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Load-Bearing Capacity of Fiber-Reinforced Composite Abutments and One-Piece Implants

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ABSTRACT

Fiber-reinforced composites (FRC) can potentially help in a physiologic stress transmission due to its excellent biomechanical matching with living tissues. Novel one-piece FRC implants and abutments with two different fiber orientations were loaded until failure to assess the load-bearing capacity, fracture patterns, and precision of fit. The one-piece FRC implants showed significantly higher load-bearing capacity compared to FRC abutments regardless of the fiber orientation (p<0.001). For FRC abutments, bidirectional abutments showed significantly higher loads compared to unidirectional abutments (p<0.001). The type of structure and fiber orientation are strong determinant factors of the load-bearing capacity of FRC implants and abutments.

INTRODUCTION

Current implant systems cannot adjust to occlusal loads similarly as natural teeth with sound periodontal ligaments. Therefore, occlusal loads are transmitted directly to the underlying tissues unless these loads are balanced by shock-absorber elements.[1,2] This transmission of energy is influenced by the material and design of the implant restoration.

Contrary to biomimetic principles, the mechanical properties of traditional implant and prosthetic materials (i.e. metals and ceramics) are superior to the ones of bone and dentine.[3] However, the stiffness of traditional materials in addition to the corresponding load transfer to the surrounding tissues does not appear to affect the long term behavior of implants.[4,5] Nevertheless, it can be postulated that a resilient material would mimic the biomechanics of natural dentition and thus help in transmitting physiologic forces to the underlying tissues.

In the past, the acrylic resin occlusion approach aimed to reduce the load applied on metallic implants. Contrary to this assumption, acrylic resin materials did not have shock-dampening ability and showed high incidence of resin fractures and metallic substructure overloading.[6,7] Metal-composite abutments have recently been proposed as shock-absorber elements.[8,9] However, the poor bonding between composite and metals resulted in weak points showing metal substructure exposure. This fact could be attributed to the mismatch of the modulus of elasticity of both materials.

Fiber-reinforced composites (FRC) seem to fulfill stress principles as these materials are characterized by a low elastic modulus which is close to living tissues but have high fracture and tensile strength.[10] Fiber-reinforced composite materials have been successfully used in restorative and prosthetic dentistry for many years. Its close elastic modulus with dentine allows fabrication of load-bearing substructures without metallic framework. Satisfactory results have been observed after five years of fatigue testing.[11]

The clinical use of FRC implants has shown success in cranial reconstructions.[12] In addition effective FRC implant have been developed in orthopaedics for load-bearing applications.[13,14]

FRC surfaces have shown excellent biocompatibility in oral soft and hard tissues,[15,16] along with a bacterial response similar to current implant abutment materials.[17] Additionally, FRC materials possess several advantages such as good esthetic properties, avoidance of artifacts at CT and MRI imaging, allowance of computer-aid-designing computer-aid-manufacturing (CAD-CAM), and the permission of intraoral adjustments rendering them potential candidates in implant dentistry. However there is still a lack of scientific data about the structural aspects of FRC oral implant devices.

Structural properties of FRC ought to fulfill clinical performance criteria. FRC show directional physical properties hence, a proper design of the fiber orientation is essential to withstand the multidirectional loads existing in the oral cavity. Susceptibility to delamination has been one of the major drawbacks for failure of FRC in high stress-bearing applications.[18] This may be explained by the anisotropic behavior of unidirectional FRC structures. Thereby, design strategies including multidirectional reinforcement to minimize the highly anisotropic behavior of unidirectional FRC could be favorable, although the fracture strength may decrease.

The physiologic maximum bite forces in the incisor area have been reported to range between 40 to 370N.[19,20] Nonetheless, higher parafunctional loads (e.g. bruxism) must be taken into account when selecting a material for oral stress-bearing device. Static load testing until fracture (i.e. load-bearing capacity) is the most commonly used test in preclinical strength assessment/screening of newly developed materials. To the best of our knowledge, there are no published reports that compare the effect of different structural designs of FRC for oral load-bearing applications. Hence, the aims of this *in vitro* study were to evaluate the influence of structure type on the load-bearing capacity, fracture patterns, and precision of fit of FRC implants and abutments.

MATERIALS AND METHODS

Table 1 shows the materials used for the fabrication of FRC specimens.

THREE-POINT BENDING TEST

Rod-shaped Ø 4.0mm and 66mm length unidirectional (longitudinally oriented) and cross-sectioned in plain-weave (concentrically oriented) fiber rods were manufactured as described previously.[10] Briefly, the fibers were pre-impregnated for 48h with light-polymerizable BisGMA-TEGDMA (50-50%) in an incubator (D 06062, Modell 600) at 37ºC. Subsequently, they were subjected to an initial polymerization using a light-emitting diode (LED) polymerizing unit (Elipar S10) for 2 min per side. The irradiance was 950 mW/cm2 measured using a curing radiometer. Subsequently, the rods were post-cured in a Targis Power unit for 25 min at 95 ºC. Additionally, in order to optimize the degree of monomer conversion (CD%), the substrates were post-polymerized for 24 hours in hot-air oven at 120ºC. Three-point bending test was used to determine the flexural strength, flexural modulus, toughness, and load-bearing capacity of FRC rods (n=9). The specimens were tested with a universal testing device (LR 30K plus) adapted to ISO 10477:92 standards[21] (crosshead speed 5.0 mm/min), and the stress-strain curves were recorded with a PC-computer program (Nexygen).

Table 1. Materials used for the fabrication of FRC abutments.

Product	Description	Manufacture	Lot no.	Composition
***E-glass fiber**	Unidirectional fiber	Ahlstrom, Karhula, Finland	11372313	55% SiO_2, 15% Al_2O_3, 22% CaO, 6% B_2O_3, 0.5% MgO, and >1.0% Fe + Na + K
***E-glass fiber**	Bidirectional fiber	Ahlstrom, Karhula, Finland	240299	55% SiO_2, 15% Al_2O_3, 22% CaO, 6% B_2O_3, 0.5%MgO, and >1.0% Fe + Na + K
Stick Resin	Light curing resin	Stick Tech, Turku, Finland	54031672	BisGMA-** TEGDMA*** (50-50%)

* E-glass, electrical glass.
** Bis-GMA, bisphenol A-glycidyl dimethacrylate.
*** TEGDMA, triethylenglycoldimethacrylate.

FRACTURE LOAD TEST

Four different experimental FRC groups in addition to two control groups were prepared (n=6), as follows:

- Experimental group A: One-piece unidirectional FRC implant. Unidirectional fiber rods (longitudinally oriented) were manufactured as described previously,[10] and the one-piece implants were prepared from the rods using CAD/CAM technology (Zirkonzahn).
- Experimental group B: One-piece bidirectional FRC implant. Cross-sectioned in plain-weave fiber rods (concentrically oriented) were manufactured as described previously,[10] and the one-piece implants were prepared from the rods using CAD/CAM technology (Zirkonzahn).
- Experimental group C: Unidirectional FRC abutment. Unidirectional fiber rods (longitudinally oriented) were manufactured as described previously,[10] and the abutments were prepared using CAD/CAM technology (Zirkonzahn) and connected to external hexagon implants (size 3.75/11.5 Lance).
- Experimental group D: Bidirectional FRC abutment. Cross-sectioned in plain-weave fiber rods (concentrically oriented) were manufactured as described previously,[10] and the abutments were prepared using CAD/CAM technology (Zirkonzahn) and connected to external hexagon implants (size 3.75/11.5 Lance).
- Group E: Custom-made zirconia abutment (control group). Custom-made zirconia abutments (ICE Zircon translucent, Zirkonzahn, Gais, Italy) were prepared using CAD/CAM technology (Zirkonzahn), and connected to external hexagon implants (size 3.75/11.5 Lance).
- Group F: Commercially available titanium abutment (control group). External hexagonal commercially available titanium grade V abutments (Teknimplant) were connected to external hexagon implants (3.75/11.5 Lance).

FABRICATION OF THE ABUTMENTS AND ONE-PIECE IMPLANTS

A commercially available screw retained titanium abutment was shaped at 7.2mm length to simulate a central incisor abutment and served as the master abutment. The master abutment was scanned (Zirkonzahn) for fabrication of identical abutments for groups C, D, and E. The abutments were fixed onto an implant with external hexagonal abutment joint design (size 3.75/11.5 Lance). Figure 1 shows one-piece implants and abutments.

Figure 1: Representative images of the experimental groups, left to right: one-piece unidirectional FRC implant; one-piece bidirectional FRC implant; unidirectional FRC abutment; bidirectional FRC abutment; zirconia abutment; titanium abutment.

Table 2. Comparison of the mechanical properties of one-piece unidirectional FRC with bidirectional FRC implants.

	Unidirectional FRC	Bidirectional FRC	p*
Flexural strength (MPa)	1082.1 ± 174.5	417.8 ± 82.2	<0.0001
Flexural modulus (GPa)	34.7 ± 7.8	14.8 ± 4.2	<0.0001
Toughness (MPa)	1.1 ± 0.28	0.71 ± 0.17	0.007
Load-bearing capacity (N)	495.8 ± 48	223.2 ± 54.8	<0.0001

* Statistical significant differences between the respective values

LOAD TESTING

According to the ISO 14801[22], 36 standardized acrylic holders were custom made using a cold curing resin (Vertex™). Implants were inserted on the acrylic holders and attached using a dual-cure resin cement (RelyX™ Ultimate). The platform of the implants was positioned 3mm above the custom-made holder to simulate vertical bone resorption to mimic the worst-case scenario as recommended by ISO standard. Experimental FRC groups were manually fixed on the implants, while zirconia and titanium abutments were fixed according to the manufacturer´s instructions. The access holes were cleaned with ethanol (95%) and then conditioned with Scothbond™ Universal adhesive, and closed by placing a cotton pellet (Ø 2mm, Roeko) and short-fiber composite filling material (everX Posterior™) into the access hole. After storage in ultra pure distilled water for 24h at 37.5°C all the specimens were statically loaded using a universal testing machine (LR 30K plus). A crosshead speed of 1.0mm/min was directed on the abutments to contact the specimen at an angle of 135° according to the average interincisal angle.[23,24] A 0.5mm thick foil was used in between to ensure even force distribution during the loading. Loading was continued until fracture after which each specimen was examined to locate and determine the mode of failure. A representative specimen of each test group was observed by optical microscope (Wild M3Z).

SEM IMAGING

One abutment from each group was cleaned ultrasonically in water for 10 minutes, then dried and screwed onto stainless steel replicas (RP implant replica Branemark Sytem®) according to the manufacturers´ recommendations. The replica-abutment interface was sputtered with gold and examined with a scanning electron microscope (SEM) (LEO 1530 Gemini). SEM images of the unidirectionally and bidirectionally reinforced abutments at 1000× and 30× and the marginal gap at the implant-abutment interfaces at 250× magnification were obtained. The vertical misfit was measured at 9 different locations and the mean values were reported for each abutment.

STATISTICAL ANALYSIS

Statistical analysis was performed with Statistical Package for the Social Sciences (Version 21.0; SPSS.). For the Three-point bending test, the data were analyzed using two-tailed t test. The distribution of data was normal, which was determined by the Kolmogorov-Smirnov test. The data were analyzed using one way analysis of variance (ANOVA) followed by Tukey's post–hoc test. Differences were considered significant at 95% confidence level.

RESULTS

THREE-POINT BENDING TEST

Table 2 presents the three-point bending test results of the one-piece FRC rods. The bidirectional FRC rods showed significantly lower values compared to unidirectional FRC rods.

FRACTURE LOAD TEST

Figure 2 shows the mean load-bearing capacities and standard deviations of the experimental groups. The one-piece implants exhibited the highest fracture load among the FRC groups ($p<0.001$). Fiber orientation had no statistically significant effect on the fracture load of one-piece FRC implants. However, the bidirectional FRC abutment had significantly higher fracture load compared to the unidirectional FRC abutment ($p<0.001$). The FRC abutments, in contrast to one-piece FRC implants, had significantly lower load-bearing capacity than zirconia abutments ($p<0.01$). However, titanium abutments showed higher load-bearing values ($p<0.001$) than any of the FRC abutments or the one-piece FRC implants investigated in this study.

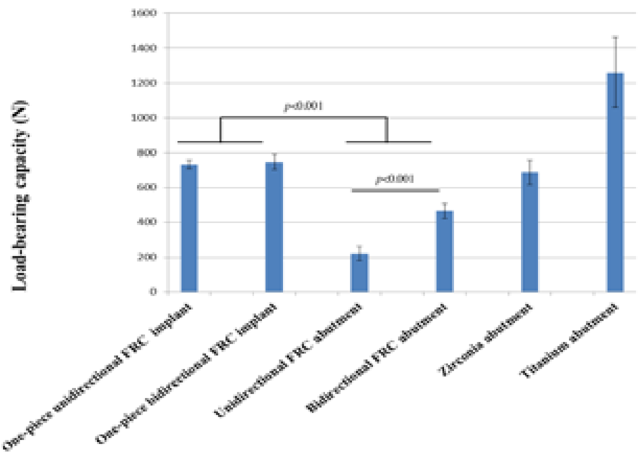

Figure 2: Mean load-bearing capacities and standard deviations of the experimental implants and abutments.

FAILURE MODE

In one-piece FRC implants, the unidirectional implants showed longitudinal delamination while the bidirectional implants showed bending in the neck region *(Figure 3)*. In case of the FRC abutments, catastrophic failure was observed in the unidirectional group, while in the bidirectional group signs of screw bending were noticed. Zirconia abutments failed catastrophically, while titanium abutments demonstrated plasticization of metallic components (implant hexagon- abutment hexagon) and screw bending. Representative fractures are shown in Figure 4.

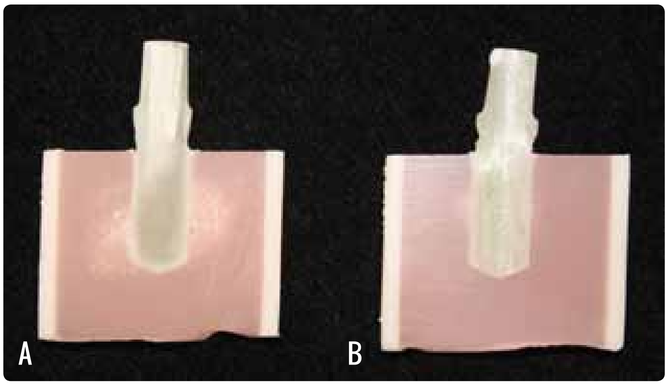

Figure 3: Representative cross-sections of the fracture patterns of one-piece FRC implants: a) unidirectional and b) bidirectional.

Figure 4: Representative fracture patterns of the abutments, left to right: unidirectional FRC; bidirectional FRC; zirconia; and titanium.

SEM IMAGING

Figure 5 shows SEM images of the unidirectionally and bidirectionally reinforced abutments at two different magnifications. Figure 6 presents the precision of fit of FRC abutments in comparison to the control groups at 250× magnification. The mean vertical gap distances and standard deviations in μm were as follows: unidirectional FRC: 0.0 ± 0.0; bidirectional FRC 5.30 ± 0.67; zirconia: 2.14 ± 0.40; and titanium: 4.60 ± 0.38.

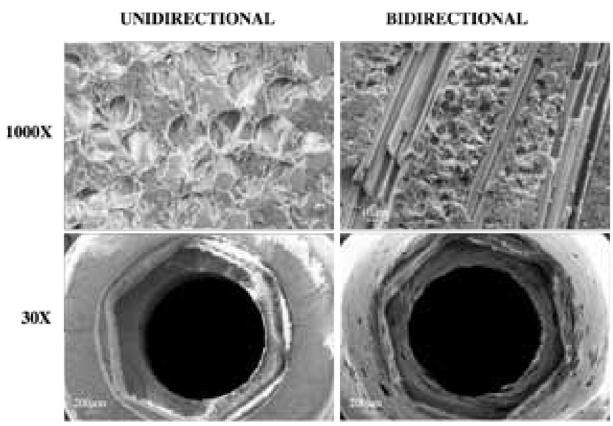

Figure 5: Scanning electron microscopic images of unidirectional reinforced matrix and bidirectional reinforced matrix.

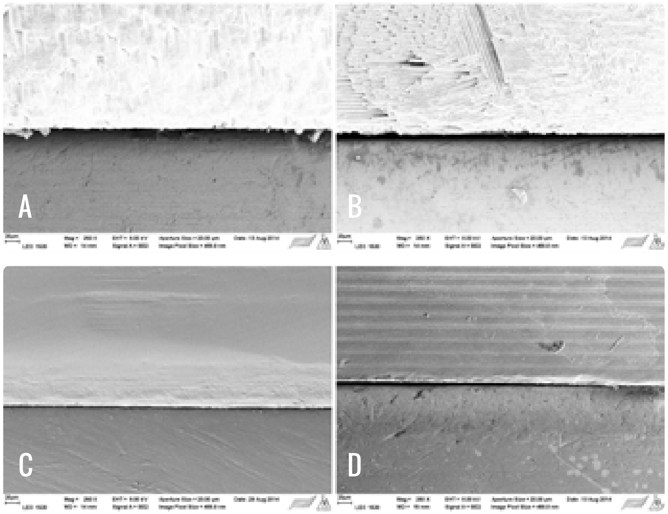

Figure 6: Precision of fit at 250X magnification: a) unidirectional FRC; b) bidirectional FRC; c) zirconia; and d) titanium.

DISCUSSION

This study was performed to assess the load-bearing capacity of novel FRC one-piece implants and abutment prototypes with two different types of fiber structures. Bidirectionally reinforced implants and abutments carry the potential to be used for oral anterior stress-bearing applications. Accordingly they showed higher load-bearing capacity than the expected maximum anterior oral loading force without material failure (delamination). One study evaluated the load-bearing capacity of FRC abutments but only unidirectional fibers were analyzed.[18] The present study is first in reporting the load-bearing capacity of FRC implants and abutments with different types of fiber structure for oral load-bearing applications.

Three-point bending test was used to determine the mechanical properties of FRC where, bidirectional FRC rods, as expected, obtained inferior values compared to unidirectional FRC. It is well documented that bidirectional reinforcement of FRC decreases its strength in comparison with unidirectional reinforcement.[14,25] Nevertheless both groups displayed an elastic modulus similar to cortical bone and dentine and adequate strength that acknowledge them for load-bearing applications.[26,27]

This study revealed that irrespective of the fiber structure, one-piece FRC implants exhibited the highest load-bearing capacities among the experimental FRC groups. Although it is known that the mechanical properties of FRC are influenced by the fiber orientation,[28] this influence was not observed, due to the fact that the high fiber vol.% of the one-piece FRC bulk structure resulted into high resistance to fracture. However, bidirectional fibers showed a greater breakage capacity since they showed bending failure without delamination. This may be explained by the fact that unidirectional fibers transfer the energy longitudinally from the abutment to the implant exhibiting intralaminar matrix fracture leading to stress concentration areas in the resin as illustrated in Figure 3. On the contrary, bidirectional fibers show superior stress bearing capacity by a more homogenous load distribution enabling bending failure without breakage. One of the main disadvantages of one-piece titanium implants is that they require abutment shaping immediately after the implant insertion, which potentially jeopardize the bone vitality and primary stability through heat transmission.[29] In fact, the controversial results in success rates of titanium one-piece implants are attributable (among other factors) to the heat transfer through underlying tissues during the abutment preparation.[30] Unlike titanium, FRC is easy to grind and modify without heat generation. Furthermore, FRC implants with bioactive glass particles (BAG) have shown osteoinductive properties.[16]

The role of the fiber structure on the load-bearing capacity of FRC orthopedic implants has been previously studied in animal experimentation.[13,14] Moritz *et al*., observed that the addition of a bidirectional fibers enhanced torsional strength of FRC implants at the expense of flexural strength. However, although showing inferior values on some mechanical properties, they showed similar load bearing performance compared to the unidirectional implants.[14]

In contrast to FRC implants, in FRC abutments fiber structure had a significant impact on the load-bearing capacity. According to this assumption, and similar to the findings of Behr *et al*., unidirectional fibers did not tolerate compressive loads directed towards the fiber´s axis direction in FRC abutments.[18] In contrast bidirectional fibers provided optimal reinforcement showing fracture loads above the maximum incisal forces. While unidirectional fibers lead to catastrophic failure, the more resilient material achieved by bidirectional reinforcement exhibited screw bending without fiber damage (e.g. delamination). Increasing the stiffness of the bidirectional FRC would provide additional support to the veneering composite in addition to show arrest crack propagation due to enhanced biomechanical matching to the veneering particle filler composite. Recent composite abutments, which showed a comparable modulus of elasticity to the bidirectional FRC, showed a similar damping behavior compared to teeth.[8] Clinically the inclusion of a resilient material helps in transmitting physiologic forces to the peri-implant tissues by mimicking biomechanics of natural dentition better than rigid implant devices do.

In the present study, the load-bearing capacity and failure modes of the control groups (i.e. zirconia and titanium) were comparable to earlier studies.[31,32] Despite the fact that titanium abutments showed the highest load-bearing capacity, such high occlusal loads are rarely encountered in the anterior region.[33]

The accuracy of passive fit has been evaluated by measuring vertical implant abutment distances.[23,34] Interestingly, the unidirectional fibers showed the material's efficacy in gap closure compared to any other abutment materials evaluated in this study. The poor marginal fit reported for titanium abutments is probably because the used implants and abutments were from different manufacturers.[35] Nevertheless, the range of misfit for all experimental groups in the current study is consistent with earlier studies and it can be considered clinically acceptable.[23,34]

Further improvements regarding the design of FRC abutments should be addressed. A higher load-bearing capacity would be expected when testing a solid FRC abutment considering the superior behavior to fracture of the one-piece FRC. Additionally, current advanced metal-resin bonding techniques could greatly improve the adhesion between the metal abutment base and the resin matrix and moreover, adhesive cementation of the abutment into the dental implant could also be considered. Regarding the type of structure, the combination of unidirectional and bidirectional may be required for the mechanical optimization of the abutment and the use of multidirectional fibers should be considered.

In vitro static loading conditions will not address in vivo conditions, but allow to evaluate new designs inexpensively in addition to obtain clinically relevant considerations.[31,32] Some limitations of the study need to be outlined: (1) Cyclic load fatigue tests are believed to be the best technique to evaluate fracture strength and long-term survival of implant abutments,[18,24] nevertheless static load tests are considered to be a basis for fatigue tests (ISO 14801); (2) The screw design could not be standardized due to manufacturer´s recommendations for the zirconia group. In the titanium and FRC abutments the screw head had a tapering design, whereas besides having more threads the zirconia´s abutment screw head had a butt-joint design; (3) This investigation did not include a full veneer crown in the model system and thus higher force failure loads can be expected with crowns (i.e. crowns act as a stress-shielding device allowing a larger load to be applied before failure).

Although the mechanical properties of bidirectional FRC were inferior compared to the unidirectional, were adequate to withstand clinically relevant loads without structural failure. The present work confirmed early studies that the bidirectional reinforcement improves the performance of implant devices.[14] However, further technological development is mandatory before the FRC implants or abutments can be recommended for clinical use.

CONCLUSIONS

Based on the findings of this study, it can be concluded that:

1. Fiber orientation and structure design have a significant influence on the load-bearing capacity of FRC abutments.
2. Bidirectional fiber reinforcement must be considered for use in implant dentistry regarding the different functional loads that are generated in the oral cavity.

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MANUFACTURERS´ DETAILS

- D 06062, Modell 600, Memmert GmbH + Co.KG, Schwabach, Deutschland
- Elipar S10, 3M Espe, Seefeld, Germany
- Targis Power, Ivoclar, Schann, Liechtenstein
- LR 30K plus, Lloyd, Sussex, UK
- Nexygen, Lloyd Instruments Ltd., Fareham, England
- Zirkonzahn, GmbH, Gais, Italy
- Lance, MIS™,Tel Aviv, Israel
- Teknimplant, Barcelona, Spain
- Vertex™, Vertex-Dental, B.V. Headquarters, The Netherlands
- RelyX™ Ultimate, 3M ESPE Dental, Seefeld, Germany
- Scothbond™ Universal adhesive, 3M, Gmbh, Neuss, Germany
- Roeko, Langenau, Germany
- EverX Posterior™ GC, Japan
- Wild M3Z, Heerbrugg, Switzerland
- Branemark Sytem®, Nobel Biocare, Goteborg, Sweden.
- LEO 1530 Gemini, Helmholtz Centrum, Berlin, Germany
- Version 21.0; SPSS. Inc, Chicago, Illinois

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