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Vascular Endothelial Growth Factors and Angiopoietins as New Players in Mastocytosis

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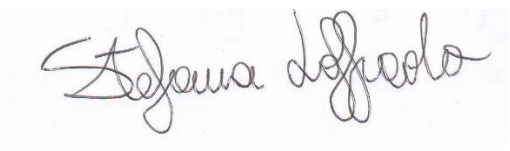

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Abstract

Background: Mastocytosis is a disorder characterized by the abnormal proliferation and/or accumulation of mast cells in different organs. More than 90% of patients with systemic mastocytosis have a gain-of-function mutation in codon 816 of the KIT receptor on mast cells (MCs). The symptoms of mastocytosis patients are related to the MC-derived mediators that exert local and distant effects. MCs produce angiogenic and lymphangiogenic factors, including vascular endothelial growth factors (VEGFs) and angiopoietins (ANGPTs).

Methods: Serum concentrations of VEGF-A, VEGF-C, VEGF-D, ANGPT1 and ANGPT2 were determined in 64 mastocytosis patients and 64 healthy controls. Intracellular concentrations and spontaneous release of these mediators were evaluated in the mast cell lines ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$.

Results: VEGF-A, ANGPT1, ANGPT2 and VEGF-C concentrations were higher in mastocytosis patients compared to controls. The VEGF-A, ANGPT2 and VEGF-C concentrations were correlated with the symptom severity. ANGPT1 concentrations were increased in all patients compared to controls. ANGPT2 levels were correlated with severity of clinical variants and with tryptase levels. VEGF-A, ANGPT1 and VEGF-C did not differ between indolent and advanced mastocytosis. ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ contained and spontaneously released VEGFs and ANGPTs.

Conclusion: Serum concentrations of VEGFs and ANGPTs are altered in mastocytosis patients.

Introduction

Mast cells (MCs) are immune cells derived from bone marrow $CD34^+/CD117^+$ pluripotent progenitor cells [1] which are localized in all tissues, including the skin [2], the mucosa of respiratory tract [3], the gastrointestinal system [4] and the heart [5]. Their number increases in several disorders such as bacterial, viral and parasitic infections [6, 7], allergic disorders [8, 9], arthritis [10], cardiovascular disorders [5, 11], cancer [12-14] and mastocytosis [15, 16].

Mastocytosis is a rare clonal disorder characterized by uncontrolled proliferation, abnormal accumulation and survival of MCs in several organs [17, 18]. This pathological condition is due to a somatic activating mutations of *KIT* gene that encodes for transmembrane tyrosine kinase receptor KIT (CD117) largely expressed on mast cells [19-21]. More than 90% of patients with systemic mastocytosis have a gain-of-function mutation in codon 816 of the receptor tyrosine kinase KIT, where a valine is substituted for an aspartate (*KIT* D816V) [22]. This mutation, located in catalytic domain of KIT, leads to an autophosphorylation of KIT receptor that flows in autonomus MC proliferation and survival also in absence of the KIT ligand, stem cell factor (SCF) [22], which induces maturation, activation and proliferation of MCs [23, 24]. Other activating *KIT* mutations including V560G, D816Y, D816A, D816N, D816T, D816F, D816H, D835Y, D816I, del 417–418, D419Y, C443Y, S476I, ITD502–503, K509I, D572A and E839K were identified in MC lines but with a lower frequency than *KIT* D816V [25, 26]. Mastocytosis is a heterogeneous group of neoplastic conditions [27] ranging from a skin-limited disorder [e.g., cutaneous mastocytosis (CM)], particularly in pediatric subjects where the majority have disease-onset within the first two years of life and commonly experience spontaneous regression of skin lesions at puberty, to severe forms involving one or multiple organs [e.g., systemic mastocytosis (SM)] that may be associated with multiorgan dysfunction/failure and shortened survival, generally seen in adult patients [27, 28]. According to World Health Organization (WHO) the diagnosis of SM is confirmed by two groups of diagnostics criteria, named minor and major criteria respectively. The diagnosis of SM is established when

patients show at least one major and one minor or at least three minor SM criteria. Major criterion is the presence of multifocal clusters of abnormal MCs (greater than 15% of MCs in clusters) in the bone marrow or extracutaneous tissues detected by tryptase-immunohistochemistry. Minor criteria are: (i) elevated serum tryptase levels (over 20 ng/ml); (ii) abnormal number of MCs in bone marrow, blood or other extracoutaneous organs express CD25 with/without CD2 in addition to normal mast cells markers; (iii) presence of *KIT* D816V mutation in bone marrow, blood or extracoutaneous organs; and (iv) presence of a number of atypical MCs (spindle-shaped) greater than 25% in a biopsy section of bone marrow or other extracoutaneous organs [28, 29].

According to the WHO patients with mastocytosis are classified based on the presence/absence of B- (burden), C (clinical)- and progressive C-findings. B-findings are referred to organ involvement without organ failure and are defined as (1) bone marrow biopsy showing more than 30% infiltration by MCs and/or serum total tryptase level more than 200 ng/mL; (2) signs of dysplasia or myeloproliferation in non-mast cell lineage, but insufficient criteria for definitive diagnosis of a hematopoietic neoplasm, with normal or slightly abnormal blood counts; and (3) hepatomegaly without impairment of liver function, and/or palpable splenomegaly without hypersplenism, and/or palpable or visceral lymphadenopathy. C-findings are referred to organ involvement with organ dysfunction and are defined by the following mastocytosis-related symptoms: (1) leukocytopenia (< 1000/µL); (2) anemia (hemoglobin < 10g/dL); (3) thrombocytopenia (< 100000/µL); (4) hepatomegaly with ascites; (5) abnormal liver tests with elevated enzyme levels or (6) with hypalbuminemia; (7) portal hypertension; (8) palpable splenomegaly with hypersplenism ; (9) malabsorption with hypalbuminemia or with (10) weight loss; (11) huge osteolysis and/or severe osteoporosis with pathologic fractures. The presence of a C- finding is sufficient to diagnose advanced SM. Progressive C-findings are defined as: (1) severe pancytopenias (neutrophils count < 500/µl and platelets < 20000/µl), (2) need for transfusion and progressive damage of liver function, (3) loss of protein synthesis and (4) severe coagulation disorder [30, 31].

The symptoms of mastocytosis are the consequence of infiltration, activation and degranulation of MCs which exert local and systemic effects [15, 16].

MC granules contain pre-formed mediators as heparin, histamine and a lot of proteases such as chymase and α- and β- tryptase [32]. MC degranulation is induced by a plethora of stimuli such as physical factors (mechanical trauma, high temperature), toxins, venoms, endogenous mediators (proteins, tissue proteases), allergens, bacterial and viral superallergens, cytokines, chemokines and immune mechanisms (IgE dependent/IgE independent and Complement activation) [1, 33-41]. MCs also release *de novo* synthesized molecules such as cytokines, chemokines, growth factors and lipid mediators (as prostaglandin D2) and leukotriene C4 [37, 42-44]. Under normal circumstances, these mediators help to orchestrate the development of a defensive acute inflammatory reaction [32]. Conversely a massive release of these mediators induces bronchoconstriction, vasodilation, gastrointestinal and bronchial smooth muscle contraction, pruritus and gastric acid production [45].

Immunological and non-immunological stimuli can induce the release of vascular endothelial growth factors (VEGFs) [46-52] and angiopoietins (ANGPTs) [53] from human MCs.

The VEGF family, in humans, consists of five separate gene products: VEGF-A, VEGF-B and placental growth factor (PlGF) are key regulators of physiological and pathological blood vessel growth [54, 55], whereas VEGF-C and VEGF–D modulate lymphangiogenesis [56]. VEGFs bind three tyrosine kinase receptors (VEGFR-1, -2, -3) expressed on blood (BEC) and lymphatic endothelial cells (LECs) [57]. VEGF-A, initially named vascular permeability factor (VPF), was discovered by Dvorak and collaborators for its permeabilizing activity [58]. It was found that VEGF-A is at least 50 times more potent than histamine in inducing vascular permeability [59-61].

The ANGPT system is another pathway regulating vascular barrier functions [62]. In humans, ANGPT1 and ANGPT2 are the two primary angiopoietins: ANGPT1 is a vascular stabilizer acting on Tie2 receptor on BECs [63]. By contrast, ANGPT2 is an inhibitory ligand of the Tie2 receptor that disrupts the integrity of the blood vessel wall, thus counteracting vascular normalization [64].

Increased concentrations of circulating VEGFs and/or ANGPTs have been found in different human disorders characterized by increased vascular permeability or angiogenesis such as cardiovascular diseases [57, 65-67], cancer [68, 69], systemic capillary leak syndrome [70], angioedema [71, 72] and sepsis [73-75].

The role of VEGFs and ANGPTs in the pathophysiology of different forms of mastocytosis has not been thoroughly investigated. The aim of this paper was to evaluate the serum concentrations of VEGF-A, VEGF-C, VEGF-D, ANGPT1 and ANGPT2 in patients with different variants of mastocytosis and the expression of angiogenic and lymphangiogenic factors in human MC lines with or without D816V mutation.

Methods

Patients

We studied 64 Caucasian patients with mastocytosis (MP) (31 males and 33 females; age range: 21–79 years; median age 46 years) followed at the University of Naples Federico II and at the University of Salerno whose clinical characteristics are summarized in Table 1 and Table 2. None of patients was treated for mastocytosis at the time of blood sampling. 64 healthy controls (HC) (31 males and 33 females; age range: 29-70 years; median age 43 years) were recruited as control. Inclusion criteria for this study were: absence of any pathological conditions at the time of enrollment; none of anti-inflammatory and immunomodulatory drugs were ingested at the time of the blood sampling; expression of written informed consent. Exclusion criteria were: presence of any condition that, in the opinion of the investigators, could interfere with the completion of the study such as pregnancy. Mediator-related symptoms were classified according to severity and frequency as follows: 13 patients had grade 0 (no symptoms), 13 had grade 1 (mild/ infrequent: prophylaxis and or as needed therapy), 26 had grade 2 (moderate: kept under control with anti-mediator type drugs daily) and 12 had grade 3 (severe and frequent: not sufficiently controlled with therapy). None of the patients had grade 4 characterized by severe adverse events which require immediate therapy and hospitalization. The diagnosis and classification of mastocytosis were made according to the recommendation of the World Health Organization (WHO) on the histological examination of a skin biopsy for cutaneous mastocytosis (CM) and of bone marrow biopsy for systemic mastocytosis (SM) [28, 76]. Patients were divided according to cutaneous and/or systemic involvement and the severity and frequency of symptoms. The first group (indolent) included maculopapular cutaneous mastocytosis (MPCM) (n=3), mastocytosis in the skin (MIS) (n=4) and indolent systemic mastocytosis (ISM) (n=38). The second group (advanced) included patients with smoldering systemic mastocytosis [66] (n=9), aggressive systemic mastocytosis (ASM) (n=7), systemic mastocytosis associated with hematologic disease (SM-AHD) (n=2) and mast cell leukemia (MCL) (n=1). The

most common mutation of KIT receptor in patients with indolent and aggressive SM is *KIT* D816V [18, 77]. The search of *KIT* D816V mutation was performed in 30 patients. In 21 of those patients the presence of *KIT* mutation was found and in 9 patients was not found. Many patients with provisional diagnosis of skin mastocytosis refused to undergo bone marrow biopsy. Circulating concentrations of angiogenic (VEGF-A) and lymphangiogenic (VEGF-C and VEGF-D) factors, angiopoietins (ANGPT1 and ANGPT2) and lipid mediators (PLA_2 and PLC), were assessed in all patients and controls.

Serum Collection

The Ethics Committee of Campania ASL Napoli 3 Sud (protocol number 68863) approved that serum, obtained during routine diagnostics, could be used for research investigating the pathophysiology of mastocytosis. Written informed consent was obtained from both MP and HC according to the principles expressed in the Declaration of Helsinki. The blood samples were collected by a clean venepuncture. After centrifugation (2,000 × *g*, 22°C, 20 min), the serum was divided into aliquots and stored at -80°C until tested. We collected the data about the clinical manifestations at onset of mastocytosis and 30% of patients have an history of anaphylaxis at the onset of disease. The collection of the samples for measurement of all metabolites was performed at least after 3 months from anaphylactic episodes.

Tryptase Assay

Serum tryptase concentration was measured by fluoro-enzyme immune assay (FEIA) using Uni-CAP100 (Phadia Diagnostics AB, Uppsala, Sweden). This technique allows to measure both α-tryptase and β-tryptase.

Phospholipases Activity Assay

A modified liposomal-based fluorescent assay was used to measure phospholipase A_2 (PLA_2) activity (Life-technologies EnzChek® phospholipase Assay). Results are expressed as units/L of PLA_2 activity. PLC activity was determined using EnzChek® Direct Phospholipase C Assay KIT (Life-technologies EnzChek® phospholipase C assay). Results are expressed as units/L of PLC activity [78].

Culture of Human Mast Cells

The human mast cell lines $ROSA^{KIT\ WT}$ and $ROSA^{KIT\ D816V}$ were a generous gift from Michel Arock (Laboratoire de Biologie et de Pharmacologie Appliquee, Ecole Normale Supérieure de Cachan) [79]. $ROSA^{KIT\ WT}$ and $ROSA^{KIT\ D816V}$ mast cell lines were cultured at the density of 4×10^5 cells/mL with and without recombinant SCF (80 ng/mL) (Peprotech, London, UK), respectively, in IMDM (Microgem®, Naples, Italy) supplemented with 0.3% bovin serum albumin (Microgem®, Naples, Italy), 1% L-glutamine (Sigma-Aldrich® St. Louis, MO, USA), 2% non-essential aminoacids (Microgem®, Naples, Italy), 1% vitamins solution (Gibco-Thermo-Fisher® Waltham, MA, USA), 1% insulin-transferrin-selenium (Thermo-Fisher® Waltham, MA, USA), and 1% sodium pyruvate (Gibco-Thermo-Fisher® Waltham, MA, USA), 1% antibiotic-antimycotic solution (Lonza, Basel, CH). $ROSA^{KIT\ WT}$ and $ROSA^{KIT\ D816V}$ cells were incubated in 25 cm^2 flask at 37°C and 5% CO_2 and counted after 4 days of culture. Primary human mast cells were isolated from lung parenchyma of patients undergoing thoracic surgery and were purified (>98%) by immunomagnetic selection, as previously described [11, 80]. The study protocol involving the use of human blood cells was approved by the Ethics Committee of the University of Naples Federico II (Protocol number 301/12), and written informed consent was obtained from donors according to the principles expressed in the Declaration of Helsinki. For VEGFs and ANGPTs analysis all types of mast cells were incubated (37°C, 5% CO_2, 24 h) in complete medium. At the end of the experiments, the cells were centrifuged

(1,000 × *g*, 4°C, 5 min) and the supernatants were stored at −80°C for subsequent determination of mediators. The cellular pellets were lysated in Tryton X-100 0.1% (Sigma-Aldrich®, Saint Louis, MO, USA) and stored at −80°C for subsequent determination of intracellular mediator content.

ELISA Assay

VEGF-A, VEGF-C, VEGF-D, ANGPT1 and ANGPT2 concentrations in serum, in supernatant and in cellular lysates of ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ were measured using commercially available ELISA KITs (R&D System, Minneapolis, MN, USA) according to the manufacturer's instructions. The serum concentrations of these mediators from MP and HC were expressed as pg/mL. Intracellular and released mediators from ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ were expressed as pg/10^6 cells.

Statistical Analysis

Data were analysed with the GraphPad Prism 5 software package. Data were tested for normality using the D'Agostino-Pearson normality test. If normality was not rejected at 0.05 significance level, we used parametric tests. Otherwise, for not-normally distributed data we used nonparametric tests. Statistical analysis was performed by unpaired two-tailed t-test or two-tailed Mann-Whitney test as indicated in figure legends. Correlations between two variables were assessed by Spearman's correlation analysis and reported as coefficient of correlation (r). A p value ≤ 0.05 was considered statistically significant. Serum levels of VEGF-A, VEGF-C, VEGF-D, ANGPT1, ANGPT2, PLA_2, and PLC are shown as the median (horizontal black line), the 25th and 75th percentiles (boxes) and the 5th and 95th percentiles (whiskers) of 47 controls and 64 patients.

Results

VEGF and ANGPT Serum Concentrations in Patients with Mastocytosis

Peripheral blood concentrations of VEGFs [57, 69, 71-73] and ANGPTs are increased in different pathological conditions compared to healthy donors [57, 68, 74, 81]. VEGF-A concentrations in mastocytosis patients have been studied only on small number of patients by Brockow *et al*. [82], whereas the ANGPT levels have not yet been investigated. Therefore, in this study we evaluated the serum concentrations of VEGFs and ANGPTs in patients with mastocytosis (N=64) compared to HC (n=64). Figure 1A shows that VEGF-A serum levels of MP were higher than HC [VEGF-A: (34.63 ± 56.76) *vs* (9.21 ± 24.59) pg/mL]. Interestingly, both ANGPT2, which increases vascular permeability [83], and its antagonist ANGPT1 [84, 85] were increased in MP compared to HC [ANGPT1: (1,538 ± 2,136) *vs* (39.93 ± 45.60 pg/mL)] [ANGPT2: (1,492 ± 976) *vs* (1,085 ± 607) pg/mL] (Figure 1B and C).

No data are available on the serum concentrations of lymphangiogenic factors in mastocytosis patients. Serum concentrations of VEGF-C were significant higher in MP compared to the control group [VEGF-C: (6,228 ± 2,188) *vs* (4,741 ± 1,266) pg/mL] (Figure 1D). Interestingly, the concentrations of VEGF-D, another lymphangiogenic factor, did not differ between the two groups [VEGF-D: (204.9 ± 213.1) *vs* (234.8 ± 184.5) pg/mL] (Fig. 1E). In MP, the concentrations of different mediators did not correlate with each other (Figure 2). Statistical significance parameters of correlated mediators are summarized in Table 3.

We have previously demonstrated that both PLA_2 and PLC activities are increased in MP compared to HC [78]. We investigated possible correlations between circulating concentrations of VEGFs and ANGPTs and of PLA_2 (Figure 3) and PLC (Figure 4). No correlations were found among these different mediators. There was no difference in VEGF and/or ANGPT concentrations between male and female values in both controls and patients (Figure 5). Moreover, the age of patients and the concentrations of the different mediators examined did not correlate (Figure 6).

Effects of Disease Severity on Serum Concentrations of VEGF and ANGPT in Patients with Mastocytosis

A triplex experimental analysis was used to verify whether enhanced levels of VEGF-A, ANGPT1, ANGPT2 and VEGF-C were correlated to mastocytosis severity. MP were divided according to the severity of mediator-related symptoms, from grading 0 to grading 3 (see Methods) and concentrations of VEGFs and ANGPTs were compared among groups. VEGF-A, ANGPT2 and VEGF-C levels were not increased in asymptomatic patients (grading 0) compared to controls (Figure 7A, C, D). Symptomatic patients (grading 1 to 3) had elevated VEGF-C concentrations compared to HC (Figure 7D); conversely, VEGF-A and ANGPT2 were altered only in symptomatic patients with grading 2 and 3 (Figure 7A, C). Interestingly, ANGPT1 levels were increased in both asymptomatic and symptomatic patients compared to HC (Figure 7B).

We also grouped patients according to their clinical variants in two groups (see methods): indolent (MPCM/MIS/ISM) and advanced (SSM/SM-AHD/ASM/MCL) mastocytosis. Figure 8 shows that VEGF-A (panel A) and ANGPT1 (panel B) concentrations did not differ between patients with indolent and advanced variants, but were altered in both groups when compared to controls. ANGPT2 levels, like tryptase (panel F), were higher in patients with advanced mastocytosis compared to indolent variants (panel C). Interestingly, VEGF-C was increased only in indolent mastocytosis compared to controls (panel D). The ANGPT2/ANGPT1 ratio (an index of vascular permeability) [72] was also increased in more severe patients (panel E).

Patients with advanced forms of mastocytosis have elevated tryptase levels compared with those with indolent forms [86, 87]. Thus, we analyzed the correlations between VEGFs/ANGPTs and this important marker of mast cell activation/proliferation (Table 3). The concentrations of VEGF-A (Figure 9A) and ANGPT1 (Figure 9B) were not correlated with tryptase levels. The concentrations of ANGPT2 positively correlated with tryptase concentrations (Figure 9C). By contrast, the serum levels of VEGF-C negatively correlated with tryptase concentrations (Figure 9D).

Angiogenic and Lymphangiogenic Factors in Primary Human Mast Cells and in Human Mast Cell Lines

We have previously reported that VEGF-A, VEGF-C, and VEGF-D can be detected by immunohistochemistry in human lung mast cells [88]. The ROSA$^{KIT\ WT}$ is a SCF-dependent human MC line expressing the high affinity receptor for IgE (FcεRI) [79]. The most frequent mutation affecting patients with mastocytosis is the D816V [22, 89]. The transfection with *KIT* D816V converted ROSA$^{KIT\ WT}$ cells into an SCF-independent clone, ROSA$^{KIT\ D816V}$, which produced a mastocytosis-like disease in mice [79].

We analyzed the basal content of VEGFs and ANGPTs in ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ and also primary human MC derived from lung tissue（HLMCs). Figure 10 shows that both ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ spontaneously released a large amount of VEGF-A (panel A), ANGPT1 (panel B), ANGPT2 (panel C) and VEGF-C (panel D). The spontaneous release of these mediators did not differ between the two mast cell lines. HLMCs release lower concentration of VEGF-A and ANGPT1 compared ROSA cells; by contrast, the release of ANGPT2 and VEGF-C did not differ among the three different human MCs.

ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ contained VEGF-A (Figure 10 A), ANGPT1 (Figure 10B), ANGPT2 (Figure 10C) and VEGF-C (Figure 10D). The content of VEGF-A and of VEGF-C was similar between wild type and mutated MC lines (Figure 10A, D). ANGPT1 in lysates of ROSA$^{KIT\ WT}$ was higher than in ROSA$^{KIT\ D816V}$. By contrast, the intracellular content of ANGPT2 was higher in ROSA$^{KIT\ D816V}$ than in ROSA$^{KIT\ WT}$ (Figure 10B, C). HLMC contained lower levels of VEGF-A and ANGPT2 compared to ROSA cells.

Discussion

Serum concentrations of VEGF-A, VEGF-C, ANGPT1 and ANGPT2 are increased in patients with mastocytosis compared to healthy controls. Some of these mediators such as VEGF-A [11, 49-52], VEGF-C [11, 47], and ANGPT1 and ANGPT2 [53] are expressed by human primary and neoplastic (e.g., LAD2, HMC-1) mast cells. There is a clinical correlation between the severity of mastocytosis and the plasma levels of these mast cell-derived mediators. In fact, circulating levels of VEGF-A, ANGPT2 and VEGF-C are increased in symptomatic, but not asymptomatic mastocytosis patients. Interestingly, the serum concentration of ANGPT1, which is mainly produced by pericytes and inhibits endothelial cell permeability [85, 90], is increased in all mastocytosis patients.

The angiopoietin (ANGPT) family is an important group of factors, specific for vascular endothelium, whose functions are mediated through two tyrosine kinase receptors, Tie1 and Tie2 [91]. The ANGPT-Tie ligand-receptor system exerts a key role in regulating vascular integrity [92, 93]. Beside their roles in the regulation of angiogenesis [84, 94] and lymphangiogenesis [95, 96], ANGPTs also modulate inflammation in several disorders [57, 67, 93, 97]. ANGPT1, produced by peri-endothelial mural cells (pericytes) [98] and immune cells [53, 99], is a potent agonist of Tie2 receptor on endothelial cells [63, 94]. ANGPT1 is an anti-inflammatory molecule [90] that maintains vascular integrity [100, 101]. ANGPT2, stored in Weibel–Palade bodies in endothelial cells [102, 103] is considered a pro-inflammatory molecule [83, 104]. ANGPT2 inhibits ANGPT1/Tie2 interaction [84, 85], resulting in vascular instability and leakage [83].

It has been demonstrated that ANGPT1 inhibits the *in vitro* activation of the mouse mastocytoma cell line P815 and experimental anaphylactic shock in mice [105]. Anaphylaxis and anaphylactoid reactions are more frequent in mastocytosis patients compared to the general population [106]. It is possible to speculate that the increase in circulating ANGPT1 in all patients

with mastocytosis might represent a protective factor in counterbalancing the vasopermeability effect of VEGF-A [59, 61, 107] and ANGPT2 [83].

Tryptase is a serine protease highly expressed by human mast cells and to a minor extent by basophils [108, 109]. Measurements of tryptase levels in serum have been used to assess mast cell load in systemic mastocytosis [86, 110-112]. In this study, we found that serum concentrations of tryptase are increased in indolent and advanced mastocytosis. Tryptase concentrations are positively correlated to the circulating levels of ANGPT2 and negatively correlated to VEGF-C. The latter observation is difficult to reconcile because there is evidence that activated human mast cells release both tryptase and VEGF-C [11, 113]. Moreover, tryptase serum concentrations are not correlated to the levels of VEGF-A and ANGPT1. Again, these results are rather unexpected because VEGF-A [46-52] and ANGPT1 [53] are expressed by human mast cells. However, many other immune and non-immune cells can produce and release VEGF-A [114-116] and ANGPT1 [85].

This study also examined the differential expression of several mediators in indolent and advanced mastocytosis. There is compelling evidence that mastocytosis is a heterogeneous condition with strikingly different prognostic profiles [18, 117]. Serum concentrations of tryptase, VEGF-A and ANGPT1 are increased in indolent and advanced mastocytosis compared to healthy controls. However, the lack of correlation between tryptase and both VEGF-A and ANGPT1 might indicate that alternative sources of the two latter mediators are involved in mastocytosis. This observation suggests that there are complex cellular and biochemical alterations in mastocytosis, in addition to the proliferation of mast cells.

ANGPT2, which is released mainly by endothelial cells [102], and ANGPT1/ANGPT2 ratio, an index of vascular permeability [72], are increased only in advanced mastocytosis. We found that serum concentrations of ANGPT2 are correlated to those of tryptase. The latter correlation might indicate that in patients with advanced mastocytosis these mediators are mainly derived from activated mast cells. These results are in line with those of our previous work in which we

demonstrated that an endothelial dysfunction is detectable in patients with mastocytosis and is more severe in patients with high tryptase levels and advanced disease. Endothelial function appears to be negatively influenced by MC proliferation rather than by the severity of mediator-related symptoms [118].

VEGF-C and VEGF-D are the most important modulators of inflammatory and tumor lymphangiogenesis [119, 120] acting on VEGF receptor 3 (VEGFR-3) on LECs [56, 121]. These factors can be detected [88] and can be produced by activated human mast cells [11, 57]. Our results indicate that the serum concentrations of VEGF-C but not VEGF-D are markedly increased in patients with mastocytosis compared to healthy controls. The differential alterations of VEGF-C and VEGF-D in these patients is intriguing but not surprising. Recent evidence indicates that VEGF-C and VEGF-D can differently modulate the immune system [119]. The possible role of VEGF-C in mastocytosis deserves further investigations.

We have previously demonstrated that plasma concentrations of PLA_2 are increased in patients with mastocytosis [78] and that these enzymes can induce the release of VEGFs and ANGPTs from macrophages [115] and neutrophils [116]. It is conceivable that the increased serum concentrations of VEGF-A, VEGF-C, and ANGPTs in patients with mastocytosis could be in part due to altered circulating levels of PLA_2.

Human mast cells constitutively express VEGF receptors and Tie receptors for ANGPTs [46, 47, 53]. These receptors are functionally active because VEGFs [47] and ANGPT1 exert a chemotactic effect on human mast cells [53]. In this scenario, one may envisage a novel autocrine-loop involving angiogenic factors (i.e., VEGFs, ANGPTs) and their receptors on mast cells. In fact, VEGFs and ANGPT1 released by activated mast cells might attract progenitors of these cells to sites of neoplastic growth through the engagement of VEGFs and Tie2 receptors, respectively.

There is compelling evidence that human mast cells are a major source of several canonical (VEGF-A, ANGPTs) [11, 49-53] and non-canonical angiogenic factors (LTC_4, LTD_4, tryptase) [122,

123]. Valent and collaborators first to demonstrated bone marrow (BM) microvessel density (MVD) is increased in patients with mastocytosis [124]. Moreover, BM MVD was significantly higher in systemic mastocytosis compared to cutaneous mastocytosis and healthy controls. Immunohistochemical staining revealed expression of VEGF-A in mast cell infiltrates. The same group of investigators extended the previous observation to canine mastocytosis by demonstrating the presence of VEGF in primary dog mastocytomas by immunohistochemistry and VEGF mRNA by PCR [125].

We have previously shown by immunohistochemistry that HLMCs contain VEGF-A, VEGF-C, and VEGF-D [88]. In this study, we confirm that immunoreactive VEGF-A is present in HLMCs and can be spontaneously released. We also examined the content and spontaneous release of several angiogenic factors in ROSA mast cell lines with ($ROSA^{KIT\ D816V}$) and without *KIT* mutation ($ROSA^{KIT\ WT}$) [79]. $ROSA^{KIT\ WT}$ is a SCF-dependent human mast cell line expressing FcεRI. $ROSA^{KIT\ D816V}$ was established by stably trasfecting KIT^{D816V} , the most frequent mutation in the catalytic domain of *KIT* found in up to 90% of systemic mastocytosis [126], in $ROSA^{KIT\ WT}$. Both $ROSA^{KIT\ WT}$ and $ROSA^{KIT\ D816V}$ contained and spontaneously released VEGF-A, VEGF-C, and ANGPT1. These findings agree with previous observations that the histamine content and FcεRI expression did not differ between both $ROSA^{KIT\ WT}$ and $ROSA^{KIT\ D816V}$ cell lines [79].

This study has a limitation that should be pointed out. Although more than 90% of patients with systemic mastocytosis have a mutation in codon 816 of KIT (*KIT* D816V) [22, 77], alternative *KIT* mutation in codon 816 (e.g., D816A/F/H/I/N/T/Y) have been described. In addition, to the tyrosine kinase domain (exons 17 and 18; e,g, D820G or N8221/K), at least 30 different *KIT* mutations have been identified in the extracellular (exon 8-9), transmembrane (exon 19; e.g., F522C) and juxtramembrane domains (exon 11; e.g., V560 G/I) in a small percentage of mastocytosis patients [127-132]. In this study, the identification of *KIT* D816V was not performed in all patients examined. In addition, other less common mutations were not investigated.

Conclusions

Mastocytosis is an heterogeneous group of neoplastic disorders characterized by complex pathology, distinct subtypes, and highly variable clinical courses [18, 27]. Our findings indicate that VEGF and ANGPT concentrations are increased in patients with mastocytosis compared to controls. More than 90% of patients with systemic mastocytosis have the *KIT*^{D816V} mutation. Several studies have shown that in addition to activating KIT mutations, additional mutations in other genes may occur in mastocytosis [127-131]. The contribution of *KIT* and other mutations to the altered production of VEGFs and ANGPTs in different patients with forms of mastocytosis remains to be investigated. In addition, further studies should evaluate the diagnostic and prognostic value of VEGFs and ANGPTs in different forms of mastocytosis. Finally, classical and novel inhibitors of angiogenesis and/or lymphangiogenesis alone or in combination with other anti-neoplastic drugs, are used in the treatment of cancer [85]. The current treatment options for patients with advanced mastocytosis need to be improved [18, 117]. Perhaps, the use of angiogenic/lymphangiogenic inhibitors could be considered for the treatment of selected patients with severe mastocytosis and high levels of circulating angiogenic factors.

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Table 1. Characteristics of patients with mastocytosis compared to healthy donors.

Characteristics			Healthy (n = 64)	Patients (n = 64)
Age (years range)			43 (29-70)	46 (21-79)
Gender Male (%)			31 (48%)	31 (48%)
Tryptase (µg/L) *			5.6 ± 3.3	99.5 ± 243.4§
Symptom Grading (%)		0	NA	13 (20%)
		1		13 (20%)
		2		26 (41%)
		3		12 (19%)
Clinical Variants (%)	Indolent:		NA	
		MPCM		3 (5%)
		MIS		4 (6%)
		ISM		38 (60%)
	Advanced:		NA	
		SSM		9 (14%)
		ASM		7 (11%)
		SM-AHD		2 (3%)
		MCL		1 (1%)
Skin lesions (%)			NA	30 (47%)
Anaphylaxis (%)			NA	19 (30%)
Urticaria (%)			NA	35 (55%)
Flushing (%)			NA	46 (72%)
Pruritus (%)			NA	51 (80%)

*Data are expressed as median values ± SD. ASM: aggressive systemic mastocytosis; ISM: indolent systemic mastocytosis; MCL: mast cell leukemia; MIS: mastocytosis in skin; MPCM: macupapular coutaneous mastocytosis; SM-AHD: systemic mastocytosis associated with hematologic disease; SSM: smouldering systemic mastocytosis; NA: not applicable. Data were analyzed by t-test.

§ $p < 0.005$

Table 2. Characteristics of 64 adult patients with mastocytosis

Patient No.	Sex	Age	Disease Category	Tryptase µg/L	Symptom Grading
1	F	26	ISM	14.4	0
2	F	28	MPCM	5.7	0
3	M	49	MPCM	2.9	0
4	M	32	ISM	95.5	0
5	M	52	ISM	17.2	0
6	F	59	ISM	44.8	0
7	M	44	ISM	5.6	0
8	F	32	ISM	10.1	0
9	M	40	MIS	1.5	0
10	M	55	ISM	106	0
11	F	61	ISM	40.3	0
12	F	31	ISM	11.8	0
13	M	52	ISM	60	0
14	M	39	ISM	37.3	1
15	M	21	MPCM	5.8	1
16	M	47	ISM	66	1
17	F	44	SSM	46.1	1
18	F	57	ISM	59.2	1
19	F	43	ISM	17.7	1
20	F	35	ISM	46.1	1
21	M	44	ISM	9.6	1
22	F	50	ISM	24.4	1
23	F	36	SM-AHD	9.8	1
24	M	51	ISM	34.7	1
25	F	30	MIS	6.3	1
26	F	28	ISM	33.3	1
27	M	79	ASM	150	2
28	F	23	ISM	6.87	2
29	M	48	SSM	16.2	2
30	M	52	ISM	1.7	2
31	M	41	ISM	18.8	2
32	M	28	ISM	24.6	2
33	M	37	SSM	717	2
34	M	59	ISM	57.3	2
35	F	44	SSM	128	2
36	M	44	ISM	167	2
37	F	35	ISM	27.7	2
38	F	52	ISM	37.8	2
39	M	54	ISM	44.1	2
40	M	37	MIS	18	2
41	F	32	MIS	11.6	2
42	M	56	ISM	51.9	2
43	F	79	SM-AHD	54.8	2
44	M	43	ASM	23.8	2
45	F	48	ISM	21.2	2

Table 2 (continued)

Patient No.	Sex	Age	Disease Category	Tryptase µg/L	Symptom Grading
46	M	59	ISM	68.7	2
47	F	48	ISM	56.4	2
48	F	34	ISM	30.8	2
49	F	54	ISM	59.4	2
50	F	41	ISM	32.8	2
51	M	69	ASM	532	2
52	M	40	ASM	290	2
53	F	59	ASM	720	3
54	M	76	MCL	1145	3
55	M	51	ASM	159	3
56	M	63	SSM	26.2	3
57	F	24	SSM	17.5	3
58	F	46	ASM	1.5	3
59	F	72	ISM	92	3
60	F	57	SSM	121	3
61	F	38	ISM	61.9	3
62	M	53	SSM	231	3
63	F	58	ISM	146	3
64	F	60	SSM	112	3

ASM: aggressive systemic mastocytosis; ISM: indolent systemic mastocytosis; MCL: mast cell leukemia; MIS: mastocytosis in skin; MPCM: macupapular coutaneous mastocytosis; SM-AHD: systemic mastocytosis associated with hematologic disease; SSM: smouldering systemic mastocytosis.

Table 3. Statistical correlation parameters between MCs mediators

Correlated Mediators	r^2	*p*	Correlation
VEGF-A *vs* ANGPT1	0.0009948	0.8000	N.S.
VEGF-A *vs* ANGPT2	0.003016	0.6639	N.S.
VEGF-A *vs* VEGF-C	0.001393	0.7643	N.S.
VEGF-A *vs* PLA_2	0.002925	0.6763	N.S.
VEGF-A *vs* PLC	0.01545	0.3358	N.S.
VEGF-A *vs* Tryptase	0.001427	0.7688	N.S.
ANGPT1 *vs* ANGPT2	0.01895	0.2741	N.S.
ANGPT1 *vs* VEGF-C	0.001482	0.4741	N.S.
ANGPT1 *vs* PLA_2	0.01410	0.3580	N.S.
ANGPT1 *vs* PLC	0.004822	0.5918	N.S.
ANGPT1 *vs* Tryptase	0.01536	0.3332	N.S.
ANGPT2 *vs* PLA_2	0.02815	0.1924	N.S.
ANGPT2 *vs* PLC	0.009743	0.4453	N.S.
ANGPT2 *vs* Tryptase	0.08140	0.0258	Positive

Table 3 (continued)

Correlated Mediators	r^2	p	Correlation
VEGF-C *vs* PLA_2	0.003118	0.6664	N.S.
VEGF-C *vs* PLC	0.01038	0.4308	N.S.
VEGF-C *vs* Tryptase	0.1324	0.0034	Positive

Data were assessed by Spearman's correlation analysis and reported as coefficient of correlation (r). $p<0.05$ was considered statistically significant. N.S.: not significant.

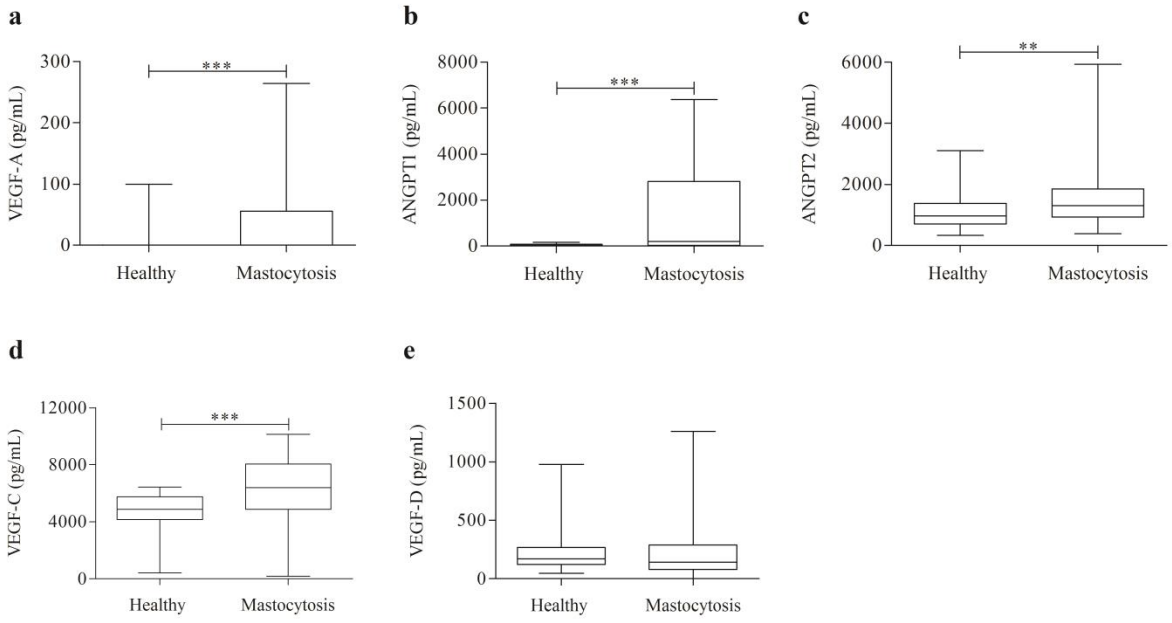

Figure 1. VEGF-A (**a**), ANGPT1 (**b**), ANGPT2 (**c**), VEGF-C (**d**) and VEGF-D (**e**) serum levels in healthy donors and in patients with mastocytosis. Data are shown as the median (horizontal black line), the 25th and 75th percentiles (boxes) and the 5th and 95th percentiles (whiskers) of 64 patients with mastocytosis and 64 healthy donors. ** p<0.01; ***p<0.001

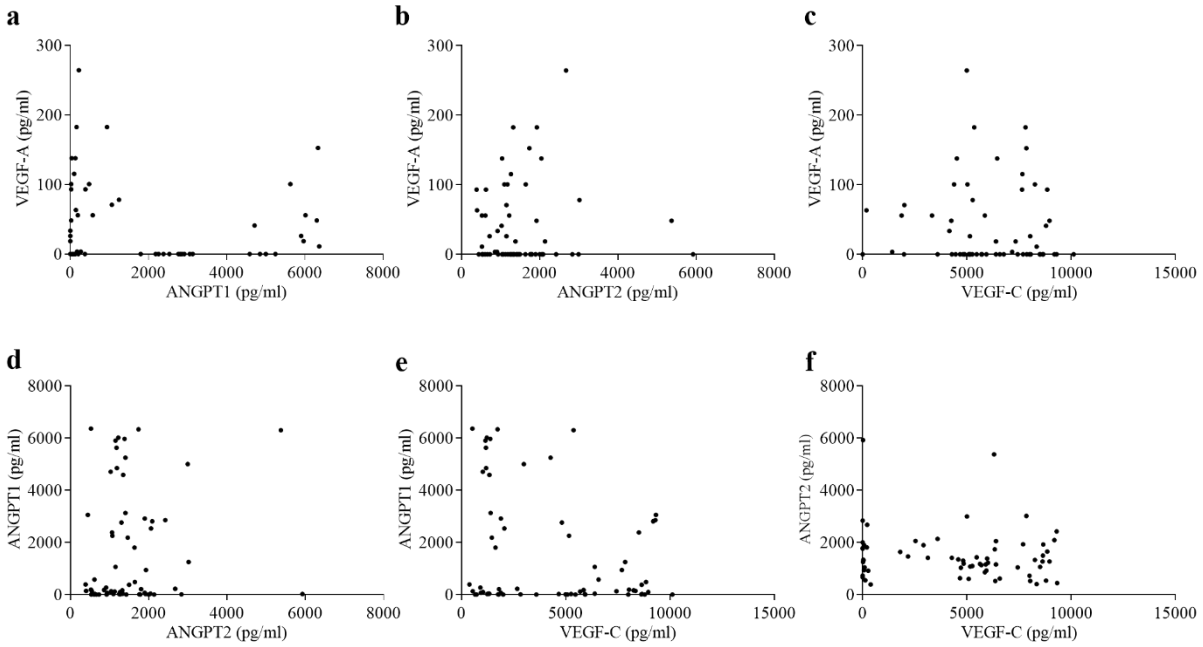

Figure 2. Correlations between serum concentrations of VEGF-A and ANGPT1 (**a**), ANGPT2 (**b**) and VEGF-C (**c**) in patients with mastocytosis. Correlations between ANGPT1 and ANGPT2 (**d**) and VEGF-C (**e**) in patients with mastocytosis. Correlations between ANGPT2 and VEGF-C (**f**) in patients with mastocytosis. Spearman's correlation coefficients (r) were calculated.

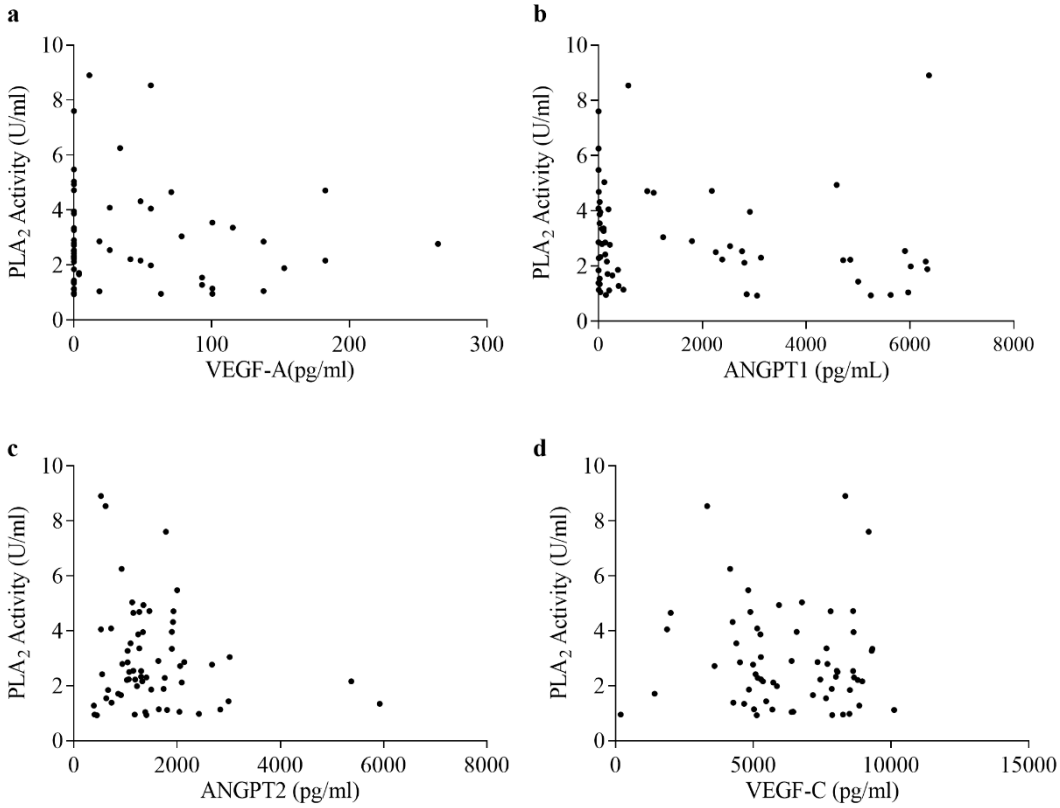

Figure 3. Relationships among VEGF-A, ANGPT1, ANGPT2, VEGF-C and PLA_2 serum concentrations. Correlations between two variables VEGF-A and PLA2 (**a**), ANGPT1 and PLA2 (**b**), ANGPT2 and PLA2 (**c**) and VEGF-C and PLA2 (**d**) were assessed by Spearman's correlation analysis. and reported as coefficient of correlation (r).

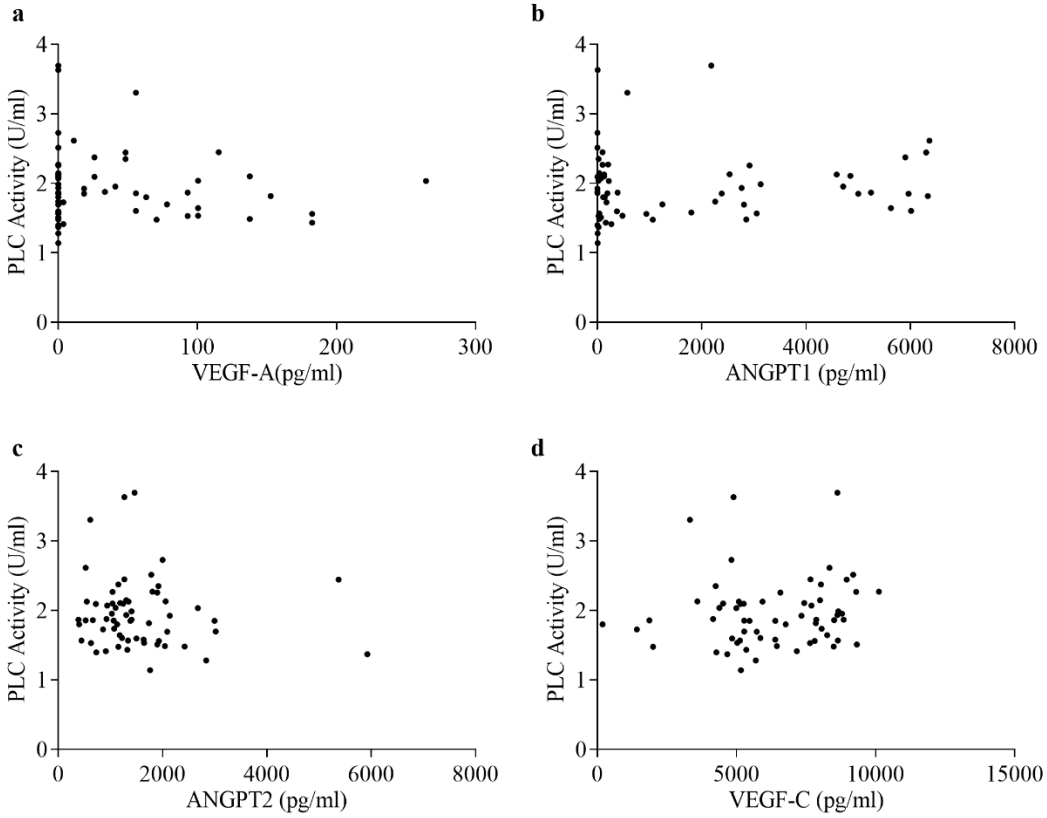

Figure 4. Relationships among VEGF-A, ANGPT1, ANGPT2, VEGF-C and PLC serum concentrations. Correlations between two variables VEGF-A and PLC (**a**), ANGPT1 and PLC (**b**), ANGPT2 and PLC (**c**) and VEGF-C and PLC (**d**) were assessed by Spearman's correlation analysis. and reported as coefficient of correlation (r).

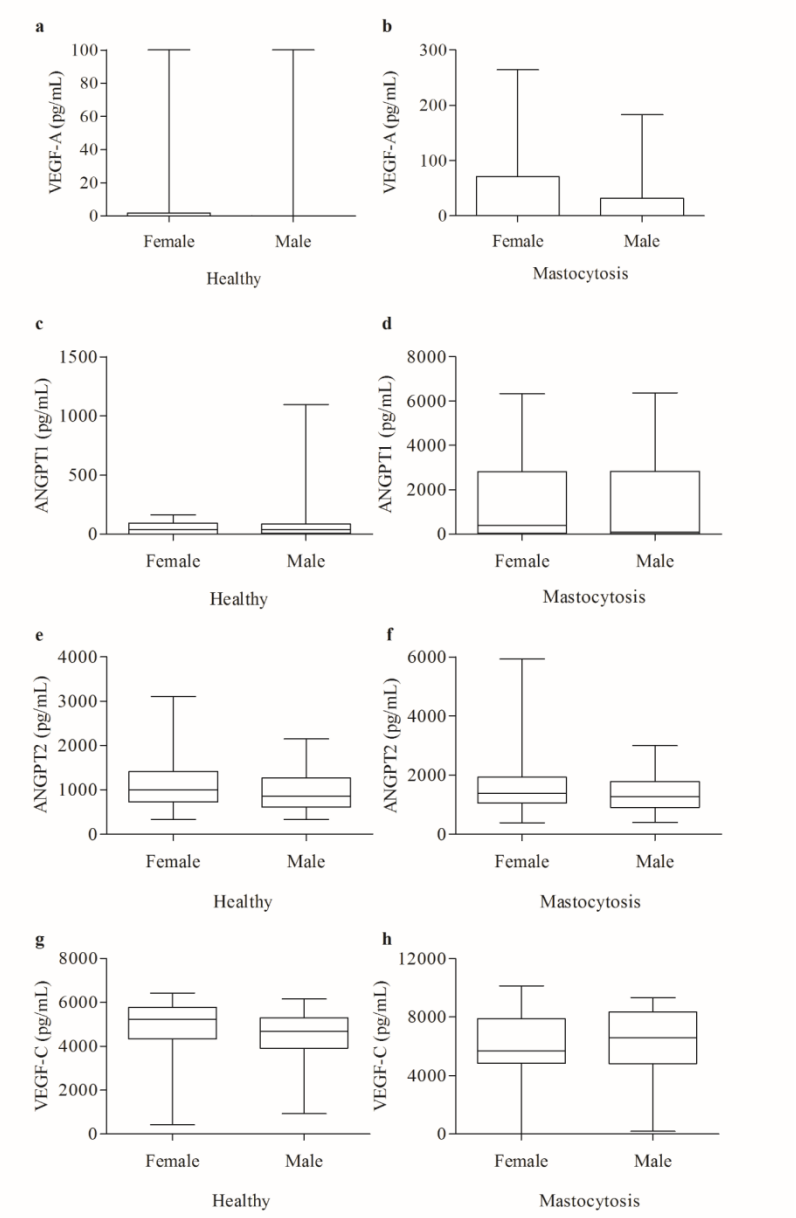

Figure 5. Relationships between VEGF-A, ANGPT1, ANGPT2 and VEGF-C serum levels and gender of mastocytosis patients and healthy donors. VEGF-A (**a**-**b**), ANGPT1 (**c**-**d**), ANGPT2 (**e**-**f**) and VEGF-C (**g**-**h**) serum concentrations were measured in females (n=25) and males (n=22) healthy donors (**a**, **c**, **e**, **g**) and in females (n=33) and males (n=31) mastocytosis patients (**b**, **d**, **f**, **h**).

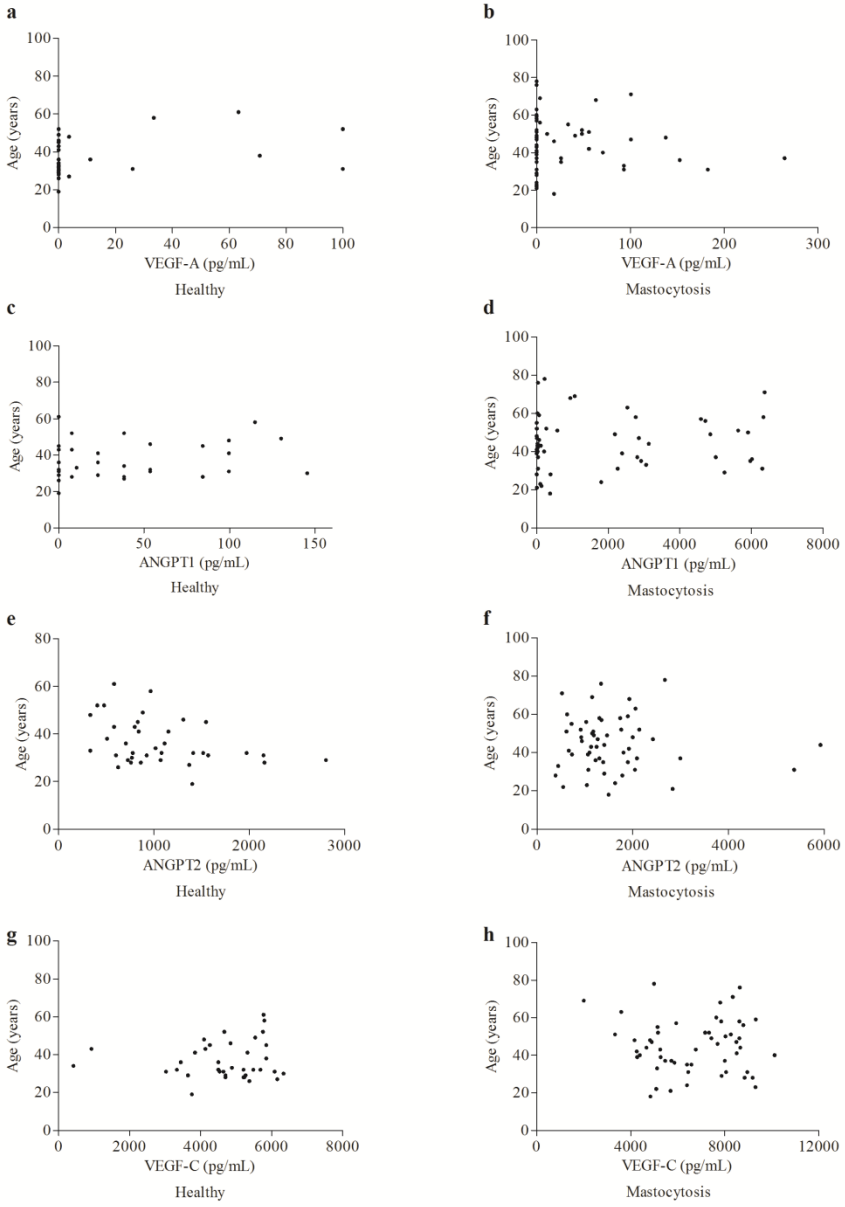

Figure 6. Correlations between VEGF-A, ANGPT1, ANGPT2 and VEGF-C serum levels and age of patients affected by mastocytosis and healthy donors. VEGF-A (**a**-**b**), ANGPT1 (**c**-**d**), ANGPT2 (**e**-**f**) and VEGF-C (**g**-**h**) serum concentrations were measured in healthy donors (age range: 29-70 years; median age 43 years) (**a**, **c**, **e**, **g**) and in patients with mastocytosis (age range: 21–79 years; median age 46 years). Correlations between two variables: VEGF-A (**a**-**b**), ANGPT1 (**c**-**d**), ANGPT2 (**e**-**f**), VEGF-C (**g**-**h**) and age were assessed by Spearman's correlation analysis and reported as coefficient of correlation (r)

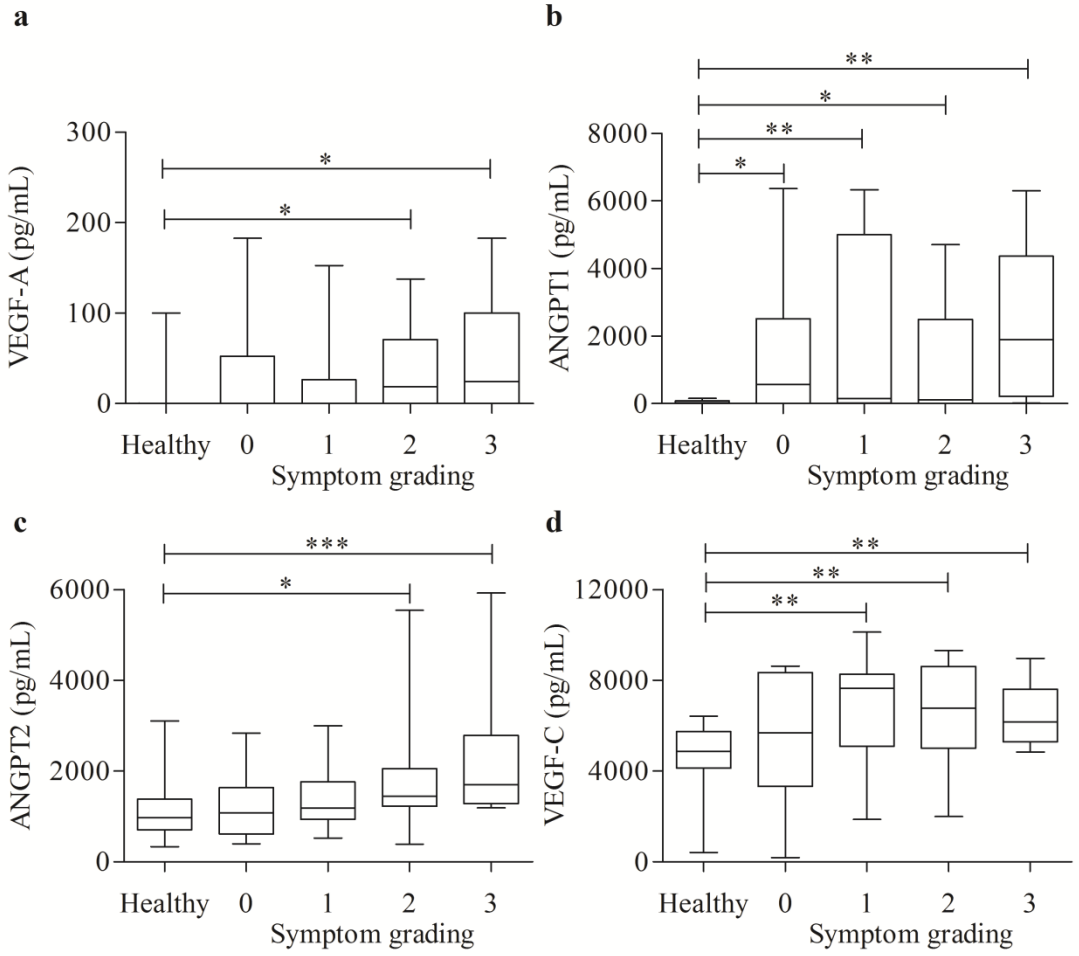

Figure 7. Effects of symptom grading on serum concentrations of VEGF-A (**a**), ANGPT1 (**b**), ANGPT2 (**c**) and VEGF-C (**d**). Serum levels of VEGFs and ANGPTs were measured in 13 patients with symptom grading 0, 13 patients with symptom grading 1, 20 patients with symptom grading 2 and 12 patients with symptom grading 3. *p<0.05; ** p<0.01; ***p<0.001

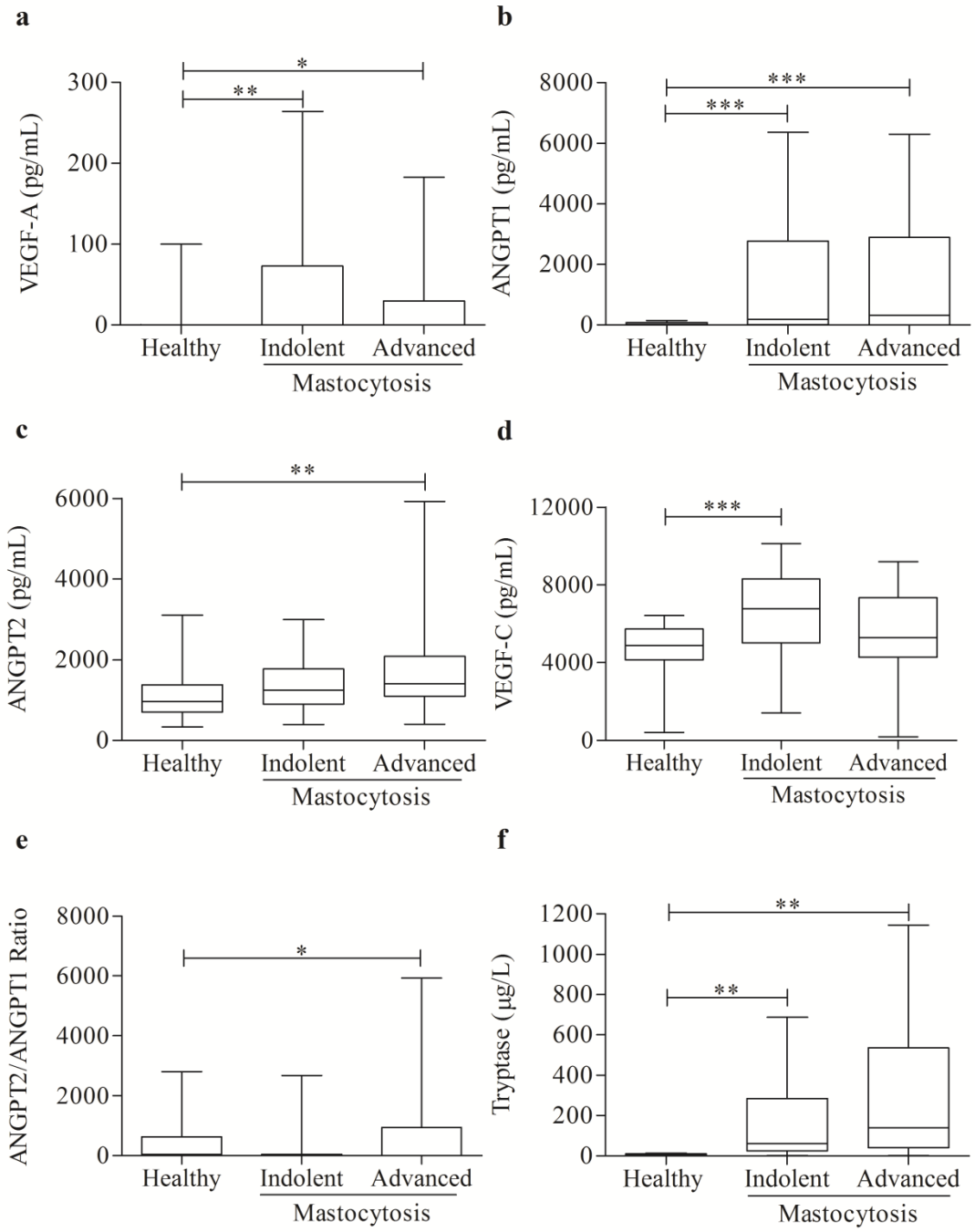

Figure 8. Effects of clinical variants of mastocytosis on serum concentrations of VEGF-A, VEGF-C, ANGPT1, ANGPT2, ANGPT2/ANGPT1, ratio, tryptase. VEGF-A (**a**), ANGPT1 (**b**), ANGPT2 (**c**), VEGF-C (**d**), ANGPT2/ANGPT1 (**e**) and tryptase (**f**) serum levels were determined in 64 healthy controls, in 45 patients with indolent variants and in 19 patients with advanced variants. *p<0.05; ** p<0.01; ***p<0.001

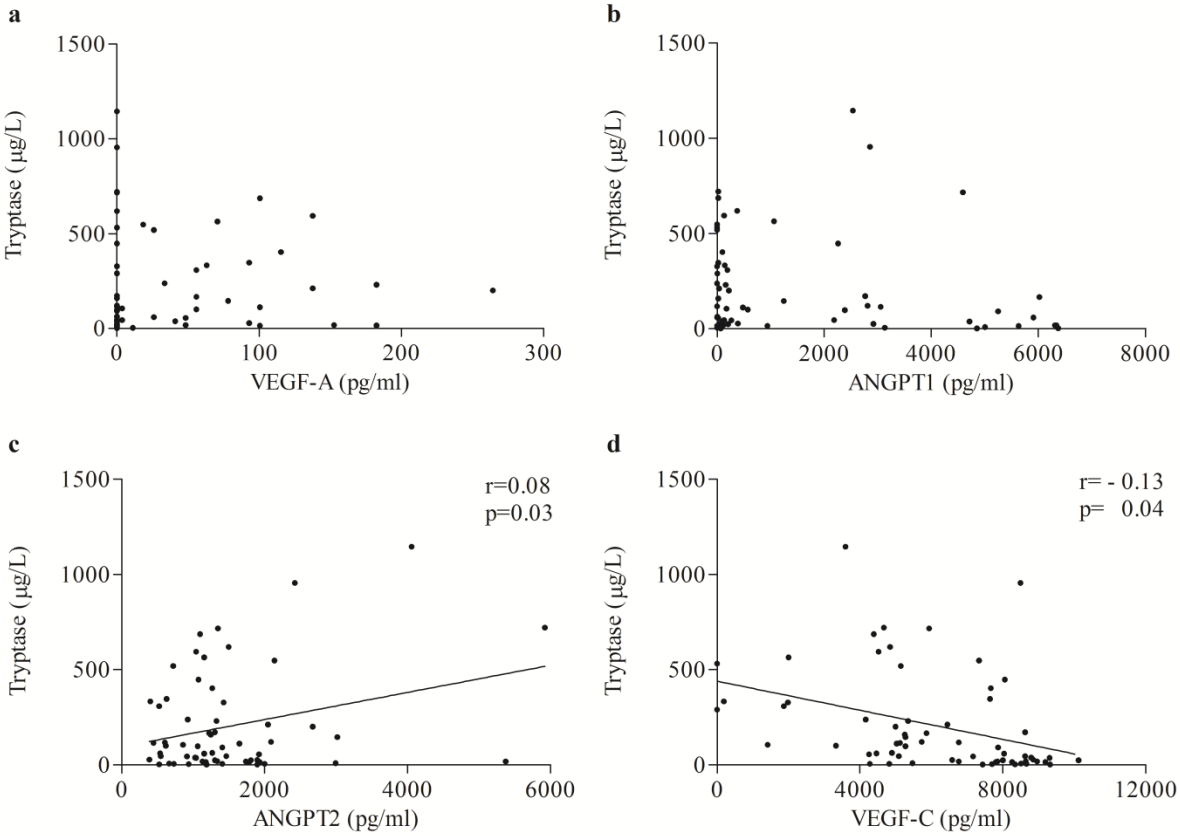

Figure 9. Correlations between VEGF-A, ANGPT1, ANGPT2, VEGF-C and tryptase concentrations. Correlations between two variables: VEGF-A and tryptase (**a**), ANGPT1 and tryptase (**b**), ANGPT2 and tryptase (**c**) and VEGF-C and tryptase (**d**) were assessed by Spearman's correlation analysis and reported as coefficient of correlation (r). $p<0.05$ was considered statistically significant.

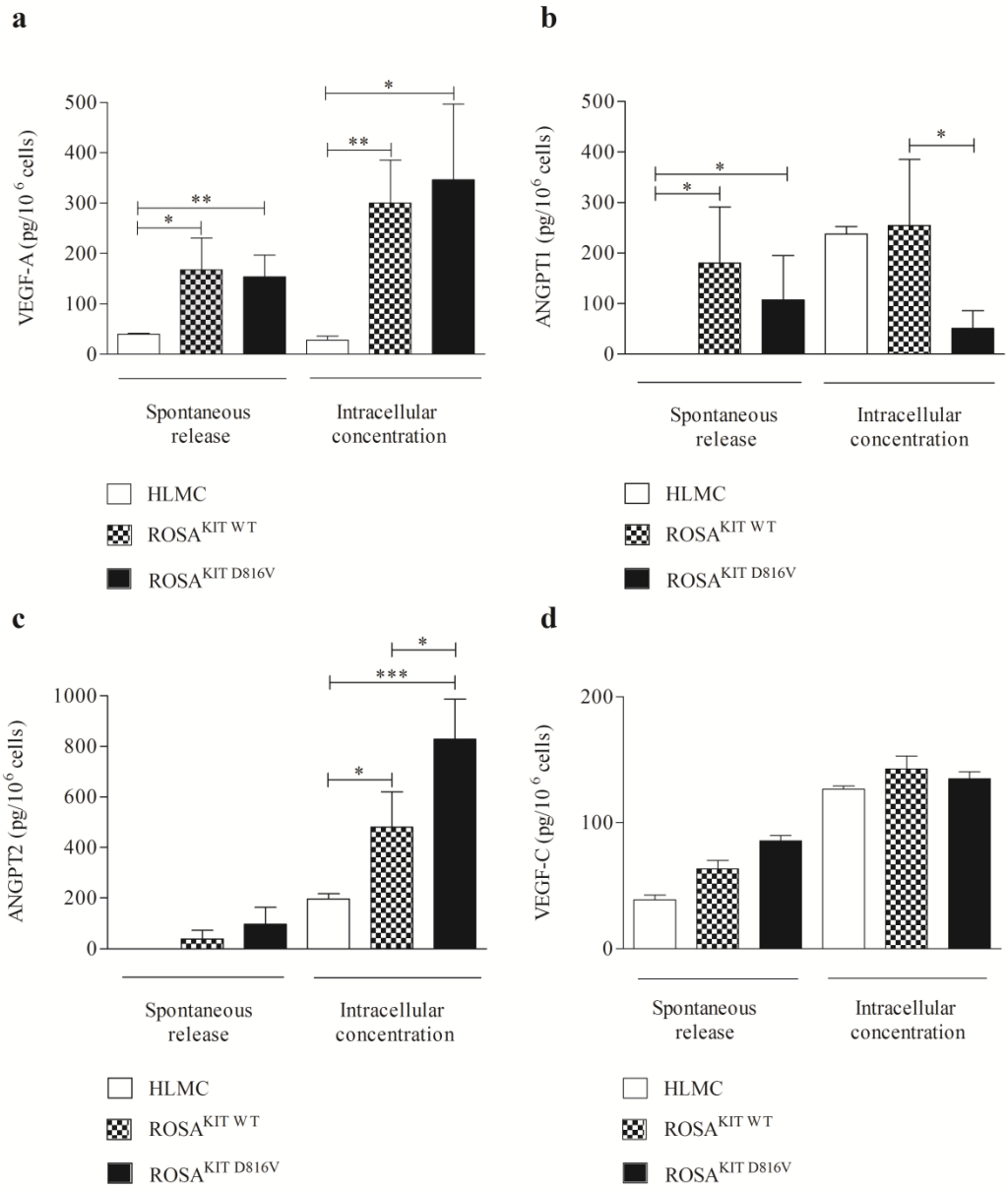

Figure 10. Spontaneous release and intracellular concentrations of VEGF-A (**a**), ANGPT1 (**b**), ANGPT2 (**c**), and VEGF-C (**d**) from human lung mast cells (HLMC), ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816}$. ROSA$^{KIT\ WT}$ and ROSA$^{KIT\ D816V}$ were incubated (5% CO2, 37°C, 24 h) with and without SCF (80 ng/ml), respectively. Data are the mean ± SD of 5 independent experiments. *p<0.05; *p<0.01; ***p<0.001