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RESEARCH AND EDUCATION

Assessment of preload, remaining torque, and removal torque in abutment screws under different frictional conditions: A finite element analysis

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ABSTRACT

Statement of problem. Contamination with salivary fluids or blood during the treatment process changes the preload, remaining torque, and removal torque of retained screws, which ultimately affects the resistance to screw loosening. In previous studies, no consensus has been reached as to whether contamination can be used as a lubricant.

Purpose. The purpose of this 3-dimensional (3D) finite element analysis study was to compare the preload, remaining torque, and removal torque under different frictional conditions in the processes of tightening, waiting period, and removal of abutment screws using a numeric method and finite element analysis.

Material and methods. Three-dimensional finite element models of a single implant restoration including a crown, dental implant, abutment, and abutment screw, along with the surrounding bone, were constructed. The geometry of all threaded interfaces was designed as a threaded helix. The Abaqus software was used to perform the dynamic simulation of 3 steps such as tightening, waiting period, and removal. Three static and kinetic friction conditions were considered to determine the effect of different frictional conditions. The values of preload at the tightening step, remaining torque at the waiting period, and removal torque at the removal step were evaluated and compared with theoretically predicted values.

Results. The amount of removal torque required to loosen the abutment screw was smaller than the insertion torque for all frictional conditions. By decreasing the coefficient of friction, the remaining torque and the preload increased, and the torsional relaxation and removal torque decreased.

Conclusions. Although the value of the removal torque decreased by decreasing the coefficient of friction, the resistance to screw loosening increased with the increase of the preload and the increase of the remaining torque in the implant complex assembly. Considering the biological complications of fluid lubricants, clinicians may contaminate the abutment screw with lubricants. Gold-coated screws should also be preferred to noncoated screws. (J Prosthet Dent 2019;121:548.e1-e7)

Because of their biological and biomechanical characteristics, titanium implants have had high success rates in both the functional and esthetic restoration of missing teeth.[1] Predictable patient therapy with an implant-supported prosthesis requires a stable and intimate connection between the implant and the superstructure with retentive screws.[2,3] The success of dental implant-supported restorations depends on biological and biomechanical factors.[4]

Screw loosening is one of the most common complications in implant-supported fixed prostheses, leading to clinical appointments for screw retightening.[5] In a systematic review, Pjetursson et al[6] reported that the incidence of abutment or screw loosening in implant-supported fixed dental prostheses was 5.3% over a 5-year observation period. In another study, Albrektsson et al[7] reported that only 66.4% of patients were completely free from any difficulties.

A failure in prompt detection of abutment screw loosening could lead to screw fracture.[8] Furthermore, secondary problems such as the instability of implant

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Clinical Implications

During the treatment process and in clinical practice, screw joint stability can be affected by fluid contamination with saliva and blood. Clinicians must be fully aware of factors such as contamination and surface coating that increase resistance to screw loosening.

complex and peri-implant bone resorption might occur after screw loosening.[3,9,10]

During the screw tightening process, insertion torque is neutralized by frictional forces in contact regions between the threads of the implant bore and screw threads and also between the screw head and the abutment.[11] The magnitude of the resulting contact frictional forces along the axis of the screw in the thread or head regions is called preload.[11] By applying torque and its consequent elongation, a screw can be considered to have elastic properties similar to a tensioned spring.[12,13]

The screw preload is created to produce a clamping force between the abutment and implant to make the screw stable against external forces.[3,14-16] Budynas and Nisbett[17] formulated Equation (4) for calculating the required torque for screw insertion (T_{In}^{W}) and Equation (6) for calculating the required torque for screw removal (T_{Re}^{W}):

$$T_{In}^{Th}=\frac{d_m}{2}\times\frac{L+(\mu\times\pi\times d_m\times\sec\alpha)}{(\pi\times d_m)-(\mu\times L\times\sec\alpha)}\times F=K_{In}^{Th}\times F \quad (1)$$

$$T_{Re}^{Th}=\frac{d_m}{2}\times\frac{(\mu\times\pi\times d_m\times\sec\alpha)-L}{(\pi\times d_m)+(\mu\times L\times\sec\alpha)}\times F=K_{Re}^{Th}\times F \quad (2)$$

$$T^{C}=\frac{\mu}{3\sin\beta}\times\frac{D^3-d^3}{D^2-d^2}\times F=K^{C}\times F \quad (3)$$

$$T_{In}^{W}=T_{In}^{Th}+T^{C}=\left(K_{In}^{Th}\times F\right)+\left(K^{C}\times F\right)=\left(K_{In}^{Th}+K^{C}\right)\times F=K_{In}\times F \quad (4)$$

$$F=\frac{T_{In}}{K_{In}}=\frac{35}{K_{In}} \quad (5)$$

$$T_{Re}^{W}=T_{Re}^{Th}+T^{C}=\left(K_{Re}^{Th}\times F\right)+\left(K^{C}\times F\right)=\left(K_{Re}^{Th}+K^{C}\right)\times F=K_{Re}\times F, \quad (6)$$

where Th represents the thread region, C represents the conical region, W represents the wrench region, In represents the insertion step, and Re represents the removal step. In addition, d_m is the pitch diameter, L is the thread pitch, μ is the coefficient of friction, α is the half angle of thread, D is the outer diameter of head friction, d is the inner diameter of head friction, β is the cone angle head, and F is the preload (Fig. 1).

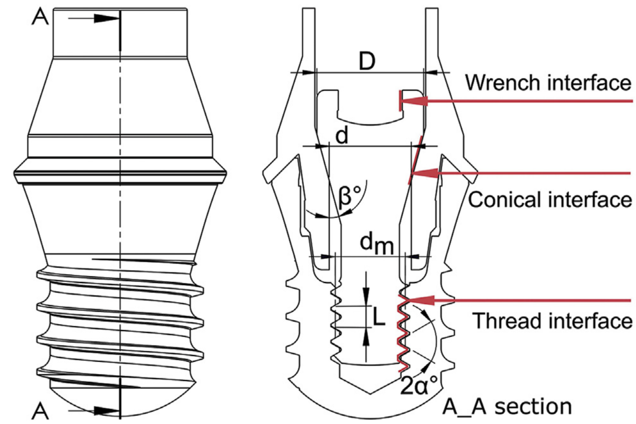

Figure 1. Geometric parameters of implant complex. D=2.6 mm; d=2.015 mm; L=0.4 mm; d_m=1.66 mm; $\alpha=2\beta=\pi/6$.

A decisive factor in the screw loosening is preload. Bowman et al[18] have recommended the optimum amount of preload to be equal to 75% of the proof load. The proof load is obtained from the following Equation (7)[17]:

$$F_p=0.85\times A_r\times S_y \quad (7)$$

$$F_i=0.64\times A_r\times S_y, \quad (8)$$

where A_r is the area of thread root[11] and S_y is the yield strength.

Furthermore, according to the study conducted by Bickford,[11] the process of screw loosening occurs in 2 steps. First, external forces such as mastication cause vibration and slippage of the threads, which release the tensile force of the screw and consequently reduce the preload. The second step begins as the preload drops below a critical value. At this step, external loads cause the screw to rotate in a counterclockwise direction, and the joint loses its function.

Parameters affecting the preload include the insertion torque, screw head, thread design, thread number, screw diameter, mechanical properties of materials,[19] and coefficient of friction between contact surfaces.[12,20,21] Friction coefficient is influenced by hardness, surface finishing, and lubricant (either dry or wet).[2,12,22] To reduce the coefficient of friction, implant manufacturers have used gold, diamond-like carbon, or nitride coating as a dry lubricant.[15,23-25] Higher preload is achievable with a lower coefficient of friction for the same insertion torque.[11,21,23]

Furthermore, the cover screw, healing abutment, prosthetic abutment, and abutment screw are closed and opened several times during the treatment. Hence, contamination with saliva or blood can fill the implant thread bore and subsequently change the frictional conditions of the surfaces. The effect of contamination and coating on preload, resistance to screw loosening, and removal torque is unclear, with inconsistencies reported. Some have reported[2,3,26] that the preload increased with contamination by wet lubricants (blood or saliva) and dry lubricants (gold, dimond-like carbon [DLC], or nitride coating) because of the reduction of coefficient of friction. However, Lee at al[27] concluded that contamination with titanium nanoparticles decreased the preload. Also, the effect of contamination on resistance to screw loosening is unclear. Some have reported[26,28] a positive effect, whereas others[3,27,29,30] concluded a negative effect. Nigro et al[26] reported that the use of lubricant increased the removal torque, but others[3,27-30] reported a lower removal torque for coated screws or those contaminated with a lubricant.

These conflicting results have been attributed to differences in the implant system, material, and methodologies,[29] although the screw tightening and removal processes may have been misunderstood. Therefore, the purpose of this study was to compare the preload, remaining torque, and removal torque in different frictional conditions in the processes of tightening, waiting period, and removal of the abutment screw by using a numerical method and finite element analysis. The research hypothesis was that the use of lubricants would have a positive effect on the resistance to screw loosening.

MATERIAL AND METHODS

Computer-aided design (CAD) models of a trabecular bone surrounded by a cortical bone were constructed by using a 3D product software program (CATIA V5-6R2016; Dassault Systèmes) to model appropriate boundary conditions. A premolar restoration with 2 separated regions of metal framework and porcelain was modeled by using a CAD software program (SOLIDWORKS 2016; Dassault Systèmes).

The exact geometric dimensions of a single implant (Roxolid SLActive 033.043S; Institut Straumann AG), an abutment (048.642, RN synOcta gold abutment; Straumann), and an abutment screw (048.356, synOcta basal screw; Straumann) were measured, and their CAD models were prepared by using the CAD software SOLIDWORKS 2016 (Dassault Systèmes). The exact threaded helix geometries were constructed for the inner threads in the implant and the bone. The outer threads of the abutment screw and the implant were also constructed using the same method (Fig. 2).

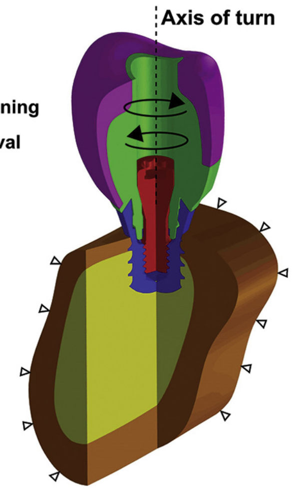

Figure 2. Three-dimensional models of implant complex surrounded by bone.

Table 1. Mechanical properties of materials

Material Component	Young Modulus (GPa)	Poisson Ratio	Density (g/cm^3)	Ultimate Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Gold abutment*	136	0.37	17.5	765	480	10 Min
Titanium grade 4*	110	0.34	4.5	550	–	15 Min
Porcelain[31]	68.9	0.28	2.44	145	–	2 Max
Cortical bone[32]	13.70	0.3	3	190	–	2 Max
Trabecular bone[32]	1.37	0.3	3	10	–	2 Max

*From manufacturer specifications.

The materials were considered to be isotropic and homogeneous. The mechanical behavior of the materials in the implant complex was considered in both elastic and plastic regions. However, the behavior of the materials in the surrounding bone was only considered in the elastic region (Table 1).

A dynamic explicit simulation of the screw tightening and removal processes was performed. The CAD models were imported into a finite element analysis software program (Abaqus; Dassault Systèmes Simulia Corp). A free meshing technique with a linear geometrical order was used to generate tetrahedral elements (Fig. 3). Table 2 presents the number of elements for each component. The elements of the implant-bone interface were defined as "tie" on the assumption that complete osseointegration exists between the implant and its surrounding bone.

Explicit simulation was performed in 3 steps. First, the abutment screw was tightened with a virtual wrench to achieve the recommended 35-Ncm torque. Then, the virtual wrench was removed for 5 seconds without any functional forces (waiting period). Finally, the virtual

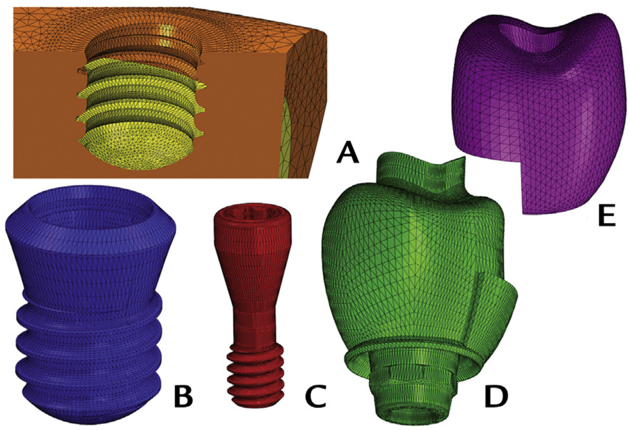

Figure 3. Finite element models. A, Bone. B, Fixture. C, Abutment screw. D, Abutment+metal frame. E, Porcelain.

Table 2. Number of tetrahedral elements

Part	Number of Elements
Implant	84 528
Abutment screw	34 881
Abutment+metal frame	54 401
Porcelain	26 649
Cortical bone	50 053
Trabecular bone	48 025

wrench was turned in the opposite direction of tightening to loosen the abutment screw.

The penalty method and Coulomb friction were used to simulate the frictional conditions between the contact surfaces. To determine the effect of different frictional conditions on the removal torque and preload, 3 different frictional conditions were considered. The kinetic friction coefficients (μ_k) of 0.12, 0.16, and 0.20 were assumed for screw tightening and removal. Also, the static friction coefficients (μ_s) of 0.16, 0.20, and 0.24 were assumed for the waiting period (step 2).[21,33]

The values of wrench torque, conical torque, thread torque, and preload were assessed for the tightening process, waiting period, and removal process of the abutment screws under different frictional conditions. The predicted values of the preload (Eq. 5) and the removal torque (Eq. 6) were calculated and compared with those obtained from the finite element method.

RESULTS

The values of wrench torque, conical torque, thread torque, and preload under different frictional conditions are shown with respect to the time taken for the 3 steps such as closing, waiting period, and opening of abutment screws (Fig. 4). The maximum values of the preload in the tightening process (first step) were 484 N (μ_k=0.12), 373 N (μ_k=0.16), and 303 N (μ_k=0.20). The average magnitudes of the remaining torque in the waiting period (second step) were 4.25 Ncm (μ_k=0.12), 3.62 Ncm (μ_k=0.16), and 3.23 Ncm (μ_k=0.20). The maximum magnitudes of the removal torque in the third step (removal) were 27.66 Ncm (μ_k=0.12), 29.33 Ncm (μ_k=0.16), and 30.04 Ncm (μ_k=0.20).

The comparison between the simulated results obtained from finite element method (FEM) and the predicted results (Eqs. 5 and 6) for the preload and the removal torque as a function of the coefficient of friction is illustrated in Figure 5. The maximum values of the preload in the first and third steps, the average magnitude of the remaining torque in the second step, and the maximum values of the removal torque in the third step are presented in Table 3 for the same insertion torque of 35 Ncm.

DISCUSSION

The results of this study support the hypothesis that the use of lubricants with reduction of the coefficient of friction would result in a positive effect on the resistance to screw loosening. The effect of lubricants either dry (gold coating or diamond-like carbon)[15,23,24,30] or wet (saliva or blood contaminations)[26,27,29,34] has been evaluated in regard to screw loosening. Stability and resistance to screw loosening are affected by changes in the coefficient of friction.[11,23] Moreover, contamination of the abutment screw hole with blood is especially important for bone-level implants.[28]

Previous studies have reported that by decreasing the coefficient of friction, the preload increases,[2,3,26] whereas the removal torque decreases.[3,27-30,34] Furthermore, no consensus has been reached as to whether lubricants can be used. Although some researchers[25,26,28] have suggested the use of lubricants (dry or wet) to prevent screw loosening, others[27,29,30] have suggested avoiding their use. The disagreements may be due to a misunderstanding of the concepts of removal torque and remaining torque.

Because direct measurement of the preload requires a strain gauge and advanced sensing technology, in most studies, the removal torque was used as an indirect method of preload measurement. Finite element method does not have the limitations of the experimental methods such as access to preload measurement. Thus, FEM is an appropriate technique for studying the effect of parameters such as coefficient of friction, screw head design, screw diameter, and the length of the implant fixture and provides qualitative results.

In the present study, the amount of removal torque required to loosen the abutment screw was smaller than the initial torque (35 Ncm) under all frictional conditions (Table 3). This is consistent with the findings of other studies.[27,35-37]

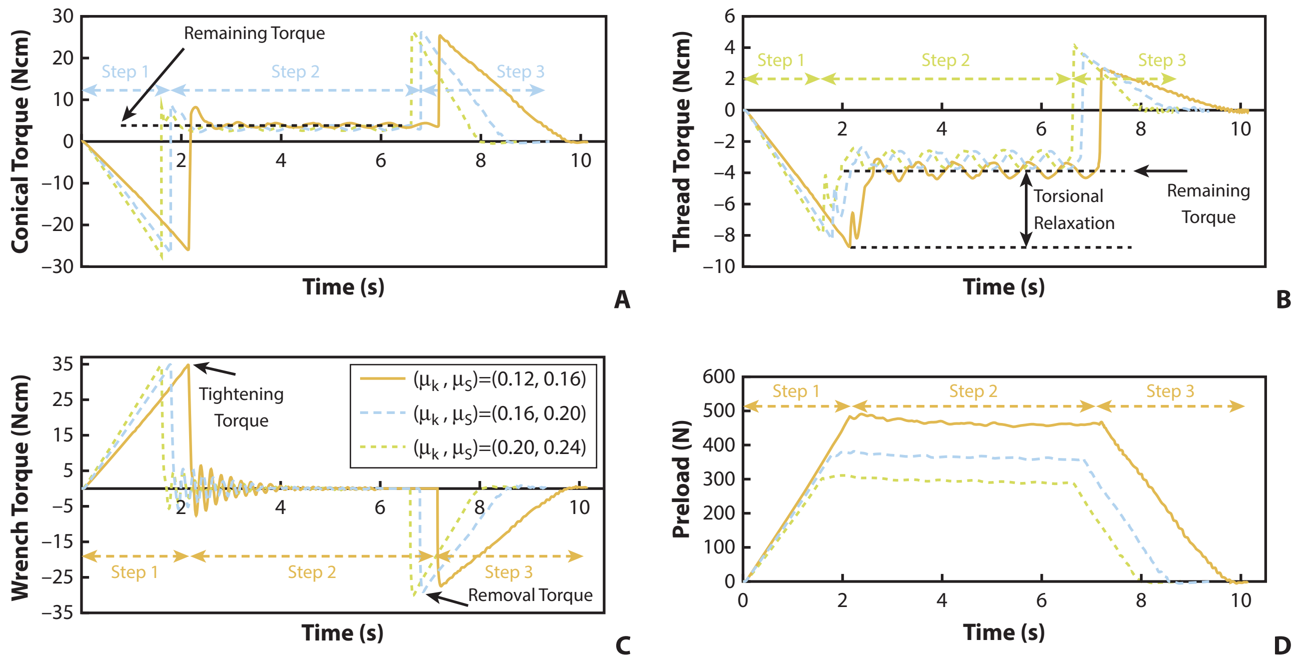

Figure 4. A, Conical torque. B, Thread torque. C, Wrench torque. D, Preload as function of time.

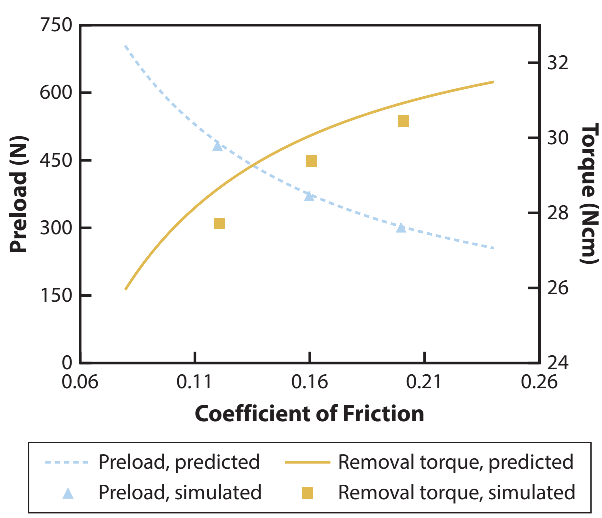

Figure 5. Comparison of simulated and predicted values.

In the abutment screw, the remaining torque at the waiting period and the removal torque at the removal process were measured for all frictional conditions. As illustrated in Figure 4, decreasing the coefficient of friction at the contact surfaces of the implant complex increased the remaining torque and the preload and decreased the torsional relaxation and the removal torque (Table 3). There was good agreement between the FEM results and the predicted results (Fig. 5).

Both the preload and the remaining torque are effective parameters in increasing the resistance to screw loosening. Therefore, factors that reduce the coefficient of friction have a positive effect on stability and resistance to screw loosening.

Taneja et al[38] reported that the shear strength of the bond contaminated with saliva was higher than that contaminated with blood. Furthermore, by increasing the lubricant viscosity, its cohesion is enhanced and a thinner film is created on the contact surfaces.[29] The viscosity of blood (3.33 cP) is lower than that of saliva (1.9 cP).[39] As a result, a higher preload and better stability are expected for the screws contaminated with blood because the screw turns more for the same torque.

The results of the present study are in good agreement with those of previous studies discouraging the use of lubricant (dry or wet) as it can reduce the removal torque.[27,29,30] However, their conclusions incorrectly rejected the use of lubricants in clinical practice because they assumed that removal torque would be the same as the remaining torque.

Gumus et al[29] studied the effects of fluid contamination on removal torque and also measured the mean of removal torques for different contamination conditions: 18.95 Ncm for blood contamination, 19.37 Ncm for salivary contamination, and 21 Ncm for noncontamination. The authors concluded that clinicians should avoid blood contamination because it can cause screw loosening by creating biofilm on the surface of the abutment screw, which decreases the coefficient of friction. However, according to the results of the present study, by decreasing the removal torque before the functional load is applied, the remaining torque in the implant complex increases, which subsequently enhances

Table 3. Values of preload, remaining torque, and removal torque at three different coefficients of friction

Coefficient of Friction	Preload (N)					Removal Torque (Ncm)	
(μ_k, μ_s)	Simulated (First Step)	Simulated (Third Step)	Predicted	Remaining Torque (Ncm)	Torsional Relaxation (Ncm)	Simulated	Predicted
(0.12, 0.16)	484	463	489	4.25	4.51	27.66	28.65
(0.16, 0.20)	373	358	375	3.62	4.68	29.33	30.06
(0.20, 0.24)	303	290	304	3.23	4.74	30.4	30.92

the resistance to screw loosening. Thus, contamination with blood or saliva positively affects the joint stability.

In another study, Lee et al[27] studied the effect of contamination with titanium nanoparticles on the removal torque. The authors incorrectly reported that contamination decreases the preload values in the abutment screw because of the settling effect. However, according to their results, nanoparticles decrease the removal torque before any external force is applied. Therefore, according to the results of the present study, the use of an abutment screw coated with titanium nanoparticles is recommended. As titanium nanoparticles along with fluid lubricant have a positive effect on increasing the preload and remaining torque, they consequently enhance the stability and resistance to screw loosening.

Assuncao et al[30] assessed the maintenance of tightening torque in screws with different material types by measuring the removal torque and concluded that further studies should include the functional load deemed necessary to illustrate the effect the material type of screw has on preload maintenance. Although the maximum amount of removal torque was measured for a noncoated titanium screw type in this study, in the study by Byrne et al,[15] the preload for gold-coated screws was twice that for noncoated titanium screws. Comparisons of their results (not the conclusions) are in good agreement with those of the present study, as by decreasing the coefficient of friction, the amount of removal torque decreased while the amount of preload and remaining torque increased. Consequently, this reduction in coefficient of friction enhanced resistance to screw loosening.

The key issue in applying lubricants (dry or wet) is their overall effect as they can lead to abutment screw failure due to an excessive increase in preload.[11,40] Moreover, because contamination with titanium nanoparticles or chlorhexidine (as a lubricant) was used to decrease the coefficient of friction, further studies are necessary to determine their biologic effect.

CONCLUSIONS

Based on the findings of this FEM analysis, the following conclusions were drawn:

1. Although decreasing the coefficient of friction decreased the value of the removal torque, the resistance to screw loosening within the implant complex assembly increased with the increase in the preload and remaining torque.
2. Gold-coated screws should be preferred to noncoated screws.
3. Clinicians should contaminate the abutment screw with lubricants. However, the biological complications of fluid lubricants need to be considered.

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