



**HAL**  
open science

## **Bone morphogenetic protein-9 is a circulating vascular quiescence factor.**

Laurent David, Christine Mallet, Michelle Keramidas, Noël Lamandé, Jean-Marie Gasc, Sophie Dupuis-Girod, Henri Plauchu, Jean-Jacques Feige, Sabine Bailly

► **To cite this version:**

Laurent David, Christine Mallet, Michelle Keramidas, Noël Lamandé, Jean-Marie Gasc, et al.. Bone morphogenetic protein-9 is a circulating vascular quiescence factor.: BMP9 is present in serum and inhibits angiogenesis. *Circulation Research*, 2008, 102 (8), pp.914-22. 10.1161/CIRCRESAHA.107.165530 . inserm-00277236

**HAL Id: inserm-00277236**

**<https://inserm.hal.science/inserm-00277236>**

Submitted on 29 Aug 2008

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1  
2 BMP9 IS A CIRCULATING VASCULAR QUIESCENCE FACTOR  
3 Running title: BMP9 is present in serum and inhibits angiogenesis  
4 Laurent David<sup>1,2,3</sup>, Christine Mallet<sup>1,2,3</sup>, Michelle Keramidas<sup>1,2,3</sup>, Noël Lamandé<sup>4</sup>,  
5 Jean-Marie Gasc<sup>4</sup>, Sophie Dupuis-Girod<sup>5,6,7</sup>, Henri Plauchu<sup>5,6,7</sup>, Jean-Jacques  
6 Feige<sup>1,2,3</sup> and Sabine Bailly<sup>1,2,3</sup>

7 <sup>1</sup>Institut National de la Santé et de la Recherche Médicale, U878, 17 rue des Martyrs, 38054  
8 Grenoble, France;

9 <sup>2</sup>Commissariat à l'Energie Atomique, Institut de Recherches en Technologies et Sciences  
10 pour le Vivant/LAPV, Grenoble, France;

11 <sup>3</sup> Université Joseph Fourier, Grenoble, France;

12 <sup>4</sup>Institut National de la Santé et de la Recherche Médicale Unité 833, Collège de France,  
13 Paris, France;

14 <sup>5</sup>Hospices Civils de Lyon, France;

15 <sup>6</sup>Hôpital Hôtel-Dieu, Lyon, France;

16 <sup>7</sup>Département de Génétique Clinique and Centre National de Référence pour la maladie de  
17 Rendu-Osler, Lyon, France.

18 **Corresponding author:** Sabine Bailly, U878, iRTSV/LAPV, 17 rue des Martyrs, 38054  
19 Grenoble, France. Tel: (33) 4 38 78 92 14; Fax: (33) 4 38 78 50 58; E-mail: [sbailly@cea.fr](mailto:sbailly@cea.fr)

20 Subject codes: 97,129,138,147,17.

This is an un-copied author manuscript that was accepted for publication in *Circulation Research*, copyright The American Heart Association. This may not be duplicated or reproduced, other than for personal use or within the "Fair Use of Copyrighted Materials" (section 107, title 17, U.S. Code) without prior permission of the copyright owner, The American Heart Association. The final copyedited article, which is the version of record, can be found at <http://circres.ahajournals.org>. The American Heart Association disclaims any responsibility or liability for errors or omissions in this version of the manuscript or in any version derived from it

## 1 Abstract

2 Angiogenesis is a complex process, requiring a finely tuned balance between numerous  
3 stimulatory and inhibitory signals. ALK1 is an endothelial-specific type 1 receptor of the  
4 TGF $\beta$  receptor family. Heterozygotes with mutations in the ALK1 gene suffer from  
5 Hereditary Hemorrhagic Telangiectasia type 2 (HHT2). Recently, we reported that BMP9 and  
6 BMP10 are specific ligands for ALK1 that potently inhibit microvascular endothelial cell  
7 migration and growth. These data lead us to suggest that these factors might play a role in the  
8 control of vascular quiescence. To test this hypothesis, we checked their presence in human  
9 serum. We found that human serum induced Smad1/5 phosphorylation. In order to identify  
10 the active factor, we tested neutralizing antibodies against BMP members and found that only  
11 the anti-BMP9 inhibited serum-induced Smad1/5 phosphorylation. The concentration of  
12 circulating BMP9 was found to vary between 2 and 12 ng/ml in sera and plasma from healthy  
13 humans, a value well above its EC<sub>50</sub> (50 pg/ml). These data indicated that BMP9 is circulating  
14 at a biologically active concentration. We then tested the effects of BMP9 in two *in vivo*  
15 angiogenic assays. We found that BMP9 strongly inhibited sprouting angiogenesis in the  
16 mouse sponge angiogenesis assays and that BMP9 could inhibit blood circulation in the  
17 chicken chorioallantoic membrane assay. Taken together, our results demonstrate that BMP9,  
18 circulating under a biologically active form, is a potent anti-angiogenic factor that is likely to  
19 play a physiological role in the control of adult blood vessel quiescence.

20

21 Key words: BMP9, ALK1, HHT, angiogenesis

1

## 2 Introduction

3

4 Bone morphogenetic proteins (BMPs), which belong to the TGF $\beta$  superfamily, were  
5 originally identified as inducers of ectopic bone growth and cartilage formation. Since then,  
6 there has been substantial progress in our knowledge of the multiple functions of these growth  
7 factors<sup>1</sup>. BMPs regulate cell growth, differentiation and apoptosis of various cell types, and  
8 they are critically important in the morphogenesis and differentiation of tissues and organs.  
9 BMP9, also known as GDF2, is expressed in the adult liver by non-parenchymal cells (i.e.  
10 endothelial, stellate, and Kupffer cells)<sup>2</sup> and in the septum and spinal cord of mouse  
11 embryos<sup>3</sup>. BMP9 has been described as a hematopoietic, hepatogenic, osteogenic and  
12 chondrogenic factor. It has also been identified as a regulator of glucose metabolism, capable  
13 of reducing glycaemia in diabetic mice and as a differentiation factor for cholinergic neurons  
14 in the central nervous system<sup>3</sup>. More recently, it was shown to induce the expression of  
15 hepcidin, an hormone that plays a key role in iron homeostasis<sup>4</sup>.

16 ALK1 (activin receptor like-kinase 1) is an endothelial-specific type I receptor of the  
17 TGF $\beta$  receptor family that is implicated in the pathogenesis of Hereditary Hemorrhagic  
18 Telangiectasia type 2 (HHT2) also known as the Rendu-Osler disease type 2 (RO2)<sup>5</sup>. The  
19 disease is an autosomal dominant vascular disorder characterized by recurrent nosebleeds,  
20 cutaneous telangiectases, and arteriovenous malformations in the lungs, brain, liver and  
21 gastrointestinal tract<sup>6</sup>. The majority of cases are caused by mutations in either endoglin (*ENG*)  
22 or ALK1 (*ACVRL1*) genes, thus defining HHT1 and HHT2, respectively. Mutations in  
23 *SMAD4* are seen in patients with the combined syndrome of Juvenile Polyposis (JP) and HHT  
24 (JP-HHT)<sup>7</sup>. Despite the identification of these mutations as the causative factor in HHT, the  
25 mechanism by which these mutations cause the HHT phenotype remain unclear.

1 ALK1 is one of seven known type I receptors for TGF- $\beta$  family members<sup>8</sup>. Signaling  
2 through the TGF $\beta$  receptor family occurs via ligand binding to heteromeric complexes of type  
3 I and type II serine/threonine kinase receptors<sup>9</sup>. The type I receptor determines signal  
4 specificity in the receptor complexes. Activation of ALK1 induces phosphorylation of  
5 receptor-regulated Smad1, 5 and 8<sup>10</sup>, which assemble into heteromeric complexes with the  
6 common partner Smad4. These heteromeric complexes translocate to the nucleus, where they  
7 regulate the transcription of target genes.

8 ALK1 has long been known as an orphan type I receptor of the TGF $\beta$  family  
9 predominantly present on endothelial cells. Subsequently, TGF $\beta$ 1 and 3, primarily known as  
10 ligands for ALK5, were also shown to bind ALK1, albeit only in the presence of ALK5<sup>11</sup>. In  
11 2005, a publication describing the crystal structure of BMP9 reported that BMP9 specifically  
12 binds biosensor-immobilized recombinant ALK1 and BMPRII extracellular domains<sup>12</sup>. More  
13 recently, we demonstrated that BMP9 and BMP10 are potent ligands for ALK1 on human  
14 dermal microvascular endothelial cells<sup>13</sup> and this was since confirmed by another group<sup>14</sup>.  
15 BMP9 is very potent ( $EC_{50} = 2$  pM) and, in contrast to TGF $\beta$ 1 or 3<sup>11</sup>, induces a very stable  
16 Smad1/5/8 phosphorylation over time<sup>13</sup>. Interestingly, another ALK1 ligand, distinct from  
17 TGF $\beta$ 1 and TGF $\beta$ 3 and that could signal in the absence of ALK5 or TGF $\beta$ RII, had been  
18 previously described in human serum, but not identified<sup>15</sup>. The aim of the present work was to  
19 identify this circulating ALK1 ligand. Here we demonstrate that BMP9 is indeed the ALK1  
20 ligand present in human serum. BMP9 circulates in a biologically active form at a  
21 concentration of 2-12 ng/ml. Furthermore, we report that BMP9 is a potent inhibitor of  
22 angiogenesis and a regulator of vascular tone.

## 23 24 Materials and Methods

1 An expanded materials and methods is available in the online data supplement at  
2 <http://www.circresaha.org>.

3  
4 **DNA transfection and dual luciferase activity assay**

5 NIH-3T3 cells were transfected as previously described<sup>13</sup>. Firefly and renilla luciferase  
6 activities were measured sequentially with the Dual-Luciferase reporter assay (Promega).  
7 Results are expressed as ratios of firefly luciferase activity over renilla luciferase activity.  
8 (See the online data supplement).

9 **Purification of the ALK1 ligand from human serum**

10 250 ml of human serum (pool of human sera from about 250 different individuals, Cambrex)  
11 were diluted with 250 ml PBS (Phosphate Buffer Saline 0.15 M, pH 7.4) and purified through  
12 five different steps as detailed in the online data supplement.

13 **Western blot analysis**

14 Western blots were performed as previously described<sup>13</sup>. (See the online data supplement).

15 **Blood donors**

16 Between December 2006 and July 2007, blood samples (7 ml) were taken from 20 patients (8  
17 women, 12 men, mean age of  $44 \pm 12$  years) with clinical features of HHT (13 with *ACVRL1*  
18 mutations, 2 with *ENG* mutations and 5 with unidentified mutations) and 20 healthy  
19 volunteers (8 women, 12 men, mean age of  $44 \pm 10$  years) from which serum or plasma (K3E  
20 tubes, Becton Dickinson, Pont de Claix, France) were obtained. Serum and plasma aliquots  
21 were frozen at  $-20^{\circ}\text{C}$ . Informed consent was obtained from all blood donors. The  
22 investigation conformed to the principles outlined in the Helsinki declaration. The donors  
23 were randomly assigned a number. Patients were considered to be affected by HHT if they  
24 had at least three out of the four Curaçao consensus criteria<sup>16</sup>: epistaxis, telangiectases,  
25 visceral lesions and family history of HHT disease.

26 **Chorioallantoic Membrane (CAM) Assay**

1 The effect of BMP9 on vascularization in the chick chorionallantoic membrane was studied as  
2 described in the online data supplement.

### 3 **Mouse subcutaneous sponge angiogenesis assay**

4 The effect of BMP9 on neovascularization in the mouse sponge assay in response to FGF-2  
5 was studied as described in the online data supplement.

### 6 **Statistics**

7 Statistical analysis was performed using a Mann Whitney test (\*\*:  $p < 0.01$ ; \*:  $p < 0.05$ ).

## 9 **Results**

### 11 **Presence of an ALK1 ligand in human serum that differs from TGF $\beta$**

12 The luciferase reporter construct (BRE, BMP Responsive Element) which contains repeated  
13 sequences from the Id1 promoter has been developed to specifically measure activation of the  
14 Smad1/5/8 pathway<sup>17</sup>. This plasmid, together with an ALK1-expression plasmid, were  
15 transfected in NIH-3T3 cells in order to check for the presence of an ALK1 ligand in human  
16 serum. Treatment of these cells with 2% human serum strongly stimulated luciferase activity  
17 (9 fold, Fig. 1A). In order to determine whether this activity was due to TGF $\beta$ , a pan-specific  
18 TGF $\beta$  neutralizing antibody was added to serum. As shown in Figure 1A, addition of the  
19 neutralizing antibody did not affect serum activity. Furthermore, the addition of recombinant  
20 TGF $\beta$ 1 (0.5 ng/ml) did not activate this reporter gene and actually decreased basal luciferase  
21 expression (Fig. 1A). Heat-treatment, in order to activate the latent TGF $\beta$  present in serum,  
22 did not result in BRE activation (Fig. 1A). We next examined whether human serum could  
23 activate the CAGA promoter, which is known to be specifically activated by the Smad2/3  
24 pathway in response to TGF $\beta$ . We found that human serum caused a small induction of the  
25 CAGA promoter (4 fold), while heat-treated serum and recombinant TGF $\beta$ 1 strongly

1 activated it (17 and 42 fold, respectively, Fig. 1B). These activations were inhibited by the  
2 addition of the pan-specific TGF $\beta$  neutralizing antibody (Fig. 1B). The BRE promoter is  
3 specific for the Smad1/5/8 pathway and therefore can be activated by all the type I receptors  
4 known to phosphorylate these Smads, namely ALK1, ALK2, ALK3 and ALK6. Therefore, in  
5 order to confirm that the activation of BRE by human serum was actually due to ALK1  
6 activation, we tested the ability of the recombinant extracellular domains of these receptors to  
7 interfere with the human serum response. As shown in Fig. 1C, addition of ALK1ecd very  
8 strongly inhibited the human serum response. ALK3ecd and ALK6ecd only slightly inhibited  
9 this response while ALK2ecd had no effect. Interestingly, we could also demonstrate that  
10 soluble endoglin inhibited this biological response (Fig.1C). Taken together, these findings  
11 demonstrate that an ALK1-stimulating ligand, distinct from TGF $\beta$ 1, 2 or 3 is present in  
12 human serum.

### 13 **Purification and molecular weight estimation of the ALK1 ligand from human serum**

14 We next attempted to purify the activating factor from human serum. The factor was purified  
15 approximately 100 fold from 250 ml of human serum, following the purification scheme  
16 shown in Fig. 2A. After five purification steps, the fractions eluting from the Pro-RPC  
17 column were analyzed by SDS-PAGE under non-reducing conditions. The gel lanes  
18 containing the active fractions (23 and 24) were then cut into 6 bands and the proteins in each  
19 band were electroeluted, renatured and tested for ALK1-stimulating activity. The activity was  
20 detected in band 5 which corresponded to an apparent molecular weight comprised between  
21 17 and 28 kDa (Fig. 2B).

### 22 **The ALK1 activity of the human serum is due to BMP9**

23 In a recent work, we have demonstrated that BMP9 is an activating ligand for ALK1<sup>13</sup> and  
24 this was since confirmed by another group<sup>14</sup>. As the apparent molecular weight of the ALK1-  
25 stimulating activity present in human serum appears to lie between 17 and 28 kDa, we

1 hypothesized that this activity could be due to circulating BMP9 (MW 22 kDa). To test this  
2 hypothesis, we utilized a BMP9 neutralizing antibody. This antibody was highly specific as it  
3 completely abolished the BRE-luciferase response to BMP9 while it had no effect on the  
4 BMP10-induced response (BMP10 has the highest sequence homology with BMP9), or on the  
5 BMP2-induced response (Fig. 3A). We then tested this antibody on the ALK1-stimulating  
6 activity in serum and observed nearly complete inhibition of BRE-stimulating activity (Fig.  
7 3B). This was also the case for the purified active fractions (fractions 23 and 24 from Fig. 2A)  
8 from human serum (Fig. 3B). To further confirm that BMP9 is the only active circulating  
9 member of the TGF $\beta$  family present in serum capable of activating the BRE promoter in  
10 ALK1-expressing NIH-3T3 cells, we tested neutralizing antibodies for other BMPs.  
11 Neutralizing BMP2/4 and BMP7 antibodies had no effect on human serum activity (Fig. 3C)  
12 while both inhibited the BRE response to either recombinant BMP2 or BMP7 (Fig. 3D). We  
13 also evaluated whether the circulating BMP antagonist noggin inhibits human serum ALK1-  
14 stimulating activity. We observed that the addition of noggin did not inhibit the ALK1-  
15 stimulating activity from human serum (Fig. 3C) while it inhibited BMP2 or BMP7 activity  
16 (Fig. 3D). We could also demonstrate for the first time that noggin did not inhibit the  
17 induction of BRE activity by recombinant BMP9 (Fig. 3D). Finally, we tested the effects of  
18 the neutralizing BMP9 antibody on serum activation of Smad1/5 phosphorylation in human  
19 microvascular endothelial cells (HMVEC-d). As shown in Figure 3E, human serum induced  
20 rapid and strong Smad1/5 phosphorylation, that could be inhibited in a dose-dependent  
21 manner by the addition of neutralizing anti-BMP9 antibody or by the addition of ALK1ecd.  
22 Taken together these data lead to the conclusion that the ALK1-stimulating activity of human  
23 serum is due to BMP9.

#### 24 **Determination of BMP9 concentration in human serum**

1 Having demonstrated that BMP9 is present in human serum, we also evaluated its presence in  
2 human plasma. We measured BMP9 levels in the sera and the plasma of four healthy  
3 individuals and found similar levels of BRE activity in both biological fluids (Fig. 4A). Using  
4 the BRE luciferase reporter assay and recombinant mature BMP9 (R&D Systems) as a  
5 standard for calibration, we determined that the BMP9 concentration in a pool of human sera  
6 was  $7.5 \pm 0.6$  ng/ml (Fig. 4B). BMP9 binds ALK1 and endoglin<sup>13</sup>, two receptors whose genes  
7 are mutated in HHT. This prompted us to evaluate the serum levels of BMP9 in HHT patients  
8 versus a normal population. Twenty patients with clinical features of HHT were enrolled in  
9 this study. The two populations were matched for gender ratio (8 were female and 12 were  
10 male) and age (mean = 44 years). The study of BMP9 levels in the healthy population  
11 demonstrated a mean level of circulating BMP9 very close to the one found in the pooled  
12 human sera ( $6.2 \pm 0.6$  ng/ml) with a range of variation between 2 and 12 ng/ml (Fig. 4C). As  
13 shown in Fig. 4C, no statistically significant difference in the serum level of BMP9 could be  
14 detected between healthy humans and HHT patients ( $6.2 \pm 0.6$  ng/ml versus  $5.0 \pm 0.7$  ng/ml,  
15 respectively,  $n = 20$ ). Similar data were obtained using plasma (data not shown). Sera that had  
16 high levels of BMP9 (above 8 ng/ml) were tested again in the presence of the neutralizing  
17 anti-BMP9 antibody in order to confirm that all this activity was due to BMP9. The antibody  
18 totally neutralized the activity in all samples (data not shown).

### 19 **BMP9 is a potent inhibitor of angiogenesis *in vivo***

20 We and others have previously demonstrated that BMP9 inhibits endothelial cell migration  
21 and proliferation<sup>13,14</sup>. In addition, it was further demonstrated that BMP9 inhibited *ex vivo*  
22 endothelial cell sprouting from metatarsals<sup>14</sup>. Similarly, we were able to show that BMP9  
23 inhibited endothelial sprouting from embryoid bodies derived of embryonic stem cells  
24 committed to endothelial differentiation (supl. Fig. 1). Taken together these data, suggest that  
25 BMP9 might act as an inhibitor of angiogenesis. To further characterize the anti-angiogenic

1 activity of BMP9, we tested its effect in two *in vivo* angiogenic assays. First, we assessed the  
2 effect of BMP9 in the mouse subcutaneous sponge assay. In this study, Balb-C mice received  
3 under the dorsal skin a cellulose sponge hydrated with FGF-2 or FGF-2 and BMP9. Factors  
4 were re-injected into the sponge on day 1, 2 and 4 as described in Materials and Methods. The  
5 angiogenic response was then assessed on day 7. As shown in Figure 5, BMP9 treatment  
6 clearly inhibited the angiogenic response. This inhibitory effect could be quantitated by  
7 measuring the hemoglobin content of the sponges (Fig. 5B,  $1.23 \pm 0.22$  mg with FGF-2  
8 versus  $0.54 \pm 0.06$  mg with FGF-2 and BMP9,  $p < 0.05$ ). We then looked whether BMP9  
9 addition would also lead to destabilization of already formed vessels. To do this, Balb-C mice  
10 received a cellulose sponge hydrated with FGF-2, which was re-injected into the sponge on  
11 days 1 and 2. Angiogenesis, as measured by hemoglobin levels, was already strong by day 4  
12 (data not shown). BMP9 was then added on day 4, 5 and 6 and the angiogenic response was  
13 assessed on day 7. Interestingly, we found that BMP9 added after the initiation of  
14 angiogenesis by FGF-2 still significantly inhibited this process (Fig. 5C).

15 We also tested the effect of BMP9 in the chick chorioallantoic membrane (CAM) assay that  
16 allows to study fetal neoangiogenesis. BMP9 or the vehicle (PBS, BSA 0.1%) was applied for  
17 24h side by side onto the same CAM on day 9 of embryo development (Fig. 6). Four doses of  
18 BMP9 were tested (5.5, 27.5, 55 and 550 ng). BMP9 treatment impaired in a dose-dependent  
19 manner CAM angiogenesis as seen on photographs (Fig. 6B); this effect was further  
20 confirmed by FITC-Dextran injection (fig. 6C): at low dose (5.5 ng) BMP9 had minimal effect  
21 on the vasculature, at 27.5 ng only the small vessels were affected, and at 55 ng a complete  
22 disappearance of all the vessels is induced. A higher dose of BMP9 (550 ng) produced chick  
23 embryo death 4 to 6 h following its addition (data not shown). Serial cross sections of the  
24 CAM, stained either with hematoxylin/eosin, isolectin (endothelial cells) or anti- $\alpha$  smooth  
25 muscle actin (pericytes), show that this effect of BMP9 was not due to vascular pruning as the

1 number of vessels was not modified (supl Fig. 2A). These results suggested that vessels were  
2 still present but not functional. Indeed, when we follow the effect of BMP9 (550 ng) at earlier  
3 time-points, we could observe constrictions and/or thrombosis of some vessels suggesting that  
4 BMP9 might regulate vascular tone (supl Fig. 2B). These irregularities in vessel diameter are  
5 also observed on CAM cross section after a 24h treatment with BMP9 (55 ng) visualized after  
6 hematoxylin/eosin labeling (supl Fig. 2C).

## 7 8 Discussion

9  
10       Angiogenesis is a complex process, requiring a finely tuned balance between  
11 numerous stimulatory and inhibitory signals. In adulthood most blood vessels remain  
12 quiescent and angiogenesis occurs only in the cycling ovary, in the endometrium and in the  
13 placenta during pregnancy, and during wound healing<sup>18</sup>. This implicates that circulating  
14 quiescence factors must exist in blood. It was previously published that human serum is able  
15 to specifically activate the Smad1/5 pathway, suggesting the presence of active BMPs in  
16 blood<sup>15</sup>. We here report that the Smad1/5-stimulating activity present in human serum is due  
17 to biologically active BMP9. Furthermore, we demonstrate using two *in vivo* angiogenic  
18 assays that BMP9 is a potent inhibitor of angiogenesis. These data lead us to propose that the  
19 circulating anti-angiogenic BMP9 could play a role as a regulator of endothelial quiescence.

20       We found that BMP9 was present at similar levels in both human serum and plasma,  
21 suggesting that circulating BMP9 is derived from plasma rather than from platelets. The  
22 circulating concentration of BMP9 is between 2 and 12 ng/ml, as determined with the BRE  
23 reporter gene assay using recombinant mature BMP9 as a standard, is between 2 and 12  
24 ng/ml. This concentration is well above its  $EC_{50}$  (50 pg/ml, 2 pM), previously determined in  
25 microvascular endothelial cells<sup>13</sup>. In the present work, we showed that human serum activity  
26 could be inhibited by neutralizing BMP9 antibodies and by ALK1 extracellular domain,

1 confirming that this activity is due to a factor that can bind ALK1. We have previously shown  
2 that both BMP9 and BMP10 bind to ALK1<sup>13</sup>. However, we here demonstrate that the  
3 biological ALK1-stimulating activity in human serum is exclusively due to BMP9 and not to  
4 BMP10. The absence of BMP10 in blood is likely due to the pattern of BMP10 expression  
5 that appears to be restricted to the developing and postnatal heart<sup>19</sup>. In contrast, BMP9  
6 expression is high in both embryonic and adult liver<sup>2</sup>, suggesting that this is the likely source  
7 of circulating protein. Other TGF $\beta$  family members known to activate the Smad1/5 pathway  
8 have been previously described in serum or plasma, specifically BMP7 and BMP4<sup>20, 21</sup>.  
9 However, their concentrations are lower (100-400 pg/ml) and their receptor affinities are also  
10 much lower (in the nM range) than the affinity of BMP9 for ALK1 (in the pM range),  
11 suggesting that they are not circulating at biologically active levels. Furthermore, these factors  
12 appear to circulate as inactive complexes associated with antagonists such as noggin<sup>22</sup>. In  
13 contrast, we found that noggin does not inhibit BMP9- or human serum-induced BRE activity  
14 (Fig. 3C and D). This might be another reason why BMP9 is the only active circulating BMP  
15 in healthy human serum under our biological conditions.

16 HHT is a dominantly inherited genetic disorder (mutations of *ACVRL1* or *ENG*), and  
17 haploinsufficiency (reduced amount of functional protein) is likely to be the cause of  
18 associated vessel malformations. One could imagine that the organism could compensate this  
19 haploinsufficiency by increasing the synthesis of the receptor ligand. However, we observed  
20 no significant difference between the serum BMP9 levels of healthy humans and HHT  
21 patients, suggesting that there is no compensation by increased BMP9 in this disease.

22 BMP9 has been previously shown to be a potent regulator of osteogenesis,  
23 chondrogenesis, glucose metabolism, iron homeostasis<sup>4</sup> and a differentiation factor for  
24 cholinergic neurons<sup>3</sup>. In a recent study, we demonstrated that BMP9 is also a potent inhibitor  
25 of endothelial cell proliferation and migration<sup>13</sup>. This was since confirmed by another group

1 who further demonstrated that BMP9 inhibited *ex vivo* endothelial cell sprouting from  
2 metatarsals<sup>14</sup>. In the present work, we confirmed this data in another *ex vivo* endothelial cell  
3 sprouting assay and further demonstrated that BMP9 is an important *in vivo* regulator of  
4 angiogenesis. Using the mouse sponge assay, we could show that BMP9 inhibited  
5 neoangiogenesis in response to FGF-2 but also induced destabilization of already formed  
6 vessels (Fig. 5B and C). This latter point suggests that BMP9 could be a useful tool to target  
7 tumor angiogenesis. Using the CAM assay, we found that BMP9 treatment inhibited blood  
8 circulation in a dose-dependent manner (Fig. 6). This was not due to a decrease in vessel  
9 number but rather to vasoconstrictions and/or thrombosis. This point is interesting as BMP9  
10 signals through BMPRII and that mutations in *BMPRII* have been found responsible for  
11 familial pulmonary hypertension<sup>23</sup>. These data represent the first demonstration of *in vivo*  
12 effects of BMP9 on angiogenesis. As BMP9 is circulating under a biologically active form in  
13 adults, our data prompt us to suggest that BMP9 may be a systemic inhibitor of angiogenesis  
14 and a regulator of vascular tone. These data are supported by previous work demonstrating  
15 that phosphorylated Smad1, Smad5 and/or Smad8 are detectable in mouse aorta  
16 cryosections<sup>24</sup> indicating that, *in vivo*, these cells constantly receive stimulation by BMPs.  
17 The role of BMP family members on vascular development has not been extensively studied.  
18 Data are not clear and often show paradoxical effects between *in vitro* and *in vivo* assays.  
19 GDF5/BMP14 was one of the first BMPs described for its pro-angiogenic activity *in vivo*<sup>25</sup>.  
20 BMP2 was shown to increase angiogenesis in the sponge assay and to induce  
21 neovascularization of developing tumors<sup>26</sup> while it had no effect in the CAM assay<sup>25</sup>. Overall,  
22 *in vivo* data seem to indicate that BMPs acting through ALK3/ALK6 receptors are pro-  
23 angiogenic. Our data demonstrate that, in contrast to these BMPs, BMP9 inhibits  
24 angiogenesis via ALK1. This clearly separates BMPs into two categories: the pro-angiogenic  
25 BMPs that transduce via ALK3/6 and the anti-angiogenic BMPs (BMP9) that transduce via

1 ALK1. Since all of these BMPs activate the Smad1/5 pathway, it is unlikely that this pathway  
2 represents the only signaling pathway implicated in these mechanisms. This is highly  
3 consistent with our previous work demonstrating that ALK1-mediated inhibition of  
4 endothelial proliferation and migration is Smad-independent<sup>27</sup>. In accordance with these data,  
5 it has recently been described that ALK1 directly phosphorylates endoglin, resulting in  
6 inhibition of endothelial cell proliferation<sup>28</sup>. BMP9 was also recently reported to inhibit Akt  
7 phosphorylation, which is clearly implicated in the migration of endothelial cells<sup>29</sup>. The  
8 presence of both positive and negative BMP-mediated signaling responses in endothelial cells  
9 may provide a useful paradigm for the further dissection of the mechanisms by which BMPs  
10 participate in the control of angiogenesis.

## 11 Acknowledgments

12 We thank the student Solène di Prima for her helpful participation in this work. We also thank  
13 Dr J. LaMarre (University of Guelph, Ontario, Canada) for his review of the manuscript and  
14 his constant enthusiastic support. We thank Drs F. Bono and P. Schaeffer (Sanofi-Aventis,  
15 Toulouse, France) for their advice about the angiogenesis sponge assay.

## 16 Source of funding:

17 Laurent David was supported by a CFR grant from the Commissariat à l’Energie Atomique  
18 and by ARC (Association de la Recherche contre le Cancer). This research was supported by  
19 INSERM, CEA, GEFLUC (Groupement des Entreprises Françaises pour la Lutte contre le  
20 Cancer, Grenoble-Dauphiné-Savoie), PHRC (Programme Hospitalier de Recherche Clinique,  
21 Hospices Civils de Lyon, grant n°27) and AMRO (Association des Malades de Rendu-Osler).

## 22 Disclosure:

23 None.

24  
25

## 1 References

2

- 3 1. Xiao YT, Xiang LX, Shao JZ. Bone morphogenetic protein. *Biochem Biophys Res Commun.* 2007;362:550-553.
- 4 2. Miller AF, Harvey SA, Thies RS, Olson MS. Bone morphogenetic protein-9. An autocrine/paracrine cytokine in the liver. *J Biol Chem.* 2000;275:17937-17945.
- 5 3. Lopez-Coviella I, Berse B, Thies RS, Blusztajn JK. Upregulation of acetylcholine  
6 synthesis by bone morphogenetic protein 9 in a murine septal cell line. *J Physiol Paris.* 2002;96:53-59.
- 7 4. Truksa J, Peng H, Lee P, Beutler E. Bone morphogenetic proteins 2, 4, and 9 stimulate  
8 murine hepcidin 1 expression independently of Hfe, transferrin receptor 2 (Tfr2), and  
9 IL-6. *Proc Natl Acad Sci U S A.* 2006;103:10289-10293.
- 10 5. Johnson DW, Berg JN, Baldwin MA, Gallione CJ, Marondel I, Yoon SJ, Stenzel TT,  
11 Speer M, Pericak-Vance MA, Diamond A, Guttmacher AE, Jackson CE, Attisano L,  
12 Kucherlapati R, Porteous ME, Marchuk DA. Mutations in the activin receptor-like  
13 kinase 1 gene in hereditary haemorrhagic telangiectasia type 2. *Nat Genet.*  
14 1996;13:189-195.
- 15 6. Marchuk DA, Srinivasan S, Squire TL, Zawistowski JS. Vascular morphogenesis:  
16 tales of two syndromes. *Hum Mol Genet.* 2003;12:R97-R112.
- 17 7. Gallione CJ, Richards JA, Letteboer TG, Rushlow D, Prigoda NL, Leedom TP,  
18 Ganguly A, Castells A, Ploos van Amstel JK, Westermann CJ, Pyeritz RE, Marchuk  
19 DA. SMAD4 Mutations found in unselected HHT patients. *J Med Genet.* 2006.
- 20 8. Attisano L, Carcamo J, Ventura F, Weis FM, Massague J, Wrana JL. Identification of  
21 human activin and TGF beta type I receptors that form heteromeric kinase complexes  
22 with type II receptors. *Cell.* 1993;75:671-680.
- 23 9. Shi Y, Massague J. Mechanisms of TGF-beta signaling from cell membrane to the  
24 nucleus. *Cell.* 2003;113:685-700.
- 25 10. Chen YG, Massague J. Smad1 recognition and activation by the ALK1 group of  
26 transforming growth factor-beta family receptors. *J Biol Chem.* 1999;274:3672-3677.
- 27 11. Goumans MJ, Valdimarsdottir G, Itoh S, Rosendahl A, Sideras P, ten Dijke P.  
28 Balancing the activation state of the endothelium via two distinct TGF- beta type I  
29 receptors. *Embo J.* 2002;21:1743-1753.
- 30 12. Brown MA, Zhao Q, Baker KA, Naik C, Chen C, Pukac L, Singh M, Tsareva T,  
31 Parice Y, Mahoney A, Roschke V, Sanyal I, Choe S. Crystal structure of BMP-9 and  
32 functional interactions with pro-region and receptors. *J Biol Chem.* 2005;280:25111-  
33 25118.
- 34 13. David L, Mallet C, Mazerbourg S, Feige JJ, Bailly S. Identification of BMP9 and  
35 BMP10 as functional activators of the orphan activin receptor-like kinase 1 (ALK1) in  
36 endothelial cells. *Blood.* 2007;109:1953-1961.
- 37 14. Scharpfenecker M, van Dinther M, Liu Z, van Bezooijen RL, Zhao Q, Pukac L, Lowik  
38 CW, ten Dijke P. BMP-9 signals via ALK1 and inhibits bFGF-induced endothelial cell  
39 proliferation and VEGF-stimulated angiogenesis. *J Cell Sci.* 2007;120:964-972.
- 40 15. Lux A, Attisano L, Marchuk DA. Assignment of transforming growth factor beta1 and  
41 beta3 and a third new ligand to the type I receptor ALK-1. *J Biol Chem.*  
42 1999;274:9984-9992.
- 43 16. Shovlin CL, Guttmacher AE, Buscarini E, Faughnan ME, Hyland RH, Westermann  
44 CJ, Kjeldsen AD, Plauchu H. Diagnostic criteria for hereditary hemorrhagic  
45 telangiectasia (Rendu- Osler-Weber syndrome). *Am J Med Genet.* 2000;91:66-67.
- 46
- 47
- 48

- 1 **17.** Korchynskiy O, ten Dijke P. Identification and functional characterization of distinct  
2 critically important bone morphogenetic protein-specific response elements in the Id1  
3 promoter. *J Biol Chem.* 2002;277:4883-4891.
- 4 **18.** Carmeliet P. Angiogenesis in life, disease and medicine. *Nature.* 2005;438:932-936.
- 5 **19.** Neuhaus H, Rosen V, Thies RS. Heart specific expression of mouse BMP-10 a novel  
6 member of the TGF-beta superfamily. *Mech Dev.* 1999;80:181-184.
- 7 **20.** Kodaira K, Imada M, Goto M, Tomoyasu A, Fukuda T, Kamijo R, Suda T, Higashio  
8 K, Katagiri T. Purification and identification of a BMP-like factor from bovine serum.  
9 *Biochem Biophys Res Commun.* 2006;345:1224-1231.
- 10 **21.** Sugimoto H, Yang C, LeBleu VS, Soubasakos MA, Giraldo M, Zeisberg M, Kalluri  
11 R. BMP-7 functions as a novel hormone to facilitate liver regeneration. *Faseb J.*  
12 2007;21:256-264.
- 13 **22.** Gazzo E, Canalis E. Bone morphogenetic proteins and their antagonists. *Rev*  
14 *Endocr Metab Disord.* 2006;7:51-65.
- 15 **23.** Trembath RC, Thomson JR, Machado RD, Morgan NV, Atkinson C, Winship I,  
16 Simonneau G, Galie N, Loyd JE, Humbert M, Nichols WC, Morrell NW, Berg J,  
17 Manes A, McGaughan J, Pauciulo M, Wheeler L. Clinical and molecular genetic  
18 features of pulmonary hypertension in patients with hereditary hemorrhagic  
19 telangiectasia. *N Engl J Med.* 2001;345:325-334.
- 20 **24.** Valdimarsdottir G, Goumans MJ, Rosendahl A, Brugman M, Itoh S, Lebrin F, Sideras  
21 P, ten Dijke P. Stimulation of Id1 expression by bone morphogenetic protein is  
22 sufficient and necessary for bone morphogenetic protein-induced activation of  
23 endothelial cells. *Circulation.* 2002;106:2263-2270.
- 24 **25.** Yamashita H, Shimizu A, Kato M, Nishitoh H, Ichijo H, Hanyu A, Morita I, Kimura  
25 M, Makishima F, Miyazono K. Growth/differentiation factor-5 induces angiogenesis  
26 in vivo. *Exp Cell Res.* 1997;235:218-226.
- 27 **26.** Raida M, Clement JH, Leek RD, Ameri K, Bicknell R, Niederwieser D, Harris AL.  
28 Bone morphogenetic protein 2 (BMP-2) and induction of tumor angiogenesis. *J*  
29 *Cancer Res Clin Oncol.* 2005;131:741-750.
- 30 **27.** David L, Mallet C, Vailhe B, Lamouille S, Feige JJ, Bailly S. Activin receptor-like  
31 kinase 1 inhibits human microvascular endothelial cell migration: Potential roles for  
32 JNK and ERK. *J Cell Physiol.* 2007.
- 33 **28.** Koleva RI, Conley BA, Romero D, Riley KS, Marto JA, Lux A, Vary CP. Endoglin  
34 structure and function: Determinants of endoglin phosphorylation by TGFbeta  
35 receptors. *J Biol Chem.* 2006.
- 36 **29.** Liu D, Wang J, Kinzel B, Mueller M, Mao X, Valdez R, Liu Y, Li E. Dosage-  
37 dependent requirement of BMP type II receptor for maintenance of vascular integrity.  
38 *Blood.* 2007;110:1502-1510.
- 39
- 40

## Figure Legends

### Figure 1. **Presence of an ALK1 ligand in human serum that differs from TGF $\beta$**

NIH-3T3 cells were transiently transfected with pALK1 and pRL-TK-luc and either pGL3(BRE)-luc (A) or pGL3(CAGA)<sub>12</sub>-luc (B). Transfected cells were then treated either with human serum (2%), TGF $\beta$ 1 (0.5 ng/ml) or heat-activated human serum (2%) with or without pan-specific neutralizing TGF $\beta$  antibody (1  $\mu$ g/ml). C: NIH-3T3 cells were transiently transfected with pGL3(BRE)-luc, pALK1 and pRL-TK-luc. Transfected cells were then treated with human serum (2%) in presence or absence of either ALK1ecd, ALK2ecd, ALK3ecd, ALK6ecd or soluble endoglin (200 ng/ml). The luciferase activities were then measured as described in Materials and Methods. Data shown in A, B and C are expressed as mean values  $\pm$  SD from a representative experiment out of three.

### Figure 2. **Purification and estimation of the molecular weight of the ALK1 ligand from the human serum**

A: Scheme of purification of ALK1 ligand from 250 ml of a pool of human sera. The proteins present in the active fractions (23 and 24) of the Pro-RPC column and the two surrounding fractions (22 and 25), as determined with the BRE reporter gene assay (see Material and Methods), were then separated by 12% SDS-PAGE. After the migration, the gel (fractions 23 and 24) was sliced into 6 parts as indicated by the dotted lines and the proteins were electro-eluted. B: NIH-3T3 cells were transiently transfected with pGL3(BRE)-luc, pALK1 and pRL-TK-luc. Transfected cells were then treated with 100  $\mu$ l of either the active fractions (fraction 23 and 24) or 100  $\mu$ l of the proteins eluted from each gel slice. The luciferase activities were then measured as described in Materials and Methods. Data are expressed as mean values  $\pm$  SD from a representative experiment out of three.

1 **Figure 3. The ALK1 activity of the human serum is due to BMP9**

2 A, B, C and D: NIH-3T3 cells were transiently transfected with pGL3(BRE)-luc, pRL-TK-luc  
3 and pALK1. A: Transfected cells were then treated with BMP9 (0.1 ng/ml), or BMP10 (20  
4 ng/ml), or BMP2 (100 ng/ml) in the presence or the absence of a neutralizing BMP9 antibody  
5 (1 µg/ml) or an isotype-matched control antibody (1µg/ml) . B: Transfected cells were then  
6 treated with human serum (1%) or 100 µl of active fraction (fractions 23 and 24 of Fig. 2A).  
7 C: Transfected cells were treated with 2% human serum in the presence or the absence of  
8 neutralizing antibodies (anti-BMP9 (2 µg/ml), anti-BMP2/4 (10 µg/ml), or anti-BMP7 (10  
9 µg/ml)) or with recombinant noggin (1 µg/ml). D: Transfected cells were treated with either  
10 BMP9 (0.05 ng/ml), BMP2 (50 ng/ml) or BMP7 (100 ng/ml) in the presence or the absence of  
11 neutralizing antibodies (anti-BMP9 (2 µg/ml), anti-BMP2/4 (10 µg/ml), or anti-BMP7 (10  
12 µg/ml)) or with recombinant noggin (1 µg/ml). The luciferase activities were then measured as  
13 described in Materials and Methods. Data shown in A, B, C and D are expressed as mean  
14 values ± SD from a representative experiment out of three. E: HMVEC-d were serum-starved  
15 for 1 h and were then treated with 2% human serum for 1 h in the presence or absence of  
16 neutralizing BMP9 antibody (1 or 10 µg/ml) or ALK1ecd (100 ng/ml). Cell lysates (20 µg  
17 proteins) were resolved by 10% SDS-PAGE, and immunoblotted with antibodies against  
18 phosphoSmad1/5/8 or against α-tubulin.

19 **Figure 4. Determination of BMP9 concentration in human serum**

20 A: NIH-3T3 cells were transiently transfected with pGL3(BRE)-luc, pRL-TK-luc, pALK1.  
21 Transfected cells were treated with 0.5% of human serum or plasma of 4 different healthy  
22 donors. B: linear regression for the determination of BMP9 serum concentration. NIH-3T3  
23 cells were transiently transfected with pGL3(BRE)-luc, pRL-TK-luc, pALK1. Transfected  
24 cells were then treated with 0.1 or 0.3% of a pool of human sera. The luciferase activities  
25 were then measured as described in Materials and Methods. Data shown in A and B are

1 expressed as mean values  $\pm$  SD from a representative experiment out of three. C: BMP9  
2 serum levels measured in 20 patients with HHT and 20 healthy donors. The line indicates the  
3 mean value. The difference was not statistically significant.

#### 4 **Figure 5. Effect of BMP9 on angiogenesis in the mice sponge assay**

5 A and B: Bal-C mice received a subcutaneous cellulose sponge treated with FGF-2 (200 ng)  
6 and/or BMP9 (20 ng) under the dorsal skin. Injections in the sponge of FGF-2 and/or BMP9  
7 diluted in PBS were performed on day 1 and day 2 and a last injection was performed on day  
8 4 with BMP9 alone. C: Bal-C mice received a subcutaneous cellulose sponge treated with  
9 FGF-2 (200 ng) diluted in PBS under the dorsal skin. Injections of FGF-2 were performed on  
10 day 1 and day 2. BMP9 (20 ng) or PBS were injected on day 4, 5 and 6. Animals were  
11 sacrificed on day 7 and the sponges were photographed (A). Hemoglobin content was  
12 measured in 1 ml of RIPA buffer extract of the sponge and adjacent vascular network (B and  
13 C). B: Data are expressed as mean values  $\pm$  SEM from a representative experiment (five mice  
14 in each groups) out of three. C: Data are expressed as mean values  $\pm$  SEM of two experiments  
15 (nine mice in each groups). (\*  $p < 0.05$ ; \*\*  $p < 0.01$ ).

16

#### 17 **Figure 6. Effect of BMP9 on vessel formation in the chick chorioallantoic membrane** 18 **assay**

19 On day 9, the CAM received either 25  $\mu$ l of BMP9 (5.5 ng, 27.5 ng, 55 ng or 550 ng) or  
20 vehicle (Control). The photographs shown were taken before (T 0h) and after treatment (T  
21 24h) and are representative of the results obtained in an additional five eggs per group. Low  
22 magnification pictures of CAMs at T 0h(A) and T 24h (B); C: 24 h after treatment, FITC  
23 dextran was injected in the CAM vessels, fluorescent images. Arrow indicates a vessel that is  
24 not affected by BMP9 treatment; arrowhead indicates a vessel that cannot be seen after BMP9  
25 treatment.

1  
2  
3  
4