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Abstract

Background: Upregulation of endogenous angiostatin levels may constitute a novel anti-angiogenic, and therefore anti-tumor therapy. In vitro, angiostatin generation is a two-step process, starting with the conversion of plasminogen to plasmin by plasminogen activators (PAs). Next, plasmin excises angiostatin from other plasmin molecules, a process requiring a donor of a free sulfhydryl group. In previous studies, it has been demonstrated that administration of PA in combination with the free sulfhydryl donor (FSD) agents captopril or N-acetyl cysteine, resulted in angiostatin generation, and anti-angiogenic and anti-tumour activity in murine models.

Methods: In this study we have investigated the angiostatin generating capacities of several FSDs. D-penicillamine proved to be most efficient in supporting the conversion of plasminogen to angiostatin in vitro. Next, from the optimal concentrations of tPA and D-penicillamine in vitro, equivalent dosages were administered to healthy Balb/c mice to explore upregulation of circulating angiostatin levels. Finally, anti-tumor effects of treatment with tPA and D-penicillamine were determined in a human melanoma xenograft model.

Results: Surprisingly, we found that despite the superior angiostatin generating capacity of D-penicillamine in vitro, both in vivo angiostatin generation and anti-tumour effects of tPA/D-penicillamine treatment were impaired compared to our previous studies with tPA and captopril.

Conclusion: Our results indicate that selecting the most appropriate free sulfhydryl donor for anti-angiogenic therapy in a (pre)clinical setting should be performed by in vivo rather than by in vitro studies. We conclude that D-penicillamine is not suitable for this type of therapy.

Background

Angiogenesis is an essential step in both tumour growth and the formation of distant metastases. Therefore, inhibition of tumour angiogenesis is currently being explored as a novel anti-tumour treatment [1-5].
Angiostatin has been shown to possess anti-angiogenic effects both in vitro and in vivo. In vitro, angiostatin inhibited endothelial cell migration, proliferation and tube formation [8-13]. In vivo, administration of angiostatin – either alone, or in combination with radiotherapy or chemotherapy – resulted in potent inhibition of tumour growth and metastasis formation in several animal tumour models [14,14-19].

Application of naturally occurring anti-angiogenic molecules in a clinical setting may be especially attractive, as these compounds have been shown to combine limited toxicity with the absence of development of drug resistance in several animal tumour models [20,16]. The step from animal model to clinical application, however, has in the case of angiostatin been hampered by problems associated with producing sufficient amounts of biologically active recombinant protein. In addition, several different angiostatin moieties have been described, possibly with different clinical efficacies [9,21,22]. As angiostatin is also present in the circulation of healthy individuals [11], Westphal, manuscript in preparation], boosting the angiostatin generating capacities of the host might provide an alternative for exogenous angiostatin administration.

In vitro, angiostatin is generated via a two-step process [23]. First, plasminogen activators (PAs) convert plasminogen into the active protease plasmin. Next, plasmin excises angiostatin from other plasmin molecules or from plasminogen, in a process requiring a donor of a free sulphydryl (-SH) group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl (S-H) group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl group (FSD). In several recent studies, plasminogen, in a process requiring a donor of a free sulfhydryl group (FSD). In several recent studies, plasminogen, In this paper we have compared the in vitro angiostatin generating capacities of a panel of FSDs. In our hands, D-penicillamine, a structural analog of cysteine, displayed a higher angiostatin generating capacity than either captopril, NAC, or other FSDs. Next, we monitored circulating angiostatin levels in mice treated with D-penicillamine and tPA, and, finally, we assessed the anti-tumour activity of the FSD/plasminogen activator treatment in an human melanoma xenograft model. Surprisingly, the superior in vitro angiostatin generation capacity of D-penicillamine was not reflected in either efficient in vivo angiostatin generation or superior anti-tumour activity. In both assays, D-penicillamine was less effective than captopril, indicating the need for further research into the most optimal free sulfhydryl group donor for clinical applications.

**Methods**

**Angiostatin formation in vitro**

uPA (Sigma-Aldrich Chemie b.v., Zwijndrecht, The Netherlands) or tPA(Actilyse, Boehringer Ingelheim b.v., Alkmaar, The Netherlands) and/or free sulfhydryl donor D-penicillamine, L-cysteine, N-acetyl-L-cysteine, reduced glutathione (Sigma-Aldrich Chemie b.v., Zwijndrecht, The Netherlands) or...
captopril (Bristol-Myers Squibb B.V., Woerden, The Netherlands) were incubated with murine serum (diluted 1:40 in sterile distilled water) at 37°C for 0, 2, 4.5 or 20 hours. Different concentrations of each compound were tested. Angiostatin generation was analyzed by western blot. Conversion of plasminogen to plasmin, and generation of angiostatin were scored semi-quantitatively, as a combination of speed of formation and amount of protein formed, relative to the amount of precursor molecule as follows:

Plasminogen to plasmin:
1 No conversion at any time point
2 Slight conversion at t = 20 hours
3 Slight conversion at t = 4.5 hours
4 Moderate conversion at t = 4.5 hours
5 Moderate conversion at t = 2 hours
6 Considerable conversion at t = 2 hours
7 Complete conversion at t = 2 hours

Plasmin to angiostatin:
1 No conversion
2 Slight conversion
3 Moderate conversion
4 Considerable conversion
5 (Almost) complete conversion

Angiostatin formation in vivo
Healthy BALB/c mice were treated with 0.1 ml 400 mM D-penicillamine (bidaily intraperitoneal injections) and/or tPA (i.v. injection, 80 µg in 100 µl saline). Control mice received saline injections. D-penicillamine administration was started on day 0, 3 days before the first tPA injection. Mice received two tPA injections, on day 3 and on day 7. On day 7, plasma samples were collected prior to tPA injection (t = 0), and 15 minutes, 2, 4, 8, 24, or 48 hours after tPA injection. Plasminogen, plasmin and angiostatin levels in plasma were determined by western blot analysis after lysozyme-sepharose purification.

Purification of angiostatin from plasma by affinity chromatography on lysozyme-sepharose
Lysine-sepharose (Pharmacia Biotech, AB, Uppsala, Sweden) was prepared according to the manufacturer's specifications. 50 µl of lysine-sepharose slurry was added to 50 µl of plasma. After incubation overnight at 4°C under continuous agitation, samples were washed three times with 50 mM phosphate buffer (pH 6.0), followed by incubation at room temperature for 30' with 50 µl 0.5 M NaCl to detach non-specifically bound proteins. Specifically bound proteins were eluted by incubation for 30' at room temperature in 50 µl 200 mM ε-aminocapronic acid. After centrifugation, supernatant was collected, mixed with an equal volume of sample buffer, and stored at -20°C prior to western blot analysis.

Generation of rabbit anti-mouse plasminogen polyclonal antibody
Mouse plasminogen was isolated from plasma by lysozyme-sepharose purification. A NZW rabbit was immunized with plasminogen in complete Freund's adjuvant, followed by boosters with mouse plasminogen in PBS every third week. After three boosters, plasma samples were collected and tested by western blot analysis to determine the anti-plasminogen antibody titer.

SDS-page and western blot analysis
Western blot analysis to detect angiostatin was performed as described previously [26]. Briefly, samples were separated on 10% polyacrylamide gels under reducing conditions, and electro blotted onto Hybond-C-extra nitrocellulose membrane (Amersham Life Science bv., Roosendaal, The Netherlands). For analysis of plasma samples from in vivo experiments, a rabbit polyclonal anti-mouse plasminogen antibody was used (concentration 1: 2000 in blocking solution; our laboratory,[26]), whereas for assessment of in vitro angiostatin generation a polyclonal rabbit-anti-human plasminogen antibody (cross-reactive with mouse plasminogen) was used.

After incubation with peroxidase conjugated goat-anti-rabbit antibody (Dako), blots were developed by chemiluminescence according to the manufacturer's specifications (Roche Diagnostics GmbH).

Human melanoma xenograft experiment
Cell line BLM [van Muijen et al., 1991]. was cultured in Dulbecco’s Modified Eagle Medium (DMEM) supplemented with glutamine (Biowhittaker, Walkersville, MD, USA), 10% fetal calf serum (Integro, Zaandam, The Netherlands) and antibiotics in plastic culture flasks (Costar, Roskilde, Denmark). For inoculation, cultured cells were detached from the culture flask by incubation with 0.05% trypsin/0.02% EDTA/PBS, washed, and resuspended in PBS at a concentration of 10 * 10^6 cells/ml. 1 * 10^6 Cells
were injected s.c. in the flank of male 8–10 weeks-old BALB/c nu/nu mice in a volume of 100 µl. Mice were kept under aseptic conditions.

D-penicillamine administration (0.1 ml of a 400 mM solution, twice daily i.p. injection, controls received saline) was started immediately after tumor take as determined by palpation of the inoculation site. When tumours had reached a volume of 100 mm³ (as determined by length × width × height measurements), intravenous tPA injections (0, or 80 µg in 100 µl saline) were administered 3 times a week, at which time points tumour volumes were determined as well. Animals were sacrificed when tumours reached a size of 1000 mm³. Tumours were removed and stored in liquid nitrogen. In each experiment, at least 5 mice per treatment modality were evaluated. Experiments were repeated three times.

**Immunohistochemical staining of blood vessels in human melanoma xenografts**

Blood vessels were stained immunohistochemically as described previously (ref Westphal). Briefly, aceton fixed 4 µm cryo tissue sections were incubated overnight at 4°C with rat-anti-mouse endothelial cell antibody 9F1 (A generous gift from Dr. A. Hamann, Hamburg, Germany). Biotinylated rabbit-anti-rat antibody (Vector Laboratories, Burlingame, CA) followed by avidin-biotin-peroxidase solution and AEC (Scytek Laboratories, Utah, USA) were used for detection and color development.

**Counting of tumour blood vessels**

The number of 9F1 positive blood vessels in melanoma xenografts was counted in three high-powered fields (magnification 200×) by two independent researchers who were blinded for treatment modality as described previously [32].

**Statistical evaluation**

Statistical significance was assessed using a one-way ANOVA. Probability values of 0.05 or less were considered significant.

**Results**

**Angiostatin generation in vitro**

The optimal concentrations for in vitro angiostatin formation were investigated by incubating murine serum with uPA, tPA, and/or a free sulfhydryl group donor, followed by western blot analysis of the reaction products. Figure 1 illustrates a typical experiment, showing conversion of plasminogen to plasmin and angiostatin by tPA and D-penicillamine. Incubation of serum with D-penicillamine alone did not result in any plasmin or angiostatin formation (figure 1b), whereas substantial amounts of angiostatin were observed after incubating serum with both tPA and D-penicillamine (d). PLG: plasminogen PLM: plasmin ANG: angiostatin
to the other FSDs D-penicillamine induced the rapid and effective plasmin and angiostatin generation.

Figure 3 shows a summary of experiments performed to determine the optimal plasminogen activator (figure 3a and 3b: tPA, figure 3c and 3d: uPA) and D-penicillamine concentrations for in vitro angiostatin generation. Conversion of plasminogen to plasmin (figure 3a and 3c) and plasmin to angiostatin (figure 3b and 3d) were scored as described above.

D-penicillamine and tPA induced conversion of plasminogen to plasmin and plasmin to angiostatin showed a clear dose-dependency. 2 mM D-penicillamine combined with 2 µg/ml tPA or more resulted in complete conversion of plasminogen to plasmin after 2 hours of incubation. Angiostatin formation was optimal at 4 µg/ml tPA and 20 mM D-penicillamine.

Plasmin generation by uPA in the presence of D-penicillamine was already complete at low uPA (0.02 unit/ml) and D-penicillamine (0.2 mM) concentrations. Remarkably, angiostatin formation induced by uPA and D-penicillamine showed an inverse dose-response relationship with regard to the amount of uPA. Whereas higher D-penicillamine concentrations resulted in the formation of more angiostatin, increased levels of uPA resulted in less angiostatin formation.

Since angiostatin formation by uPA and D-penicillamine was subject to inhibition by higher uPA concentrations, all subsequent in vivo experiments were conducted with tPA and D-penicillamine.

**Angiostatin generation in vivo**
To determine whether we could induce angiostatin formation in vivo, either D-penicillamine (0.1 ml of a 400 mM solution, bidaily i.p. injections prior to tPA injection), or tPA (two i.v. injections, 3 days and 7 days after start of the D-penicillamine/saline injections), or a combination of the two, were administered to healthy BALB/c mice. After 7 days, plasma samples were collected prior to the tPA injection (t = 0), and 15 and 120 minutes after tPA injection. Plasminogen, plasmin, and angiostatin levels were analyzed by western blot (figure 4).

In plasma from mice receiving only saline injections (figure 4a) or D-penicillamine (figure 4c), both plasminogen (110 kDa) and plasmin heavy chain (approximately 70 kDa) were observed in the circulation. No detectable levels of angiostatin were present. In mice receiving only tPA (figure 4b), an incomplete conversion of plasminogen to plasmin was observed 15 minutes after tPA injection. After two hours the levels of plasminogen and plasmin had returned to normal. The generation of an angiostatin band at 36 kDa was observed 15 minutes after the tPA injection. 120 Minutes after tPA injection, no angiostatin was detectable anymore.

Administration of both tPA and D-penicillamine resulted in a complete conversion of plasminogen to plasmin, and formation of angiostatin 15 minutes after tPA injection. Remarkably, the increased conversion of plasminogen to plasmin did not result in higher levels of circulating angiostatin compared to injection with tPA alone (figure 4b vs. 4d). Both plasminogen and angiostatin levels had returned to normal two hours after tPA injection.

**Anti-tumour effect of D-penicillamine/tPA treatment**
The anti-tumour effect of D-penicillamine/tPA treatment was assessed in a human melanoma xenograft model.
After s.c. injection of human BLM melanoma cells in the flank, nude mice were treated with D-penicillamine or saline injections (i.p. injections, twice daily when tumour take was observed). The tPA or saline injections (i.v. three times a week) started when tumours reached a size of 100 mm³. Tumour volumes were measured to monitor the effect of the treatment. Figure 5 shows a representative example of three different experiments.

In mice receiving only D-penicillamine injections, a small reduction in tumour growth was observed (23% inhibition, 17 days after start of treatment), whereas tPA alone resulted in a 44% reduction in tumour growth. The combination of D-penicillamine and tPA inhibited tumor growth by 58%. The observed inhibition of tumour growth, however, was not statistically significant (p = 0.08). In contrast to healthy mice, angiostatin was not detectable by western blot analysis of plasma samples collected from xenograft-bearing mice treated with tPA and/or D-penicillamine (data not shown).

**Vascular densities of human melanoma xenografts**

To determine a possible anti-angiogenic effect of the tPA/D-penicillamine treatment, blood vessels in melanoma xenografts were stained with rat-anti-mouse endothelial cell antibody 9F1 and counted in three high-powered microscopic fields (figure 6).

The mean number of blood vessels decreased by 34 and 39% in tumours derived from mice treated with only tPA or D-penicillamine, respectively, compared to tumours from control mice. Remarkably, the reduction in vessel density was less in tumours from mice that had been received the combination treatment (16% compared to control tumours). All observed reductions in vascular density were not statistically significant.

**Discussion**

In a series of recent publications, the positive effect of a combination of a plasminogen activator (PA) and a free sulphydryl group donor (FSD) on *in vitro* and *in vivo* angiostatin generation was described. In addition, treatment with PA plus FSD, or FSD alone, displayed anti-angiogenic and anti-tumour effects in murine xenograft tumour models [24-26] and in a limited number of human patients [27]. This novel approach to anti-angiogenic therapy may utilize approved drugs such as captopril as FSD.

In this paper we set out to identify the most potent FSD with regard to angiostatin generation. In addition, testing different FSDs with different additional properties next to donating an SH group, may shed more light on the actual working mechanism of the anti-angiogenic effects induced by these drugs.

Our *in vitro* data demonstrated that, in the presence of plasminogen activators, all tested FSDs were able to induce angiostatin formation in *vitro*, in accordance with data reported by Gately et al [Gately et al., 1997]. In line with previous experiments with tPA and captopril? [26], we observed formation of angiostatin moieties with molecular weights varying between 30 and 50 kDa under reducing conditions. The 36 and 48 kDa moieties may
represent the 3 and 4 kringle forms of angiostatin, respectively. A dose response curve was observed for the angiostatin formation induced by tPA and D-penicillamine. Remarkably, increasing uPA concentrations in the presence of FSDs did not result in increased angiostatin levels, but rather in an inhibition of the formation of this molecule. The reason for this phenomenon was unclear. Hypothesizing, it could be that (too) high levels of uPA, cause the activation of negative feedback mechanisms, resulting in the inactivation of plasmin, and as a consequence in a reduced generation of angiostatin. For this reason, we decided to perform our in vivo studies with tPA.

Surprisingly, not only angiostatin generation, but also the conversion of plasminogen to plasmin was enhanced by FSD addition, suggesting that this first conversion step is, at least in part, FSD-dependent as well. To our knowledge, this has never been observed before. In future experiments, we will test this plasmin-activating capacity of FSDs. Of all tested FSDs, D-penicillamine was, on a molar basis, most potent in inducing both plasmin and angiostatin formation. Therefore, D-penicillamine was used in all subsequent in vivo studies.

Although the tPA-induced conversion of plasminogen to plasmin in vivo was also increased by co-treatment with D-penicillamine, no increased angiostatin formation compared to treatment with tPA alone was observed. In contrast to the multiple molecular weight forms of angiostatin that we observed in our in vitro experiments, in vivo only the formation of a single angiostatin species of 36 kDa, comparable to angiostatin generated by tPA and captopril in previous studies, could be observed. Different angiostatin moieties might express different anti-angiogenic effects in vivo, although this is at present unclear. Thus far, only in vitro studies have compared the anti-angiogenic properties of plasminogen fragments containing kringle 1–3, 1–4, 1–5 and 5 [Cao et al., 2002; Lucas et al., 1998; Cao et al., 1996].

The fact that plasminogen, plasmin and angiostatin levels had returned to normal within two hours after the tPA injection, suggested a relatively short biological T1/2 of both tPA and angiostatin. Whether angiostatin is subject to quick renal excretion, is degraded to shorter fragments, or disappears from the circulation due to other mechanisms, cannot be concluded from our experiments.

When treating mice bearing human melanoma xenografts, administration with either tPA or D-penicillamine alone resulted in an inhibition of tumour growth (44% and 23%, respectively). Treatment with both drugs resulted in a cumulative inhibition (58%). It should be noted, however, that the observed inhibition of tumour growth was not statistically significant, and therefore was far from convincing. In accordance with this finding, mean vascular densities in treated tumours where somewhat lower than in untreated tumours, but again not statistically significant. Matsubara et al (1989) [33] found that D-penicillamine only reduced endothelial cell proliferation in the presence of copper sulfate. Treatment of D-penicillamine alone did not alter the proliferation. The lack of administration of copper sulfate during our experiments might be the cause of the somewhat disappointing in vivo effects. However, Matsubara et al (1989) [33] also
treated rabbits with D-penicillamine, and these experiments did result into inhibition of vessels growth in the cornea. But their administration route was intravenously, and not intraperitoneal as our route was. This could made the differences in the anti-angiogenic effects of D-penicillamine observed in both experiments.

In contrast to our D-penicillamine data, co-administration of captopril to mice treated with tPA in similar experiments, resulted in a clearly enhanced formation of angiostatin, and in a significant inhibition of tumour growth [26]. We therefore concluded that the superior capacity of D-penicillamine to induce angiostatin formation in vitro compared to captopril and other FSDs, was antagonized by environmental factors present in the living organism, resulting in a failure to significantly inhibit tumour growth.

Several explanations for this finding can be offered. Both captopril and D-penicillamine possess other characteristics that may influence angiogenesis and tumour growth.

First, as discussed previously, the drop in blood pressure induced by captopril-mediated ACE inhibition may account for some of its anti-tumour activity. D-penicillamine does not alter blood pressure.

Second, captopril may inhibit MMP function, thus preventing angiogenesis. D-penicillamine, on the other hand, does not affect blood pressure, but might share with captopril the ability to inhibit MMPs, by chelating metal ions. MMPs require zinc to express their activity. Therefore, chelation of these zinc molecules by D-penicillamine prevents the activation of MMPs. Moreover, it is known
that D-penicillamine suppresses the inhibitory effects of hypochlorous acid (HOCl) on TIMP-1 (tissue inhibitor of metalloproteinase-1). As a consequence, TIMP-1 is not inhibited anymore, and could express its activity: limiting MMP activity [34].

Third, the fact that D-penicillamine binds with high affinity to albumin [35,36] might be of importance. By binding to albumin, the bioavailability, and therefore efficacy, of free circulating D-penicillamine is reduced. D-penicillamine sequestered to albumin may be less capable, or even unable, to donate its SH groups.

The fact that we could not detect angiostatin in tumour-bearing mice treated with tPA or tPA plus D-penicillamine suggested that circulating angiostatin is taken up by the tumour, for instance by binding of angiostatin to tumour blood vessels. As, however, immunohistochemical staining for angiostatin requires a specific antibody that does not stain the precursor (plasminogen) and this is not available, this could not be confirmed.

Another explanation for the absence of angiostatin could be that other anti-angiogenic factors might be present in our model. In our studies with tPA and captopril [26], and D-penicillamine (this paper), as well as in the study published by Agarwal with N-acetyl-cysteine (NAC), it is unclear whether angiostatin was in fact the effector molecule responsible for the observed anti-angiogenic and anti-tumour effects. Although Agarwal described accumulation of angiostatin in tumors derived from mice treated with NAC, no depletion studies were performed.

Agarwal et al. only administered the FSD N-acetyl-cysteine to achieve anti-angiogenic and anti-tumour activity, without the need for additional plasminogen activator administration. In vitro it was shown that tumour-derived VEGF induced expression of uPA and uPAR on HUVEC. In addition, uPA and uPAR expression was also demonstrated on tumour endothelium of NAC-treated mice. Apparently, this endothelium-derived uPA was sufficient to produce angiostatin. This notion is supported by our observations that both captopril and D-penicillamine are able to induce some (although not significant) inhibition of tumour growth. Additionally, captopril alone has been shown to possess anti-tumour activity in a human Kaposi sarcoma patient [37], and in murine tumour models [38,28,29].

Furthermore, plasminogen activators expressed by the tumours used in these experiments, may have contributed to the observed anti-tumour effects after treatment with captopril or D-penicillamine alone. The human melanoma cell line BLM we used in our xenograft growth inhibition experiments expresses high levels of tPA. In both cases, however, administration of exogenous tPA improved anti-tumour activity, suggesting that the efficacy of the N-acetyl-cysteine treatment as reported by Agarwal may benefit from administration of exogenous plasminogen activators as well.

**Conclusion**

In conclusion, recent studies have provided evidence that upregulation of endogenous anti-angiogenic molecules as a novel anti-tumour therapy is feasible. Further studies are required to identify the most efficient plasminogen activators and FSDs, their optimal concentrations, and the appropriate application strategies. Regarding the dramatically different angiostatin generating capacities of D-penicillamine *in vitro* versus *in vivo*, our results indicate that selecting the most appropriate free sulphydryl donor for anti-angiogenic therapy in a (pre)clinical setting should be performed by *in vivo* rather than by *in vitro* studies. Finally, we conclude that D-penicillamine is not suitable for this type of therapy.

**Competing interests**

The author(s) declare that they have no competing interests.

**Authors’ contributions**

RRJdGB: substantial contributions to the conception and design, to the acquisition of data, and to the analysis and interpretation of data, involved in drafting the manuscript and revising it critically, have given final approval of the version to be published.

ILE: substantial contributions to the conception and design, to the acquisition of data, have given final approval of the version to be published.

CNM: substantial contributions to the conception and design, to the acquisition of data, have given final approval of the version to be published.

RMWdW: substantial contributions to the conception and design, to the analysis and interpretation of data, involved in revising the manuscript critically, have given final approval of the version to be published.

TJMR: substantial contributions to the conception and design, to the analysis and interpretation of data, involved in revising the manuscript critically, have given final approval of the version to be published.

JRW: substantial contributions to the conception and design, to the analysis and interpretation of data, involved in revising the manuscript critically, have given final approval of the version to be published.
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