin and the 3 analogues. The HeLa cell-based NF-κB luciferase reporter system is highly sensitive in detecting chemical signals that stimulate pathways leading to NF-κB activation. The same approach was successfully employed in the recent identification of a novel non-peptide FPRL1 agonist (Nanamori et al., 2004). Here we show that isochamaejasmin was able to stimulate NF-κB activation when used at high nanomolar to low micromolar concentrations. This is a previously unreported property of compounds isolated from the root of *Stellera chamaejasme* L. The finding may partially explain the immunomodulatory functions of this plant (Zhang et al., 2000), but the linkage between the reported anti-tumor and bactericidal effects and isochamaejasmin remains to be further investigated.

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It is known through clinical practices and laboratory research that *Stellera chamaejasme* L. is toxic and has to be handled with care (Lin and Zhu, 1992). The present study confirmed this historical experience and found that isochamaejasmin, along with neochamaejasmin A, neochamaejasmin B and chamaejasmin B, are cytotoxic when used at high micromolar concentrations. However, isochamaejasmin was much less toxic than the other 3 biflavonoids, and it could partially rescue apoptosis of cells treated with cycloheximide (Figure 8A). We speculated that the reduced cytotoxicity and the anti-apoptotic effect of isochamaejasmin might be caused by its ability to stimulate NF-κB, because NF-κB is generally considered to be anti-apoptotic (Karin and Yinon, 2000; Sonenshein, 1997; Van Antwerp, et al., 1996). Indeed, treatment of a cell-permeable NF-κB inhibitory peptide abolished the anti-apoptotic effect of isochamaejasmin (Figure 8B). Therefore, isochamaejasmin joins a list of anti-cancer compounds that lower their cytotoxic potential through induction of NF-κB (Arlt and Schafer, 2002). In other clinical applications, isochamaejasmin has been shown to have anti-microbial functions. The reduced cytotoxicity offers a clinical advantage and allows for the use of higher doses in treating relevant conditions. Although NF-κB activation is critical to the induced expression of numerous pro-inflammatory cytokines and to cell survival, this transcription factor also plays dual roles in the regulation of the pathological processes of inflammation and cancer development. Factors such as the stages of tumor progression (early *vs.* late) and inflammation (acute *vs.* chronic) can affect the outcome of treatment (Perkins, 2004; Philip et al., 2004). These mechanisms may be also applicable to the mode of action of isochamaejasmin.

Our experimental data indicate that isochamaejasmin does not require FPRL1 for its NF-κB stimulating effect, although the cell line used for the initial screening contains this receptor. Based on its structure, isochamaejasmin is likely cell-permeable and able to directly activate signaling molecules inside the cell. However, it cannot be ruled out that isochamaejasmin exerts its effect through a cell surface receptor. Based on the finding that isochamaejasmin, but not the three structurally similar compounds, was able to induce NF-κB activation, it is speculated that the binding mechanism for this biflavonoid is highly specific. HPLC chromatograms show that the individual compounds are more than 98.5% pure except for chamaejasmin B, which has a purity of 90.72% but did not elicit NF-κB activation in our functional assays. Moreover, the action of isochamaejasmin was not abrogated by the other 3 biflavonoids introduced respectively

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to the assay system at micromolar concentrations (data not shown). Thus, the observed biological activity of isochamaejasmin is specific and unlikely caused by contaminants from the other biflavonoids in the preparation. We also have shown that multiple signaling pathways, including the PKC and MAPK pathways, are activated by isochamaejasmin. Isochamaejasmin apparently activates more than one type of PKCs as its biological activity is sensitive to multiple PKC inhibitors. Although there is considerable overlap in the inhibitory spectrum of these pharmacological agents, the combined use of the 3 inhibitors provides a preliminary assessment of the PKC isoforms that may be involved in its functions. It is unclear whether isochamaejasmin can directly interact with these kinases or activate them through an upstream signaling molecule. However, these signaling mechanisms appear to work together as suggested by the additional inhibition of NF-κB activation when both SB203580 and U0126 were applied together. There remains the possibility that isochamaejasmin binds to more than one target protein to elicit its biological functions.

In summary, the present study represents a first step in the study of *Stellera chamaejasme* L.-derived biflavonoids for their potential cellular signaling mechanisms. Our finding that isochamaejasmin could induce NF-κB activation suggests that this compound is a unique ingredient of the plant. The observation that isochamaejasmin, but not other isomers, has this functionality indicates that cells have highly selective mechanisms in the interaction with and response to constituents from natural sources. A better understanding of the structural basis of isochamaejasmin action is expected to contribute to the development of novel therapeutics based on this class of natural compounds.

Acknowledgements

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Footnotes

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Legends for Figures

Figure 1. Chromatograms and chemical structures of the 4 biflavonoids extracted from
Stellera chamaejasme **L.** HLPC chromatograms showing the fraction of *Stellera chamaejasme*
L containing the 4 biflavonoids (A), and separation of isochamaejasmin (B), neochamaejasmin A
(C), neochamaejasmin B (D) and chamaejasmin B (E). The chemical structures of the individual
biflavonoids are shown next to the respective chromatograms. The purity of each biflavonoid is
given in Table 1.

Figure 2. Induction of NF-κB luciferase reporter expression by isochamaejasmin.
HeLa/NF-κB/FPRL1 cells (1.5×10^4 per well) were stimulated with either isochamaejasmin (169)
or one of the other biflavonoids tested, at different concentrations. Five hours after stimulation,
the produced luciferase activity was assayed as described in *Materials and Methods.* Data shown
are means±SEM of relative luminescence units (RLU), based on triplicate measurements from
one of the representative experiments (n=3).

Figure 3. Isochamaejasmin induces NF-κB activation independently of FPRL1. A, HeLa
cells (without FPRL1) were transiently transfected with vector (pcDNA3.1, control) or FPRL1 in
pcDNA3.1, together with the 5×NF-κB luciferase reporter plasmid and a constitutive β-
galactosidase expression construct. Forty-three hours after transfection, the cells were stimulated
with or without isochamaejasmin (169, 1 μM) for 5 hours. The expressed luciferase activity was
normalized against the activity of β-galactosidase and shown as relative luciferase activity (RLA;
means±SD based on duplicate measurements; n=3). Functional expression of FPRL1 was
confirmed by its response to WKYMVm in NF-κB luciferase reporter assay (data not shown). B,
calcium mobilization in RBL-FPRL1 cells in response to isochamaejasmin (169, 1 μM), and to
WKYMVm (W-pep, 100 nM), which was used as a positive control. C, chemotaxis of RBL-
FPRL1 in response to WKYMVm (left panel) and isochamaejasmin (169, right panel) at various
concentrations. Data shown are means±SEM from quadruplicate measurements.

Figure 4. Nuclear translocation of NF-κB and involvement of IκBα. A, HeLa cells were stimulated with vehicle (buffer with 1% DMSO, control, Ctl, upper panel), isochamaejasmin (169, 20 μM, middle panel), or neochamaejasmin A (168, 20 μM, lower panel). After 40 minutes, the cells were fixed and stained with an antibody against p65/RelA (see *Materials and Methods*) for visualization of NF-κB translocation (arrows in the middle panel). The left column was stained with Hoechst for nuclei, the center column represents NF-κB staining, and the right column is combined images of both. Approximately 35% of the cells in isochamaejasmin (169)-stimulated samples showed nuclear staining of the NF-κB protein as compared to less than 10% in the unstimulated or neochamaejasmin A (168)-stimulated samples. B, the isochamaejasmin-induced NF-κB activation involves IκBα. HeLa cells were transiently transfected with the 5×NF-κB luciferase reporter construct together with one of the following: a pcDNA3.1 vector (control), a dominant negative (DN) construct of IκBα (IκBαm), a dominant negative IKKα construct, and a dominant negative IKKβ construct. Forty-three hours after transfection, the cells were stimulated with isochamaejasmin (169, 1 μM) or buffer (vehicle) for 5 hours. Measurement of the luciferase activity and normalization were made as described in the legend for Figure 3A. RLA, relative luciferase activity (as defined in *Materials and Methods*). A representative set of data from 3 experiments was shown as mean±SD, based on duplicate measurements.

Figure 5. A role of PKC in isochamaejasmin-induced NF-κB activation. A, HeLa cells were transiently transfected with the 5×NF-κB luciferase reporter as described above. After 43 hours, the cells were treated with buffer (control) or with isochamaejasmin (169, 1 μM). Some samples were pretreated for 10 min with the PKC inhibitors GF109203X (0.1 μM), Gö6976 (0.1 μM), or rottlerin (20 μM) as indicated. The normalized luciferase reporter activities were shown as mean±SD based on two independent experiments, each with duplicate samples. B, phosphorylation of PKCδ as detected in total cell lysate prepared from isochamaejasmin (1 μM)-stimulated HeLa cells. The samples were blotted with an anti-phospho-PKCδ antibody recognizing the phosphorylated Thr505. Loading control was shown in the lower panel with an antibody against total PKCδ.

Figure 6. Isochamaejasmin-induced activation of ERK1/2 and p38, and their involvement in the induction of NF-κB activity. HeLa cells were stimulated with isochamaejasmin (1 μM) for the indicated time. Cell lysate was prepared, electrophoresed, transferred to membrane, and blotted with an anti-phospho-ERK1/2 antibody (A) or anti-phospho-p38 antibody (B). These experiments were repeated at least 3 times and one representative blot from each is presented. C, transiently transfected HeLa cells expressing the NF-κB luciferase reporter were pretreated with the p38 inhibitor SB203580 (10 μM), the MEK inhibitor U0126 (5 μM), or both for 10 minutes. Buffer treatment was served as control (first two samples). The cells were then stimulated with isochamaejasmin (169, 1 μM) or buffer (control) for 5 hours. The expressed luciferase reporter activity was normalized against β-galactosidase activity (relative luciferase activity, RLA) and shown as means±SD from duplicate samples, based on two separate experiments.

Figure 7. Comparison of the cytotoxic effects of isochamaejasmin and other biflavonoids.
HeLa cells (3×10^3 per well in 96-well plate) were cultured in the presence of serial dilutions of the biflavonoids for 48 hours at 37°C. MTT was added for 2 hours and formazan extracted with DMSO for absorbance measurement at 560 nm. The cell viability is shown as percentage change in cell numbers (means±SEM from triplicate samples), based on two separate experiments.

Figure 8. Rescue of cycloheximide-induced apoptosis by isochamaejasmin and its association with NF-κB activation. HeLa cells (3×10^3 per well in 96-well plate) were cultured in the presence of cycloheximide (CHX, 5 μg/ml) alone, or cycloheximide plus various concentrations of isochamaejasmin, for 24 hours at 37°C (A). A peptide inhibitor of NF-κB, SN50, or the negative control peptide (SN50M) were added 30 minutes prior to the above reagents (B). MTT assay was performed thereafter. The cell viability is shown as percentage change in cell numbers (means±SEM from triplicate samples), based on three separate experiments. *$p<0.05$ and **$p<0.01$ compared with cycloheximide-treated panel; [#]$p<0.05$ compared with the cycloheximide plus 169 treated panel (Student t-test).

Tables

Table 1

Stereo-configuration and bioactivity of the 4 biflavonoids isolated from *Stellera chamaejasme* L.

Compound	Configuration at				Purity (HPLC)	NF-κB activation
	C2	C3	C2''	C3''		
Isochamaejasmin (169)	S	R	R	S	98.67%	+
Neochamaejasmin A (168)	S	S	S	S	99.83%	-
Neochamaejasmin B (548)	S	S	S	S	100.00%	-
Chamaejasmin B (549)	S	S	R	S	90.72%	-

Figure 1

A

B Isochamaejasmin (NPLC0169)

C Neochamaejasmin A (NPLC0168)

D Neochamaejasmin B (NPLC0548)

E Chamaejasmin B (NPLC0549)

Figure 2

Figure 3

Figure 5

A

B

Figure 7

A

B