JOURNAL OF MATERIALS SCIENCE: MATERIALS IN MEDICINE 5 (1994) 314–319

Tensile and torsional shear strength of the bone implant interface of titanium implants in the rabbit

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The effect of three different titanium plasma flame spray coatings on the tensile strength and the effect of macrostructures on the torsional shear strength of the bone implant interface was studied. Titanium cylinders, of 8 mm length and 4 mm diameter, were implanted into distal rabbit femurs. For tensile testing, two porous titanium plasma flame spray coatings, Plasmapore®, fine-grain Plasmapore®, 1 dense, unporous coating, Plasmapore® fine on cylinders with axial grooves, and corundum blasted specimens as control group were used. For torsional loading smooth, and macrostructured cylinders with axial grooves, both with Plasmapore® fine-coating, were used. After 168 days the implant–bone interface was biomechanically tested. A tensile test and a torsional shear test was performed. The results indicated, that the titanium plasma flame spray coatings did not differ in their tensile interface strength, but yielded a stronger interface as sandblasted surfaces and that the macrostructures did not influence the torsional shear strength.

1. Introduction

Titanium plasma flame spray coatings for dental implants have been in use for almost twenty years [1, 2]. Bone ingrowth into the surface roughness and porosity of these coatings has been demonstrated and is considered responsible for the biomechanical anchorage of such coated implants in bone [2–7].

The aim of the present study was to evaluate the effect of different qualities of titanium plasma flame spray coatings on the tensile strength of the bone implant interface and the effect of macrostructures on the torsional shear strength of titanium plasma flame sprayed implants in the distal femur of the rabbit.

2. Materials and methods

2.1 Implantation

Titanium (ASTM grade 4) cylinders, 8 mm length and 4 mm diameter, were implanted into the distal femur of female chinchilla rabbits (mean body weight 3.4 kg) according to a standardized surgical procedure, which has been used in previous studies [8–11]: perioperatively the animals received 20 mg gentamycine and 100 mg o-carbamoyl-phenoxy-acetic acid sodium salt as antibiotic and antiphlogistic prophylaxis. After general anesthesia with a ketaminehydrochloride-xylazine mixture an incision medial to the knee preceded an arthrotomy of the knee joint. Using a cylindrical diamond burr internally irrigated with 0.9% sodium chloride solution, a bone cavity 8–9 mm deep was prepared into the distal epiphysis of the femur. As the burr's diameter was approximately 50 μm smaller than one of the implants, a press-fit was obtained. The implants were seated in a manner, that their end surfaces did not protrude over the articulating condyle surface. Thus the development of postoperative arthroses was effectively eliminated. After suturing, the wounds were treated with neomycine sulfate antibiotic powder. The animals were fed with standard diet hard pellets (Altromin® Standard, Lage Co., Lippe, FRG) and water *ad libitum*.

2.2. Implants

For the tensile test the following implant types were studied: titanium (ASTM grade 4) cylinders 8 mm long and 4 in diameter. The titanium plasma flame

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spray coatings were two porous coatings (Plasmapore® (coded PP in the following) with a mean surface roughness $RT = 175$ μm, fine-grain Plasmapore® (F), $RT = 101$ μm); one dense coating, called unporous by the manufacturer (FD) $RT = 103$ μm, while uncoated, corundum blasted specimens (AL) $RT = 63$ μm served as control groups. Additionally, macrostructured cylinders with 12 axial grooves 0.2 mm deep (GF) were used. The different surfaces were depicted with a scanning electron microscope (Figs 1–5). However, there was no dramatic qualitative visual difference between the three coatings (Figs 1–3). For the torsional shear test, titanium cylinders with F-coating and macrostructured cylinders with axial grooves (GF) were investigated. All implants were sterilized with gamma rays.

2.3. Explanation and biomechanical testing

After 168 days the animals were sacrificed under general ketaminehydrochloride-xylazine anesthesia by inhalation of carbon dioxide. The distal femur condyles containing the implants were excised and prepared for biomechanical testing (four implants of each surface for the tensile test, and six of F and GF surfaces for the torsional test). For the tensile test 4/5 of the cylinder surface was freed of bone using a diamond disc cooled with physiological sodium chloride solution. The remaining distal 1/5 of the implant–bone interface was loaded in a tensile test alignment perpendicular to the implant axis (Fig. 6) and the rupture load newtons recorded. A

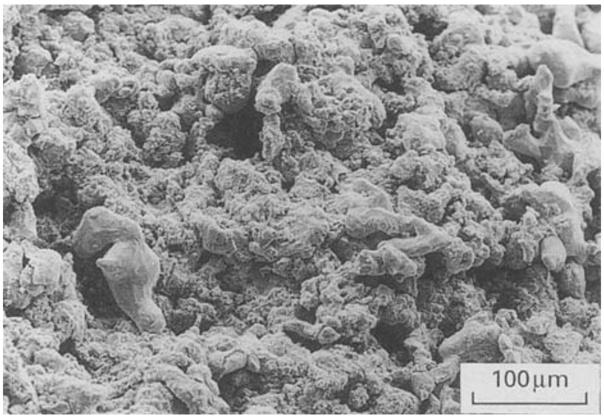

Figure 1 Scanning electron microscope (SEM) micrograph of the Plasmapore®-titanium plasma flame spray coating (PP). Pores are present between the coating particles.

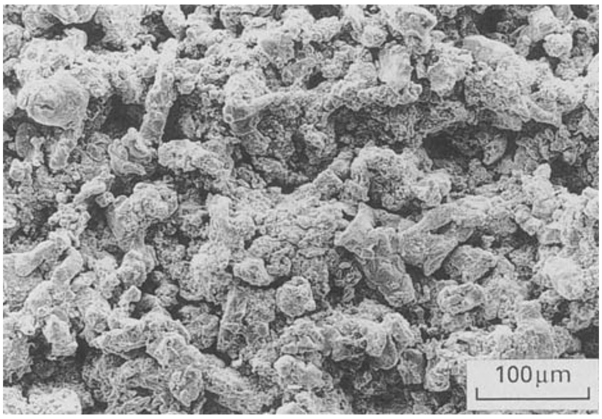

Figure 2 SEM micrograph of the Plasmapore®-fine titanium plasma flame spray coating (F). Grain size is smaller, however, the visual difference in comparison to the PP coating is not impressive.

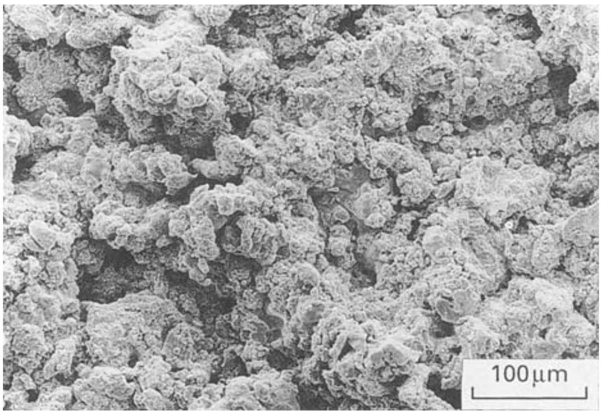

Figure 3 SEM micrograph of the fine-grain, dense "unporous" titanium plasma flame spray coating (FD). Grain are more densely packed.

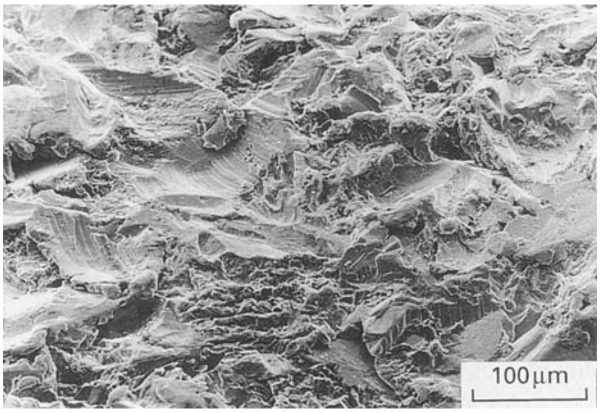

Figure 4 SEM micrograph of corundum-blasted titanium cylinder (AL).

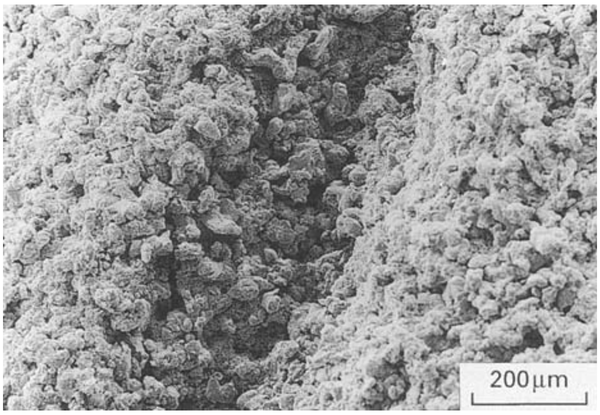

Figure 5 SEM micrograph of a cylinder with axial grooves 0.2 mm deep and coated with Plasmapore®-fine titanium plasma flame spray coating (GF)

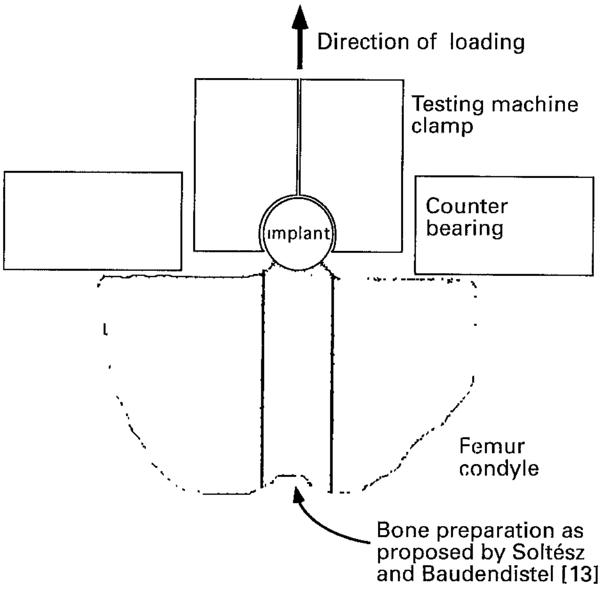

Figure 6 Schematic illustration of an implant–bone sample in the tensile test alignment.

Schenk–Trebel universal testing machine was used with a crosshead speed of 1 mm/min. After collection, the specimens were stored at 4 °C in physiological NaCl solution, until testing was performed within 48 h after explanation. The interface area was measured in square millimetres using callipers, and the tensile strength was calculated in N/mm^2.

For the torsional shear test the femur condyles were embedded in acrylic resin, the ventral implant surface was prepared with a cooled diamond disc and the interface was torsionally loaded via an internal hexagon in the implant (Fig. 7). A Schenk–Trebel universal testing machine with a torque generator and recorder designed and constructed by the Federal Institute for Material Research and Testing was used. Testing was also performed within 48 h after explantation, while the specimens were stored at 4 °C in physiological NaCl solution. The maximum torque was recorded and the shear stress calculated in relation to the cylinder mantle surface in N/mm^2.

2.4. Histology

After biomechanical testing the bone specimens were fixed in Lillie's buffered 5% formaldehyde solution for 48 h. After dehydration in graded ethanol the specimens were embedded in methylmethacrylate (3 days immersion and following polymerization at 40 °C). Polished sawn sections 50 to 70 μm thick were prepared transverse to the long axis of the implants using a Leitz 1600 sawing microtome (E. Leitz Co., Wetzlar, FRG). The sections, at least four of each specimen, were alternately stained with von-Kossa-Fuchsin and Giemsa staining and enclosed with Corbit-Balsam (Hecht Co., Kiel, FRG).

Histological evaluation of the slides was performed with the light microscope in transverse light and the following criteria were evaluated:

1. fracture at the interface, i.e. the failure of the interface occurred close to the implant surface (abbreviated in the following as FM1, "fracture mode 1");

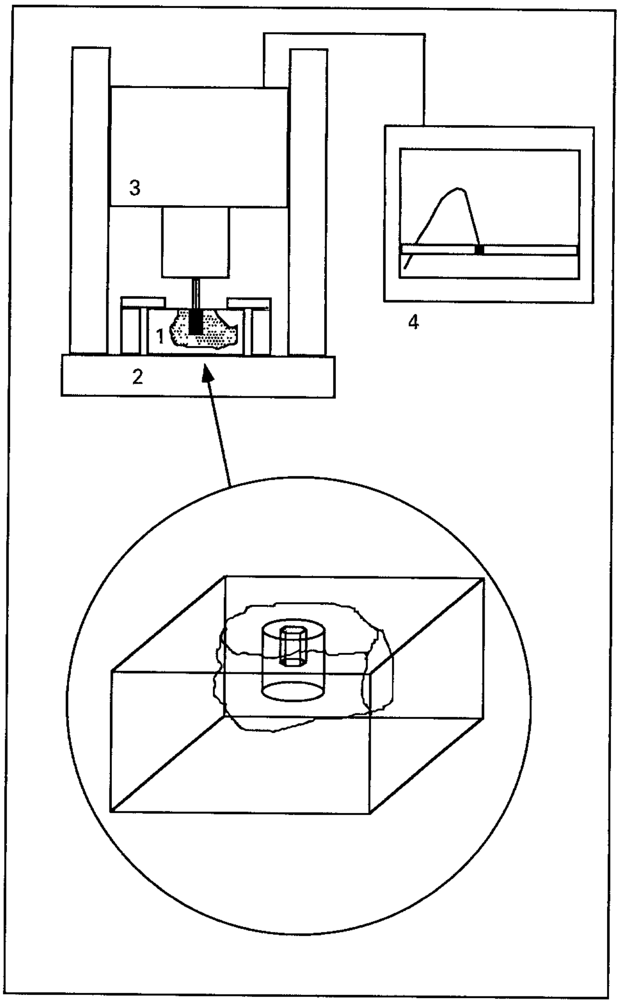

Figure 7 Scheme of the torsional shear test alignment. (1) embedded implant–bone sample with internal hexagon in the implant; (2) mounting table; (3) torque generator and recorder; (4) X–Y-writer.

TABLE I Tensile strength (*TS*) and torsional shear strength (*TSS*) (in N/mm^2 + / − SEM) of titanium implants after 168 days in the rabbit femur (AL = corundum blasted, F = Plasmapore® fine, PP = Plasmapore®, FD = unporous titanium plasma sprayed, GF = cylinders with 12 axial grooves 0.2 mm deep and F-coated, *n* = number of implants, *RT* = mean surface roughness in μm)

Surface	*n*	*RT*	*TS*	*SEM*(TS)
AL	4	63	1.55	0.22
F	4	101	2.81	0.11
PP	4	175	3.08	0.68
FD	4	103	2.52	0.28
GF	4	109	3.20	0.48
Surface	*n*	*RT*	*TSS*	*SEM*(TSS)
F	6	101	6.39	0.80
GF	6	109	7.34	0.39

2. fracture within bone, i.e. a fracture line within bone was visible, indicating a bone bonding without a soft-tissue layer between implant and bone (FM2);
3. presence of coating remnants, i.e. particles of the plasma coating were present in the bone sample (FM3);
4. fracture distant to the interface, i.e. a fracture within the surrounding bone with substantial bone remnants on the implant (FM4);

TABLE II Histological evaluation of the tensile test specimens (the numbers of occurrences wtih implants and sections)

Code	Number of implants	Number of sections	Fracture mode					
			FM 1		FM 2		FM 3	
			implants	sections	implants	sections	implants	sections
AL	4	16	3	12	3	12	0	0
FD	4	16	3	12	3	12	1	2
F	4	16	4	14	4	14	4	13
GF	4	16	4	16	4	16	4	12
PP	4	16	4	13	4	13	3	10

5. fracture within the coating, i.e. a fracture line within the coating, with coating remnants at the bone as well as the implant side (FM5);
6. fracture between coating and implant body, i.e. separation of the coating from the implant (FM6);
7. fracture of the implant body, i.e. a fracture within the implant body (FM7).

3. Results

3.1. Tensile strength

The means and standard errors of the means of the results of the tensile test are given in Table I. Statistical analysis using the Wilcoxon U-test at the $p < 0.05$ significance level revealed significantly higher tensile strength values for the plasma-coated implants than for the corundum-blasted specimens. No significant difference was found between the results of the different plasma coatings.

3.2. Torsional shear strength

The means and standard errors of the means of the results of the torsional test are given in Table I. Statistical analysis using the Wilcoxon U-test at the $p < 0.05$ significance level revealed no significantly higher torsional strength values for the macrostructured implants.

3.3. Histology

Only fracture modes FM1, FM2, and FM3 were observed after tensile testing (Figs 8, 9 and Table II); i.e. the fractures of the interface occurred close to the implant surface (FM1), or the fracture was visible within the bone (FM2) and coating remnants were present in the bone sample (FM3). After the torsional test, the interface of all implants without grooves was sheared off close to the implant surface (Fig. 10). The grooved implants showed a fracture line at the outer implant perimeter, while the interface within the grooves remained unharmed. One grooved implant exhibited bone trabecule fractures 1–2 mm distant from the implant surface (Fig. 11).

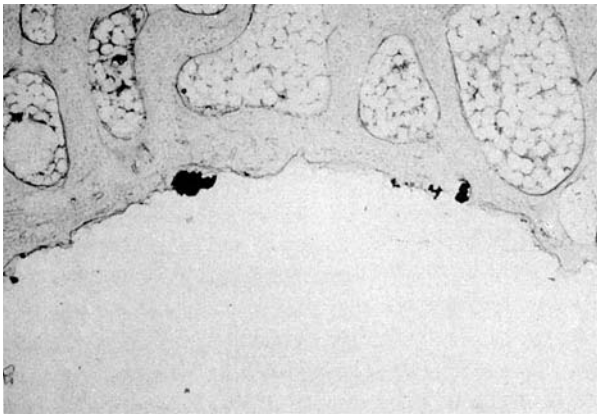

Figure 8 Sawn section of the bone side of a Plasmapore®-coated implant after tensile testing. Fracture at the interface between bone and coating (FM1), with torn off coating particles (FM3) (Giemsa staining, magnification 75x).

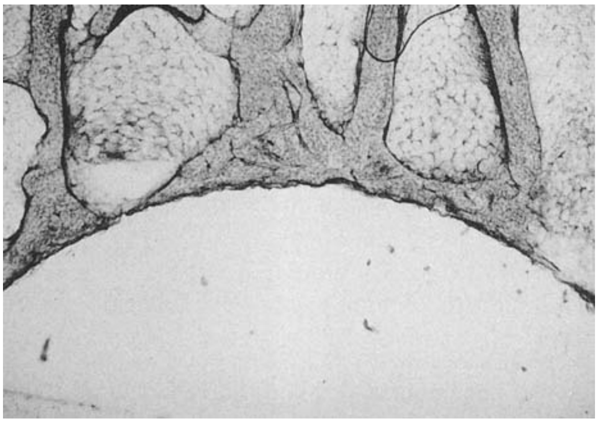

Figure 9 Bone side of corundum-blasted titanium implant after tensile testing. Clean fracture line resembling the contour of the implant (fracture mode FM 1) (sawn section, Giemsa, 75x).

4. Discussion

4.1. Tensile strength

The results of the tensile strength test yielded no statistically significant differences (Wilcoxon U-test at $p < 0.05$) between the different titanium plasma flame spray coatings (Table I). The mean surface roughness of the coatings was between 100 and 200 μm, a range which has shown the highest tensile implant–bone interface strength in another study [12]. Mechanical interlocking of the bone in the undercuts of the coating was held responsible for the relatively high values. The interface strength approached the internal strength of the bone itself [8]. The smoother surfaces of the corundum-blasted implants do not show the

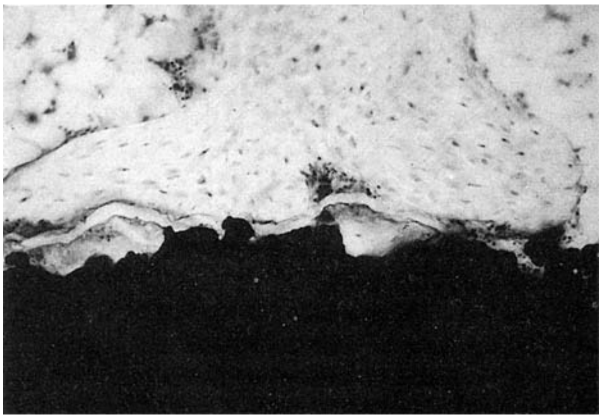

Figure 10 Sawn section of an Plasmapore®-fine coated implant (F) after torsional loading. The fracture line is close to the implant surface (Giemsa, 300x)

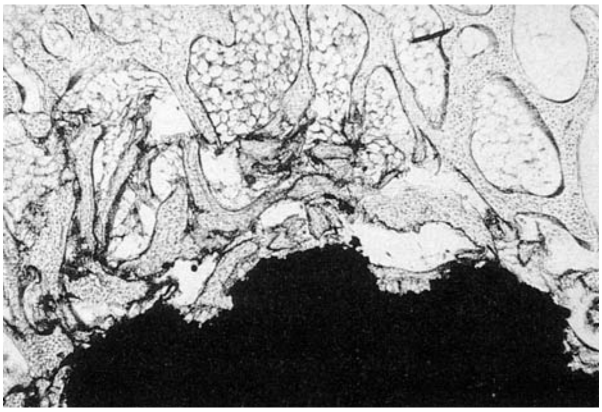

Figure 11 Plasmapore®-fine coated implant with axial grooves (GF) after torsional loading. Fractures of bone trabecules at a distance 1–2 mm from the implant surface (sawn section, Giemsa, 30x).

same number of undercuts and yield a significantly lower interface strength [11]. The influence of the surface roughness on bone apposition has also been confirmed in another animal model [12]. The differences of the three coatings studied, i.e. particle size and porosity were obviously of minor influence on the tensile strength. In a finite element analysis, the tensile test alignment method used in this study has been criticized [13]. According to the cited study, this form of preparation would lead to a systematic underestimation of the tensile strength values. A rod-shaped preparation of the bone left on the opposite side of the implant has been proposed to ensure a more even tension distribution. However, the practical performance of such a preparation and safe fixation of the specimens in the testing machine is not possible. This is due to the anatomy of the femur condyles; the remaining spongy bone or bone marrow proximal to the implant does not allow rigid fixation of the specimen for a tensile test (Fig. 6).

4.2. Torsional shear strength

No statistically significant difference (Wilcoxon U-test at $p < 0.05$) could be found between the smooth (F) and grooved (GF) implants, which were both coated with Plasmapore® fine (Table I). A higher load bearing capacity for the grooved cylinders, which had been found in an *in vitro* experiment [14], could not be confirmed with this *in vivo* torsional test. From the results of the present experiment, it is assumed that the load bearing capacity of an implant–bone interface of titanium plasma flame-spray coated implants is dominated by the bone anchorage in the surface roughness of the coating. Macrostructures seem to play an inferior role in stabilizing the implant in bone. Therefore it was assumed that the torsional interface strength approaches that of the internal bone. The clinical effectiveness of macrostructures, for instance apical vents as used with many commercial dental implants, might be questioned.

4.3. Histology

With tensile testing, the fracture line was always found close to the implant–bone interface. Fractures distant from the interface, within the coating or within the implants, were not observed. Torn-off particles were found with at least one implant of each coatings (Fig. 8). The dense coating (FD) showed the least number of torn-off particles (Table II).

After the torsional shear test, the interface of the specimens without grooves sheared off close to the implant surface (Fig. 10). This was interpreted as showing that a constant and monotonous increase of shear stress had taken place. With the grooved implants, the fracture line was determined by the outer perimeter of the implant, while the bone–implant contact remained intact within the grooves. Also, bone trabecule fractures were observed 1–2 mm away from the interface (Fig. 11). It was assumed, that uneven stress build-up led to this phenomenon.

5. Conclusion

Three different qualities of titanium plasma flame spray coatings did not differ in the tensile strength of the bone–implant interface. A surface roughness between 100 and 200 μm was common to the coatings studied and was held responsible for the matching tensile interface strength, which is a little lower than the tensile strength of the rabbit bone itself. All plasma flame spray coatings had a significantly higher tensile strength than the sandblasted surfaces. Axial grooves had no effect on the tensile strength or on the torsional shear strength of the bone–implant interface. It appears that a titanium coating with a mean surface roughness of the order 100 μm yields an interface strength which comes close to the internal bone strength.

Acknowledgements

The implants were provided and the study was supported by AESCULAP AG, Tuttlingen, Germany. The authors also gratefully acknowledge the technical assistance of Ms G. Turowsky, Mrs M. Dilger and Mrs I. Borchert.

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