Soluble HLA-G1 inhibits angiogenesis through an apoptotic pathway and by direct binding to CD160 receptor expressed by endothelial cells

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HLA-G is a major histocompatibility complex class Ib molecule whose constitutive tissue distribution is restricted mainly to trophoblast cells at the maternal–fetal interface during pregnancy. In this study, we demonstrated the ability of the soluble HLA-G1 (sHLA-G1) isoform to inhibit fibroblast growth factor-2 (FGF2)–induced capillary-like tubule formation. Using a rabbit corneal neovascularization model, we further showed that sHLA-G1 inhibits FGF2-induced angiogenesis in vivo. We also demonstrated that sHLA-G1 induces endothelial cell apoptosis through binding to BYSS/CD160, a glycosylphosphatidylinositol–anchored receptor expressed by endothelial cells. Furthermore, we showed that the specific CL1-R2 anti-CD160 monoclonal antibody mimics sHLA-G1–mediated inhibition of endothelial cell tube formation and induction of apoptosis. Thus, the engagement of CD160 in endothelial cells may be essential for the inhibition of angiogenesis. sHLA-G1/CD160–mediated antiangiogenic property may participate in the vascular remodeling of maternal spiral arteries during pregnancy, and, given that we found that CD160 is strongly expressed in the vasculature of a murine tumor, it offers an attractive therapeutic target for preventing pathologic neovascularization.

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Introduction

HLA-G is a human major histocompatibility complex (MHC) class Ib gene characterized by a unique promoter region, limited polymorphism, restricted constitutive tissue distribution, and several spliced transcripts encoding either membrane-bound or soluble proteins. The soluble HLA-G1 (sHLA-G1) isoform derives from mRNA retaining intron 4, which contains a stop codon that precludes translation of the transmembrane domain. Such intron 4 retention is unique among all HLA class I molecules described to date. This 37-kDa, intron 4–retaining sHLA-G1 isoform associates with preeclampsia,10,11 a common complication of pregnancy in which HLA-G expression in extravillous cytotrophoblasts and maternal spiral arteries is abrogated, compromising blood flow to the maternal interface.12 In addition, it has been shown that HLA-G inhibits the transendothelial migration of NK cells13 and the rolling adhesion of activated NK cells on endothelial cells.14 To date, the potential role of sHLA-G1 in the modulation of angiogenesis has not been addressed.

Angiogenesis, the formation of new capillaries from preexisting blood vessels, is a crucial component of embryonic vascular development and differentiation, wound healing, and organ regeneration. It also contributes to the progression of pathologic conditions that depend on neovascularization, including tumor growth, ischemic ocular disease, and rheumatoid arthritis.

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Although the most important mediators of angiogenesis, the vascular endothelial growth factor (VEGF) and the fibroblast growth factor (FGF) families, are well defined, angiogenesis is a complex process involving multiple gene products expressed by different cell types, all contributing to an integrated sequence of events.

To test our hypothesis that shLA-G1 is a regulator of endothelial-cell activity, we first investigated its in vitro effect. This study demonstrated that shLA-G1 inhibits FGF2- or VEGF-induced angiogenesis and triggers apoptosis of endothelial cells by interaction with the glycosylphosphatidylinositol (GPI)–anchored CD160 receptor29,30 expressed on endothelial cells. Moreover, in vivo, shLA-G1 abolishes angiogenesis. Interestingly, we show by immunohistochemistry performed ex vivo that CD160 is expressed solely at the vascular level in a mouse tumor model.

Materials and methods

Cells and reagents

Human umbilical vein endothelial cells (HUVECs; Tebu, Le Perray-en-Yvelines, France) and human microvascular endothelial cells (HMVECs; Cambrex, San Diego, CA) were maintained in endothelial basal medium (EBM; Cambrex) supplemented with 5% fetal calf serum (FCS) and 1 ng/mL FGF2 or VEGF-A 165 (R&D Systems, Minneapolis, MN) every other day. SGHEC-7 cells, a HUVEC-derived cell line, and the SGHPL-4 extravillous trophoblast cell line were cultured as previously described.21,22 Human aortic smooth muscle cells (HAOSMCs; Cambrex) were maintained in RPMI supplemented with 10% FCS. Primary human fibroblasts were obtained from skin biopsy specimens of healthy subjects and were grown in Dulbecco modified Eagle medium (DMEM) containing 10% FCS. Human Jurkat T cells and Jurkat transfected with CD160 (Jurkat-CD160) have been previously described.23,24 NK92 is a human NK-cell line expressing CD160.23 CD4+ T cells were purified from human peripheral-blood mononuclear cells using the MACS separation system (Miltenyi Biotec, Auburn, CA). The B-lymphoblastoid cell line 721.221-shLA-G1, a gift from Dr D. Geraghty (Fred Hutchinson Cancer Research Center, Seattle, WA), was obtained by transfection of intron 4 containing shLA-G1 cDNA, as described. The resultant transfected protein corresponded to the shLA-G1 heavy chain noncovalently associated with endogenous β2m. The shLA-G1-β2m fusion monochain (shLA-G1mono) construct was engineered by connecting the last residue of the α3 domain of HLA-G to the first codon of the human β2m sequence through a 15-residue spacer.24 shLA-G1mono was transfected in the HLA class I–negative trophoblast-derived cell line JAR.24 Recombinant shLA-G1 and shLA-G1mono molecules were purified from the corresponding transfected cell-culture supernatants by W6/32 monoclonal antibody (mAb) immunos affinity column and were eluted at basic pH, as described.24 Positive fractions evaluated by HLA–specific ELISA were pooled, whereas adherent cells were harvested by trypsin-EDTA solution to produce a single-cell suspension. The cells were then pelleted by centrifugation and washed twice with PBS. Apoptotic cell death was identified by double staining with FITC-conjugated annexin-V and PI using the annexin V/PI assay, 2×10^5 cells were seeded into a 6-well plate in RPMI 1% FCS for 24 hours and then incubated for an additional 12 hours in RPMI 0.5% FCS. Cells were left untreated or were treated with shLA-G1 (1 μg/mL), mAb CD160 (10 μg/mL), or control IgG1 (10 μg/mL) for 50 hours in the presence of VEGF (50 ng/mL). At the end of the treatment, the floating cells were collected by centrifugation, and the total length of the capillaries in each field of view, 40 cells were randomly chosen. The experiments were repeated at least 4 times. Apoptotic cells were scored according to the time at which clear apoptotic morphology was first observed.21,22 For the annexin V/PI assay, 2×10^5 cells were seeded into a 6-well plate in RPMI 1% FCS and PI staining was repeated at least 4 times.

Western blot analysis of cleaved PARP expression

SGHEC-7 endothelial cells were seeded in culture plates. After 16 hours, the cells were incubated with shLA-G1 (0.1 μg/mL) for 60 hours. Cells were lysed in RIPA buffer with 0.1 mg/mL PMSF, 30 μL/mL aprotinin (Sigma A6279 solution at 5-10 trypsin-inhibitor U/mL Sigma, Gillingham, United Kingdom), and 1 mM sodium orthovanadate at 4°C for 30 minutes. Equal amounts of proteins determined by Bradford assay were loaded and transferred to nitrocellulose membrane. After incubation in blocking buffer for 1 hour at room temperature, the membrane was incubated with rabbit polyclonal anti–human cleaved PARP (Promega, Southampton, United Kingdom) for 1 hour. Anti–rabbit IgG peroxidase (A6154; Sigma) was added for 1 hour. Detection of membrane-bound mAb was carried out by chemiluminescence (ECLPlus; Amersham Biosciences, Balfont, United Kingdom). Autoradiography after stripping and reprobing the blot confirmed equal loading.
Rabbit corneal angiogenesis assay

The corneal pocket assay used in this study has been previously described. Male New Zealand albino rabbits were anesthetized. A corneal pocket was created by incision on the superior side of the corneal stroma 2 mm from the limbus. Slow-releasing implants of hydrogel hydrated with PBS containing FGF2 (500 ng) were inserted into this pocket. Twenty-four and 72 hours after pellet implantation, 5 μg sHLA-G1 (1 ng/mL in PBS) or an equal volume of PBS (control) was injected into the subconjunctiva on the superior side near the limbus. Neovascularization of the cornea was measured on day 8 after implantation by microscopic examination with a slit lamp and was scored according to a 5-grade scale (grade 0, normal avascular cornea; grade 1, less than 1-mm–long neovessels; grade 2, 1-mm–long neovessels; grade 3, 1- to 2-mm–long neovessels; grade 4, neovessels extending to the implant). The average mean score obtained after implantation of a pellet containing no angiogenic factor was less than 0.5. Mean ± SD was determined on 8 implants per group.

VEGF and sHLA-G1 cell-binding competition experiments

VEGF and sHLA-G1 were radiolabeled with Na125I to a specific activity of 2.4 × 106 and 1.1 × 105 cpm/ng, respectively. Wells containing 2 × 105 serum-starved HUVECs were untreated or were pretreated with VEGF (0.1 μg/mL) or FGF2 (0.1 μg/mL) or sHLA-G1 (0.1, 1.0, or 10 μg/mL) at 37°C for 24 hours or were processed immediately for binding assays. Briefly, dishes were rinsed in cold DMEM supplemented with 0.2% gelatin and 20 mM HEPES (pH 7.3) and were incubated at 4°C for 2 hours with 2 ng/mL 125I-VEGF or 125I-sHLA-G1 in the absence or presence of indicated concentrations of cold competitors. Cells were then rinsed in the same medium and lysed in 0.02 M Tris, 10 mM EDTA, 0.3 M NaCl, 0.1% SDS, 1% Triton X-100, and 0.05% Tween 20 RIPA buffer, and radioactivity was counted in a γ counter.

Cell phenotyping

Subconfluent HUVECs, HVMECs, HAOSMCs, or fibroblasts were scraped in PBS-EDTA and incubated in the presence or absence of 0.1 μg/mL HLA-G1 at 4°C. After 2 hours, cells were incubated with anti-CD8, anti-CD85d, anti-CD85j, or CL1-R2 anti-CD160–specific mAbs or immunoglobulin-isotype control (20 μg/mL) or FGF2 (0.1, 1.0, or 10 ng/mL) for 24 hours. Cells were then stained with biotin-labeled goat anti–mouse IgG and avidin–biotin complex (Vector Laboratories). They were stained with DAB (Vector Laboratories), counterstained with hematoxylin, viewed under a microscope (E-800; Nikon, Tokyo, Japan), and digitized with a DMX 1200 camera (Nikon) equipped with a Nikon Plan Fluor 40×/0.75 numeric aperture (NA) objective. Images were acquired using Nikon ACT-1 software version 2.63 and were processed using Explora Nova Macrowriter T1.20 software (Explora Nova, La Rochelle, France).

Statistical analysis

Where applicable, results were presented as mean ± SEM or SD of “n” independent experiments and were assessed with the Mann–Whitney U test, analysis of variance, or Student t test, as appropriate, and Easierstat (SAS Institute, Cary, NC) or Prism (GraphPad, San Diego, CA) software; P values of less than .05 were considered significant.

Results

sHLA-G1 inhibits FGF2-mediated capillary tube formation

We investigated whether sHLA-G1 heavy chain noncovalently associated with β2m could interfere with proangiogenic factor functions in vitro. We evaluated the capacity of sHLA-G1 to inhibit capillary tube formation by endothelial cells cultured on Matrigel. Purified recombinant sHLA-G1, when added exogenously to HUVECs, significantly inhibited FGF2-induced tubule-like formation (morphology [Figure 1A] and quantification [Figure 1B]). In contrast, the sHLA-G1 mono–negative control had no effect. These findings indicated that sHLA-G1 inhibits in vitro proangiogenic factor–mediated endothelial-cell capillary tube formation.

sHLA-G1 induces apoptosis of endothelial cells

Having shown the inhibitory effect of sHLA-G1 on a function relevant to angiogenesis (tube formation), we then used apoptosis

![Figure 1. sHLA-G1 inhibits FGF2-mediated HUVEC capillary tube-like formation.](image)
assays to interrogate the possible mechanisms by which sHLA-G1 altered the end point of angiogenesis. Apoptosis is indeed an important regulator of angiogenesis.33 We found that incubation of HUVECs with recombinant sHLA-G1 clearly induced apoptosis, as determined by time-lapse digital image microscopy (Figure 2). Phase-contrast images of the experiment (Figure 2A) and supplemental video data (Video S1: sHLA-G1; Video S2: control) show that sHLA-G1-treated cell morphology was characterized by cytoplasmic and nuclear shrinkage, by a change to a phase-bright appearance, and by the formation of membrane blebs/blisters (Figure 2A). Such an effect of sHLA-G1, but not of sHLA-G1mono, was time dependent (Figure 2B). Comparable kinetics curve was obtained using SGHEC-7 cells (data not shown). The endothelial-cell type specificity of this sHLA-G1–induced apoptosis was demonstrated by the absence of any significant effect of this molecule on human trophoblast cells (Figure 2C). Use of the broad-spectrum caspase inhibitor zVAD-fmk prevented recombinant sHLA-G1–mediated apoptosis (Figure 2D), implicating the caspase pathway in the sHLA-G1–mediated apoptosis of endothelial cells. This was further demonstrated by the detection of cleaved poly (ADP-ribose) polymerase (PARP) by Western blot analysis after sHLA-G1 treatment of endothelial cells (Figure 2E). By contrast, no p85-cleaved PARP was detected after a similar sHLA-G1 treatment of trophoblast cells (Figure S2). These findings together demonstrated that sHLA-G1 induced caspase-dependent apoptosis of endothelial cells.

sHLA-G1 inhibits corneal angiogenesis in vivo

A rabbit corneal pocket assay was used to determine whether sHLA-G1 could also inhibit angiogenesis in vivo. Neovascularization arose from the limbus toward the FGF2-containing pellet and was easily detected after 8 days in the control corneas (Figure 3A, left). In contrast, the injection of sHLA-G1 (Figure 3A, right) almost totally abrogated corneal neovascularization. These results, reproduced on 8 implants per group (Figure 3B), clearly demonstrated that sHLA-G1 had an antiangiogenic effect on FGF2-induced angiogenesis in vivo.

sHLA-G1 binds directly to the CD160 receptor

It was then important to identify the receptor involved in the antiangiogenic effects of sHLA-G1. We first tested whether sHLA-G1 interfered with VEGF receptors by performing radioreceptor assay–binding experiments at 4°C on HUVECs incubated for 2 hours (equilibrium time) with 125I-VEGF or 125I-sHLA-G1 in the presence of various concentrations of cold competitors. We analyzed the binding of 125I-sHLA-G1 to HUVECs and found that cold VEGF or PFG2 competitors had no effect, whereas unlabeled sHLA-G1 inhibited this binding as a function of concentration, with IC50 values in the nanomolar range (Figure 4A). In competition experiments using 125I-VEGF as ligand, we found that cold VEGF displaced its binding to HUVECs with IC50 values in the nanomolar range, whereas sHLA-G1 had no effect (Figure 4B).
Furthermore, we found that cold sHLA-G1 competitor did not inhibit the binding of 125I-VEGF to porcine aortic endothelial cells (PAECs)–VEGF-R2 or PAEC-NPL1 transfectants (data not shown). These results demonstrate that sHLA-G1 bound specifically to endothelial cells without interfering with the VEGF receptors.

With the use of flow cytometry and specific mAbs, we investigated whether HUVECs expressed some of the HLA-G receptors described to date, including CD8, ILT4/CD85d, ILT2/CD85j, and CD160. We found that HUVECs expressed CD160, though not at constant levels, but not CD8, CD85d, or CD85j (Figure 5A). Similarly, HMVECs bound anti-CD160 mAb (Figure 5A), as did bovine endothelial cells (data not shown), suggesting that the CD160 epitope recognized by this mAb was conserved among species. In contrast, smooth muscle cells and fibroblasts in primary culture did not express CD160 (Figure 5A). To confirm that CD160 is expressed by HUVECs, we performed reverse transcription–polymerase chain reaction (RT-PCR) analysis with CD160-specific primers. We demonstrated that the CD160 mRNA was present in HUVECs, as in the NK92-cell line, whereas CD4+ T cells were negative (Figure 5B). It should be noted that HUVECs did not express the potential HLA-G receptor KIR2DL4 transcripts (data not shown). Then HUVECs and NK92 cDNA were isolated and sequenced. Predicted amino acid sequence alignment of HUVECs and NK92 CD160 proteins showed that they were both similar to the CD160 sequence already published, with the exception of 2 substituted residues (Figure 5C), indicating a possible allelic form.

We then investigated whether CD160 was also expressed on endothelial cells in vivo and did not result from culture conditions.

For this purpose, Lewis lung carcinoma cells were injected subcutaneously in C57/BL6 mice. Immunohistochemical analysis of the tumor was performed on day 21 with the CL1-R2 anti-CD160 mAb. We found that this mAb strongly stained endothelial cells of microvessels at the periphery of the tumors (Figure 6A-B) and inside them (Figure 6C-D), whereas no staining was detected with IgG isotype control (data not shown). In contrast, tumor cells remained unstained. Such reactivity of this anti–human CD160 mAb was not surprising because the previous identification and sequencing of human and mouse CD160 encoding cDNA revealed a strong homology between the 2 species. We then analyzed whether sHLA-G1 could effectively bind to the CD160 receptor expressed by endothelial cells. We first found that an HLA-G1 tetramer specifically bound to HUVECs as it did on CD160-transfected Jurkat, but not on parental Jurkat, cells (Figure 7A). sHLA-G1–CD160 direct interaction on HUVECs was further demonstrated by showing that preincubation of HUVECs with recombinant sHLA-G1 specifically blocked the binding of anti-CD160 mAb (Figure 7B), whereas preincubation with VEGF did not (data not shown).

To further demonstrate that sHLA-G1 antiangiogenic function was mediated through interaction with CD160, we tested whether soluble anti-CD160 mAb could antagonize or mimic sHLA-G1 activity in the in vitro Matrigel tube and apoptosis assays. The results clearly showed that CL1-R2 mAb mimicked sHLA-G1 because it inhibited FGF2-mediated tubule vessel growth (Figure 7C) and induced HUVEC apoptosis, as demonstrated by annexin V/PI assay (Figure 7D) and time-lapse microscopy (data not shown and Figure 2). CD160 mAb–mediated apoptosis of HUVECs was similar to sHLA-G1–mediated apoptosis, whereas none of these apoptosis inducers were active on control fibroblast cells in primary culture (Figure 7D) or on trophoblast cells (Figure 2C). Altogether, these data further demonstrated that CD160 expressed by endothelial cells is a functional receptor able to trigger an antiangiogenic cell response.

**Discussion**

In this study, we demonstrated that the sHLA-G1 molecule, known to exert immune regulatory function, also displays antiangiogenic properties in vitro and in vivo. This included the inhibition of vessel formation, the induction of endothelial cell apoptosis, and the in vivo inhibition of FGF2-induced rabbit corneal neangiogenesis. Spatial and temporal regulation of the vasculature at the
maternal–fetal interface plays an important role in ensuring adequate blood supply to nourish the developing embryo, suggesting that locally acting factors regulate vascular cells. The ability of sHLA-G1 to induce apoptosis of confluent and proliferating endothelial cells might be relevant in the utero-placental environment because effacement of preexisting maternal endothelial cells rather than inhibition of angiogenesis would be required. Soluble HLA-G1 is indeed secreted by endovascular trophoblasts that replace vascular cells of the maternal spiral arteries, thereby increasing the diameter of these vessels several fold and transforming them into high-conductance vessels. We hypothesize that during early pregnancy, sHLA-G1 apoptotic effects on these maternal endothelial cells might contribute to such replacement and vascular remodeling. Defects of HLA-G expression, including diminishment of soluble HLA-G in preeclamptic placentas characterized by a shallow cytotrophoblast invasion and a reduced flow of maternal blood to the feto-placental unit, favor such a hypothesis. A recent report using an ex vivo model of maternal spiral artery perfused with extravillous cytotrophoblast has shown that adding these cells induced the apoptosis of endothelial cells. Knowing that extravillous cytotrophoblasts do produce sHLA-G might lead to the conclusion that such apoptosis is mediated by sHLA-G.

Different mechanisms have been reported to explain the activity of angiogenesis inhibitors, including inhibition of endothelial-cell remodeling, induction of endothelial-cell apoptosis, or chemorepulsion of endothelial cells. In this report, we demonstrate novel inhibitory actions of sHLA-G1 directed to endothelial cells. In addition, we report that sHLA-G1–treated endothelial cells progressively showed apoptotic morphology. The mechanism of this induced apoptosis remains incompletely characterized despite clear implication of caspases (Figure 2D-E). The Fas/FasL pathway might also be involved, as it has been shown for the sHLA-G1–induced apoptosis of activated CD8+ T cells. It is interesting that a role for apoptosis and Fas/FasL interactions in the remodeling of uterine arteries during pregnancy has recently been demonstrated.

In this study, we also used the sHLA-G1–β2m fusion monochain (sHLA-G1mono) as a negative control molecule prepared and purified exactly like the conformational sHLA-G1. This control molecule did not exhibit antiangiogenic activities in the assays described in this report. It is unlikely that the conformation of this construct was grossly altered because the W6/32 conformational mAb still recognized it (see “Materials and methods”). However, it is possible that the presence of a β2m-linked 15-residue spacer to sHLA-G1 heavy chain impairs the formation of sHLA-G1mono multimers. The oligomerization of sHLA-G1 is essential for its activity and efficient recognition by CD85j/ILT2 receptors, which might explain the unresponsiveness of sHLA-G1mono, which might not bind to CD160 for the same reason. This hypothesis is supported by the recently published crystal structure of the HLA-G protein presenting a model of HLA-G oligomers and the relative position of the CD85j/ILT2 receptor near the complex. It has also been shown that HLA-G can be found as a free heavy chain because of the dissociation of β2m from the conformed protein. Moreover, β2m-free HLA-G and conform HLA-G can form complexes able to modulate HLA-G affinity to some NK receptors. In the sHLA-G1mono construct, the β2m is covalently linked.
linked to the HLA-G1 heavy chain. Such a mechanism of dissociation of the β2m from the heavy chain would thus be impossible, and this might contribute to the inefficiency of sHLA-G1 mono to activate CD160 present on endothelial cells.

The direct inhibitory effect of sHLA-G1 on vessel formation is most likely mediated through the functional CD160 receptor because the CL1-R2 anti-CD160 mAb mimics the inhibition of FGF2-induced capillary tubule formation by endothelial cells cultured in Matrigel and the induction of endothelial cell apoptosis. sHLA-G1 acts directly on CD160 receptor. Given that various HLA class I molecules may bind to CD160, it cannot be excluded that other soluble MHC class I molecules could also trigger this receptor to exert antiangiogenic functions. Collectively, these findings provide important mechanistic insight into the antiangiogenic action of sHLA-G1. Further investigation is needed to determine and compare the signaling pathways used by endothelial cells and NK cells after CD160 engagement and leading to antiangiogenic activities and endothelial cell apoptosis for the former and cytokine production for the latter.

In addition to the clear importance in the placental/uterine environment, the identification of CD160 as an inhibitory signaling receptor for angiogenesis could be useful for experimental antiangiogenic therapy to prevent tumor cell growth. Our immunohistochemical analysis of a mouse-grafted tumor showed that CD160, encoded by a gene conserved in this species, was present in endothelial cells of the tumor vasculature but was not expressed by tumor cells. Future goals are to examine the potential CD160/sHLA-G1–mediated antiangiogenic effect in different tumors and to explore the possible therapeutic use of CD160 mAb in the regulation of pathologic neovascularization.

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