

Analysis of the *prtP* Gene Encoding Porphyain, a Cysteine Proteinase of *Porphyromonas gingivalis*

GENEVIEVE A. BARKOCY-GALLAGHER,¹ NAIMING HAN,² JOSEPH M. PATTI,³ JOAN WHITLOCK,²
ANN PROGULSKE-FOX,² AND MARILYN S. LANTZ^{1*}

Indiana University School of Dentistry, Indianapolis, Indiana 46202¹; University of Florida School of Dentistry, Gainesville, Florida 32610²; and Institute of Biosciences and Technology, Texas A and M University, Houston, Texas 77030³

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The cloning and sequencing of the gene encoding porphyain, a cysteine proteinase previously isolated from detergent extracts of the *Porphyromonas gingivalis* W12 cell surface, are described. The *prtP* gene encoded a unique protein of 1,732 amino acids, including a putative signal sequence for protein secretion. The predicted molecular mass for the mature protein was 186 kDa, which was close to the observed molecular mass of 180 kDa. There was one copy of *prtP* in the genomes of seven *P. gingivalis* strains examined. The gene was located 5' to a region with a high degree of homology to the insertion element IS1126 in *P. gingivalis* W12. The PrtP protein had regions of high homology to HagA, a hemagglutinin of *P. gingivalis*, and to several purported proteinases of *P. gingivalis* that have Arg-X specificity. A detailed comparison of genes encoding the latter and *cpgR* suggested that *rgp-1*, *prpR1*, *prtR*, *agg*, *cpgR*, and possibly *prtH* were derived from identical genetic loci. Although an *rgp-1*-like locus was detected in seven *P. gingivalis* strains by Southern blot analyses, *agg* and *cpgR* were not detected, not even in the strains from which they were originally isolated. In addition, at least 20 copies of a repeat region common to PrtP, the Rgp-1-like proteins, and HagA were observed in each of the seven genomes examined. The repeat region hybridization patterns for strains W83 and W50 were very similar, and they were identical for strains 381 and ATCC 33277, providing further evidence that these strains are closely related genetically.

Many bacterial pathogens produce proteolytic enzymes that may play a role in the destruction of host tissues (21). *Porphyromonas gingivalis* has been implicated as an etiologic agent of human periodontitis (15, 32), diseases characterized by the loss of connective tissue and bone surrounding the roots of the teeth (13). The organism produces a number of extracellular and/or cell surface-associated proteolytic enzymes, most of which have been referred to as "trypsin-like," on the basis of their substrate specificities. However, the designation is inappropriate because all of the enzymes that have been characterized in depth recently appear to be cysteine proteinases (2, 5, 6, 10–12, 18, 20, 22, 35, 41, 44, 45). The precise number and specificities of these *P. gingivalis* proteinases are unclear at this time because of several factors. At least seven different *P. gingivalis* strains have been used in recent studies describing proteinases (1–3, 5–7, 9–12, 18, 20, 22, 35, 37, 38, 45). Some investigators have purified proteinases from spent culture medium (1, 2, 5, 10, 12, 18, 41, 45) or extracted them from cells (6, 11, 20, 22, 35, 44); others have characterized a cloned gene product (3, 9, 19, 37, 38). Moreover, a variety of substrates, activators, and inhibitors have been used in various assays to characterize the enzymes. It therefore has been difficult to compare enzymes isolated and characterized by different groups.

The most direct way to compare enzymes is to clone and express the genes encoding the respective proteinases. A number of *P. gingivalis* genes purportedly encoding proteinases have recently been cloned and sequenced, including *rgp-1*, *prpR1*, *prtR*, *prtH*, *agg*, *cpgR*, *prtT*, *tpr*, and *prtC* (1, 3, 9, 12, 19,

20, 30, 36, 37, 39). To date, the relationships among these genes have been unclear, although some authors have noted a likeness in the *rgp-1*, *prpR1*, *prtR*, *agg*, and *cpgR* sequences (1, 20, 34, 42). Except for PrtC, which apparently is a collagenase, the proteases associated with these genes cleave after arginine residues in synthetic substrates. However, the ability to cleave Lys-X substrates was not determined for several of the proteinases, and none of the recombinant proteinases have been well characterized. In addition, Pike et al. (41) have described a *P. gingivalis* proteinase, KGP, which reportedly cleaves only after lysine residues.

In contrast, workers in this laboratory have isolated a *P. gingivalis* proteinase, porphyain, that apparently has both Arg-X and Lys-X specificity, but at different active sites on the basis of inhibitor studies (6). Thus, porphyain appears to be a very unusual proteinase with either two separate active sites or one active site which can assume different conformations resulting in different specificities and sensitivity to inhibitors. The gene encoding porphyain (*prtP*) has been cloned and sequenced and is reported here; the predicted gene product is distinct from all of the other cloned *P. gingivalis* proteinases and other known cysteine proteinases. In addition, this report presents data examining the relationship of several *P. gingivalis* proteinase genes to one another.

MATERIALS AND METHODS

Reagents and bacterial strains. Human fibrinogen was purchased from Kabi (Stockholm, Sweden) and was labeled with ¹²⁵I by the chloramine T method (16) as previously described (26). The estimated specific activity of the ¹²⁵I-fibrinogen was 1.7 × 10⁶ cpm/μg. Na¹²⁵I was purchased from Amersham Corporation (Arlington Heights, Ill.). Restriction endonucleases were obtained from Gibco/BRL (Gaithersburg, Md.), Boehringer Mannheim (Indianapolis, Ind.), and New England Biolabs (Beverly, Mass.). T4 DNA ligase was obtained from Promega Corporation (Madison, Wis.). All DNA amplifications were performed in a GeneAmp 9600 Thermocycler (Perkin-Elmer, Foster City, Calif.). PCR primers

* Corresponding author. Mailing address: 1121 W. Michigan St., Indianapolis, IN 46202. Phone: (317) 278-1355. Fax: (317) 278-1411. Electronic mail address: mlantz@iustd.iupui.edu.

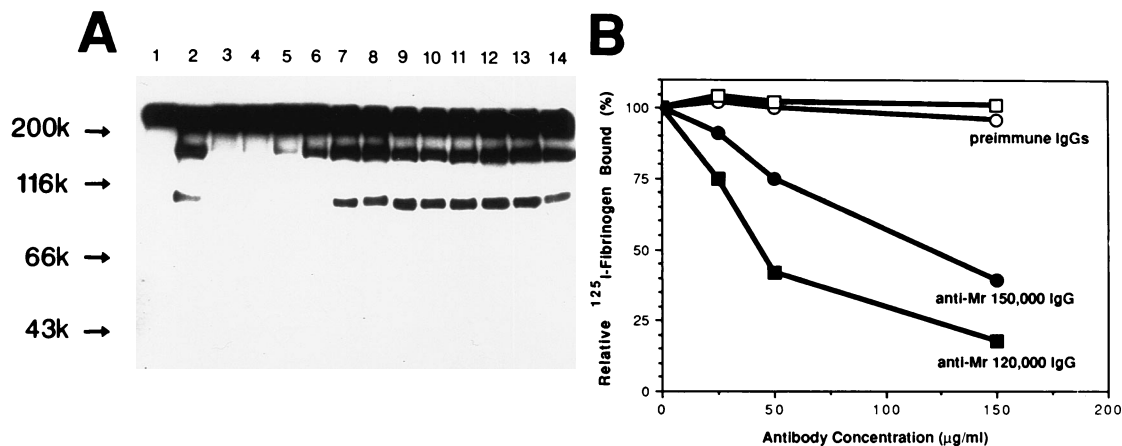


FIG. 1. Effect of anti-porphypain-1 and anti-porphypain-2 IgGs on fibrinogen binding and hydrolysis by *P. gingivalis*. (A) Freshly harvested bacteria were preincubated with no antibody (lane 2); 300, 200, 100, or 50 µg of anti-porphypain-2 IgG per ml (lanes 3 to 6); 300 or 100 µg of preimmune IgG per ml (lanes 7, 8, 13, and 14); or 300, 200, or 100, or 50 µg of anti-porphypain-1 IgG per ml (lanes 9 to 12) prior to addition of ¹²⁵I-fibrinogen. After incubation at 22°C for 180 min, the supernatant fraction of the incubation mixtures was analyzed by SDS-PAGE and autoradiography to visualize fibrinogen and its degradation products. Lane 1 contains ¹²⁵I-fibrinogen that was not exposed to cells. Numbers and arrows on the left indicate migration distances and molecular sizes of standard proteins. (B) Bacteria were incubated with preimmune or immune IgGs prior to the addition of ¹²⁵I-fibrinogen as in panel A. The amount of ¹²⁵I-fibrinogen bound to the cells after 30 min at 22°C was determined.

were prepared by the Biochemistry Biotechnology Facility (Indiana University School of Medicine).

P. gingivalis HG66 was a gift from R. Arnold (School of Dentistry, University of North Carolina). All *P. gingivalis* strains were maintained as laboratory stocks and cultured as previously described (24). Culture purity was routinely confirmed by Gram staining. *Escherichia coli* JM109 (49) was used for all cloning studies and was cultured aerobically on Luria-Bertani medium. Transformants were maintained on medium supplemented with ampicillin (50 µg/ml). Lambda phage were propagated in *E. coli* Y1090 (17).

Preparation and analysis of polyclonal immunoglobulins G (IgGs). Serum IgGs to porphypain-1 and porphypain-2 were raised in New Zealand White female rabbits and isolated as previously described (22). To determine their effect on *P. gingivalis* W12 binding and hydrolysis of fibrinogen, cells were preincubated with preimmune IgGs, or various concentrations of immune IgGs, for 30 min at 22°C. Binding of ¹²⁵I-fibrinogen to the cells was determined as previously described (24, 25). Briefly, cells pretreated with IgGs were incubated with ¹²⁵I-fibrinogen in the presence of phosphate-buffered saline and bovine serum albumin for 30 min at 22°C, and then the radioactivity associated with pelleted bacteria was determined in a gamma counter (LKB, Wallac, Turku, Finland). To analyze hydrolysis of fibrinogen, cells pretreated with IgGs were incubated with ¹²⁵I-fibrinogen for 180 min at 22°C and the supernatant fraction of the incubation mixture was subjected to sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) as previously described (23).

Construction and screening of *P. gingivalis* W12 libraries, isolation of clones, and sequence analyses. A λgt11 library of *P. gingivalis* W12 genomic DNA was prepared by Clontech Laboratories, Inc. (Palo Alto, Calif.). Genomic DNA was prepared as follows. Stationary-phase bacteria were harvested by centrifugation and then washed and resuspended in 10 mM Tris-HCl-1 mM EDTA, pH 7.5 (TE). Cells were lysed by the addition of an equal volume of phenol-ethanol (1:1). Debris and cellular DNA were pelleted by centrifugation at 4°C for 15 min at 16,000 × g. The pellet was resuspended in TE with 1% SDS and 1 mg of proteinase K per ml and incubated at 37°C for 1 h. After the addition of 0.14 M NaCl, proteins were removed by phenol-chloroform extraction and the DNA was precipitated by the addition of 2 volumes of cold ethanol. The DNA was again resuspended in TE; treated with SDS, proteinase K, and RNase; and subjected to repeated phenol-chloroform extractions. Finally, the DNA was precipitated by the addition of ethanol and resuspended (after drying) in TE. Sheared, size-selected (2.0 to 7.0 kb) DNA was ligated to *EcoRI* linkers and inserted into the *EcoRI* site of λgt11. The titer of the resulting library was approximately 10¹⁰ PFU/ml. The library was screened with anti-porphypain-2 IgG with the CLIK Clontech λgt11 Immunoscreening Kit (Clontech Laboratories, Inc.), and λFBP1 was selected for further study. The 4.5-kb insert of λFBP1 was subcloned into pUC19 (Gibco/BRL) by standard techniques (43), and the resulting plasmid was designated pHW2.

The 5' end of *prtP* was recovered as follows. *P. gingivalis* W12 chromosomal DNA was digested to completion with *Bam*HI, and 2.5- to 4.5-kb fragments were extracted from low-melting-point agarose with agarase (Boehringer Mannheim). The DNA was ligated into pUC18 (Gibco/BRL) which had been treated with *Bam*HI and bacterial alkaline phosphatase (Pharmacia), and the ligation mixture was transformed into *E. coli* JM109. The resultant colonies were probed by standard techniques (43) with the 1.1-kb *EcoRI*-*Pst*I fragment of pHW2. Plas-

mids purified from positive colonies were characterized by restriction enzyme site mapping, and one of them, pNH7, was chosen for further study.

DNA sequencing was performed with the Taq Dyedeoxy system (Applied Biosystems, Inc., Foster City, Calif.) and analyzed on an ABI 373 DNA Sequencer at the University of Florida DNA Sequencing Core Laboratory (Gainesville). Both strands of the pHW2 and pNH7 DNA inserts were sequenced. All sequence analyses were performed with the Wisconsin Sequence Analysis Package (Genetics Computer Group, University of Wisconsin). After thorough analysis of the sequences obtained, plasmid pNH5, a subclone encompassing the entire *prtP* coding region, 594 bases of upstream sequence, and 995 bases of downstream sequence, was constructed by ligation of the 3.4-kb *KpnI*-*Bam*HI fragment of pNH7 to the 3.4-kb *Bam*HI-*EcoRI* fragment of pHW2 and insertion of the ligation product into *KpnI*-*EcoRI*-digested pBlueScript SK(+) (Stratagene, La Jolla, Calif.).

Porphypain-2 tryptic peptides were prepared and purified, and their N-terminal sequences were determined, at the W. M. Keck Foundation Biotechnology Resource Laboratory (Yale University, New Haven, Conn.) as previously described (6).

Southern blot analyses. The method used to prepare genomic *P. gingivalis* DNA for Southern blot analyses was graciously provided by Margaret Duncan (8a). Bacteria were grown to early stationary phase in complete basal anaerobic broth (46) at 37°C under anaerobic conditions. Pelleted cells were resuspended in 40 mM Tris-acetate (pH 7.9)-2 mM EDTA and then lysed by the addition of an equal volume of 50 mM Tris-3% SDS, pH 12.6. The DNA was precipitated by the addition of an equal volume of isopropanol, resuspended in TE, extracted three times with phenol-chloroform, and reprecipitated by the addition of 1/8 volume of 2 M sodium acetate and 2.5 volumes of ethanol. The DNA pellet was washed with 70% ethanol, dried, and resuspended in TE.

The *P. gingivalis* genomic DNA was digested with restriction endonucleases according to the manufacturer's directions, and fragments were separated in a 0.8% agarose gel in 1× Tris-acetate-EDTA. A VacuBlot apparatus (Hofer Scientific Instruments, San Francisco, Calif.) was used to transfer the DNA to a positively charged nylon membrane, Hybond N+ (Amersham). Analyses were performed with Amersham enhanced chemiluminescence (ECL) labeling and indirect detection kits and Hyperfilm ECL. Probe 1 was obtained by gel isolation of the 1.16-kb *Hind*III fragment of pNH5 which extends from bases 589 to 1752 of *prtP*. The fragment was purified (GeneClean II; Bio 101, Vista, Calif.) and labeled by random priming (ECL System; Amersham). Probes 2 and 3 were prepared from pNH5 by labeling during PCR amplification (Probe-Amp kit; Amersham). Probe 2 extended from bases 2659 to 2868 and probe 3 extended from bases 3444 to 4005 of *prtP*. Probe 4 included bases 668 to 2179 of the *rgp-1* sequence and was obtained by PCR amplification with the Expand Long Template PCR System (Boehringer Mannheim) with genomic HG66 DNA as the template. The DNA was then labeled by random priming (ECL). Hybridizations were performed according to the manufacturer's directions (ECL System; Amersham) at 60°C in 0.5× SSC (1× SSC is 0.15 M NaCl-0.015 M sodium citrate). Washes were performed at the high-stringency conditions of 60°C in 0.2× SSC.

Nucleotide sequence accession number. The sequence of the genomic DNA region including *prtP* has been deposited in GenBank under the accession number U42210.

A

1 MRKLLLLLIAA SLLGLVGLYAQ SAKIKLDAPT TRTCTNNNSF KQFDASFSFN
 51 EVELTKVETK GGTFAVSVIP GAFPTGEVGS PEVPAVRKLI AVPVGATPVV
 101 RVKSFTEQVY SLNQYSGEKL MPHQPSMSKS DDPEKVPFVY NAAAYARKGF
 151 VGQELTQVEM LGTMRGVRIA ALTINPVQYD VVANQLKVRN NIEIEVSFQG
 201 ADEVATQRLY DASFSPPYFET AYKQLFNDRV YTDHGDLYNT PVRMLVVAGA
 251 KFKEALKPWL TWKAQKGFYL DVHYTDEAEV GTTNASIKAF IHKKYNDGLA
 301 ASAAPVFLAL VGDTDVVISGE KGKTKR WTD LYSAVVDGDY FPEMYTFRMS
 351 ASSPEELTNI IDKVLMEYKA TMPDKSYLEK VLLIAGADYS WNSQVQOPTI
 401 KYGMQYYNQ EHGVTDVVNY LKAPYTCYS HLNTGVSFAN YTAHGETAW
 451 ADPLLTSSQL KALTNKDKYF LAIGNCCITA QFDYVQPCFG EVITRVKEKG
 501 AYAYIGSSPN SYWGEDYYS VGANAVFGVQ PTFEGTSMGS YDATFLEDSY
 551 NTVNSIMWAG NLAATHAGNI GNITHIGAHI YWEAYHVLGD GSVMPYRAMP
 601 KNTI ITLPAS LPQNQASYSI QASAGSYVAI SKDGVLYGTG VANASGVATV
 651 SMTRQITENG NYDVVITRSN YLPVIKIQV GEPSPYQVNS NLTATTQGOX
 701 VTLKWEAPSA KKAEGSREVK RIGDGLFVTI EPANDVR ANE AKVVLAAADNV
 751 WGDNTGYQFL LDADHNTFGS VIPATGPLFT GTASSNLISA NFEYLVLPANA
 801 DPVVTTQNIIT VTGQGEVPIP GGVDYDICTN PEPASGKMWI AGDGGNQPAR
 851 YDDFTFEAGK KYTFPMRRAG MGDGTDMEVE DDPASVYTYT VYRDGTKIKE
 901 GLTATTFEED GVAAGNHEYC VEKVTAGVS PKVCKDVTVE GSNEFAPVQN
 951 LTGSSVGQKV TLKWDAPNGT PNNPNPNPN PGTTLSESEF NGIPASWKTI
 1001 DADGDGHGWK PGNAPGIAGY NSNGCVYSES FGLGGIGVLT PDNYLITPAL
 1051 DLPNGGKLT FVCAQDANYA SEHYAVYASS TGNDASNFNT ALLEETITAK
 1101 GVRSPKAIRG RIQGTWRQKT VDLPAQTKYV AFRHFQSTDM FYIDLDEVEI
 1151 KANGKRADFT ETFESSTHGE APAEWTTIDA DGDGQGLWCL SSGQLDWLTA
 1201 HGGSNVVSFF SWNGMALNPD NYLISKDVTG ATKVKYYAVV NDGFPDGHYA
 1251 VMISKTGTNA GDFTVVFEET PNGINKGGAR FGLSTEANGA KPQSVWIERT
 1301 VDLPAQTKYV AFRHYNCSDL NYILLDDIQF TMGGSPTPTD YTYTVYRDGT
 1351 KIKEGLTETT FEEDGVATGN HEYCVVEKYT AGVSPKCKVD VTNSTQFNP
 1401 VQNLTAEQAP NSMDAILKWN APASKRAEVL NEDFENGIPA SWKTIDADGD
 1451 GNNWTTTPPP GGSSFAGHNS AICVSSASHI NFEQPQNPND YLVTPELSLP
 1501 GGGTLTFWVC AQDANYASEH YAVYASSTGN DASNFANALL EEVLTAKTVV
 1551 TAPEAIRGTR AOGTWYQTV QLPAGTKYVA FRHFCTDFF WINLDDVVIT
 1601 SGNAPSYYT IYRNNQIAS GVTETTYRDP DLATGFYTYG VKVVYPNGES
 1651 AIETATLNIT SLADVTAQKP YTLTVVGTI TVTCQGEAMI YDMNGRRLAA
 1701 GRNTVVYTAQ GGHYAVMVV DGKSYVEKLA VK*

B

Repeat 1
 608 PYNLTattq GQKVTLKwEA P 708
 946 FVqNLtgssv GQRVTLKwDA P 967

Repeat 2
 907 YTYTVVRDGT KIKEGLTETT FEEDGVAAGN HEYCVVEKYT AGVSPKvCkd
 1341 YTYTVVRDGT KIKEGLTETT FEEDGVAAGN HEYCVVEKYT AGVSPKfCvd
 1607 YTYTiYRnnt qiasgvTETT yrddpLATGf yLYgVkvVyp nGes 1650

937 VTvegSneFa PVQNLt 952
 1391 VTvn-StqPn PVQNLt 1405

Repeat 3
 985 LsEsFENGIP ASWKTIDADG DG 1006
 1430 LnEdFENGIP ASWKTIDADG DG 1451

Repeat 4
 1041 PDNYLITPaL dLPnGkLTF VVCAQDANYA SEHYAVYASS TGNDASNFtN
 1488 PDNYLVTPeL sLPgGgLTf VVCAQDANYA SEHYAVYASS TGNDASNFAn

1091 ALLEEEtiTAK g-VrsPKAIR G-RiQGTWfQ KTVDLPAQTK YVAFRHfGqT
 1538 ALLEEEVlTAK CvvtApeAIR GrAOGTWfQ KTVQLPAQTK YVAFRHfGcT
 1293 QsvWle rTVDLPAQTK YVAFRHynCs

1139 DmFYiLdDeV eIkanG 1154
 1588 DFRwInLDDV vTtSgn 1603
 1319 DinYILLDDi qfTmGG 1334

RESULTS

Cloning of the *prtP* gene. Porphyain is a fibrinolytic *P. gingivalis* proteinase that previously was purified in this laboratory in two forms, porphyain-1 and porphyain-2. Both forms appear to be conformational variants of a single polypeptide (6). Polyclonal IgGs raised against porphyain-2 blocked fibrinogen binding and hydrolysis by *P. gingivalis* W12 cells, whereas anti-porphyain-1 IgGs blocked fibrinogen binding by bacteria but not fibrinogen hydrolysis (Fig. 1). Therefore, anti-porphyain-2 IgGs were used to screen a λ gt11 library of *P. gingivalis* W12 genomic DNA to recover the gene expressing the proteinase. One strongly positive clone, λ FBP1, was found. Phage lysates of purified λ FBP1 blotted to nitrocellulose bound 125 I-fibrinogen and 125 I-fibronectin (data not shown). The 4.5-kb insert in λ FBP1 was subcloned and sequenced; a large open reading frame (ORF) that had homology to a hemagglutinin gene, *hagA*, of *P. gingivalis* 381 was discovered (see reference 14 and results below). The ORF also encoded the peptide ANEAKVLLAADNV, which was previously identified as the N-terminal sequence of a porphyain-1 autodegradation product (6). However, the ORF lacked an initiation codon, suggesting that the 5' end of the gene had not been cloned. The remaining fragment was subsequently recovered from plasmid clones of genomic *P. gingivalis* DNA as described in Materials and Methods.

Bases downstream of *prtP* were highly homologous (97% identity) to the *P. gingivalis* insertion element IS1126 (31), except that a central 451 bp of the element were absent. The *prtP* gene encodes a predicted protein of 1,732 amino acids (Fig. 2A). All of the peptide sequences derived from tryptic digestion products of purified porphyain-2 were present in this predicted gene product (Fig. 2A), confirming the identity of the gene. Residues 1 through 19 probably constitute a signal sequence indicative of protein export, with alternate processing sites available after residue 16 or 21. An ideal signal peptide processing site is preceded by a four- to six-polar-residue region with the potential to form a turn in the peptide backbone and an Ala in the -1 position and is followed by a region with a net negative charge (40, 47, 48). Therefore, processing probably occurs after the Ala at position 19, which would result in a mature protein with a calculated molecular mass of 186 kDa. This is in good agreement with the 180-kDa observed molecular mass of porphyain (6). Several repeated regions were identified in the protein (Fig. 2B), as well as the pair Pro-Asn tandemly repeated 5.5 times.

Comparison of protein sequences. Database searches revealed a high degree of homology only between the C-terminal two-thirds of PrtP and several other *P. gingivalis* proteinases; the 5' one-third of the gene was unique at both the DNA and protein levels. Homology was detected between PrtP and the products of the *rgp-1*, *prtR* (recently revised), *prpR1*, *agp*, and *prtH* genes, all of which reportedly have Arg-X activity (1, 9, 20, 36, 39). However, these proteins and encoding DNA sequences, and the *cpgR* gene and gene product (12), were more like one another than like *prtP* and its product (Table 1). The *prtR* and *prpR1* genes, flanking sequences, and gene products were almost identical to each other and to *rgp-1* and its gene

FIG. 2. Analysis of the predicted *prtP* gene product. (A) Sequence of PrtP. The probable signal peptide is underlined; the (Pro-Asn) tandem repeat is also underlined. N-terminal sequences of peptides recovered after tryptic digestion and an autodegradation product are boxed. (B) Homologous regions within PrtP. The criteria for identifying repeats were 70% or greater identity over 20 to 39 amino acids or 50% or greater identity over 40 or more amino acids. Amino acids in common between at least two sequences are shown in capital letters.

TABLE 1. Comparison of reported *P. gingivalis* genes encoding homologous Arg-X specific proteases

Gene/strain (GenBank no.)	5' DNA region ^a		DNA coding region ^a		3' DNA region ^a		Protein ^a		
	Length ^b	% Iden. ^c	Length ^b	% Iden. ^c	Length ^b	% Iden. ^c	Length ^b	% Iden. ^c	% Sim. ^d
<i>rap-1</i> /HG66 (U15282)	948	100	5,115/5,115	100	264	100	1,704	100	100
<i>prtR</i> /W50 (L26341)	84	100	5,115/5,121	99.1	75	96.0	1,704/1,706	99.2	99.6
<i>prpR1</i> /W50 (X82680)	627	99.8	4,480/4,578	99.0	NA ^e	NA	1,493/1,526	99.1	99.6
<i>agp</i> /381 (D26470)	535	100	2,976/2,976	99.9	264	98.8	991/991	99.8	100
<i>prtH</i> /W83 (L27483)	NA	NA	2,369/2,369	98.1	264	96.9	570/657	97.4	98.2
<i>cpGR</i> /ATCC 33277 (X85186)	NA	NA	1,452/1,464	85.2	NA	NA	411/422	99.0	100

^a Regions were defined by the *rgp-1* sequence. For example, the 3' DNA region for the *prtH* gene comparison included DNA within the predicted coding region of *prtH* but beyond the *rgp-1* coding region.

^b Length of compared region in bases or amino acids. Ratios are length of the compared region to total length of available sequence. Regions of low homology due to frameshifts, gaps, or deletions were excluded.

^c % Iden., percent identity of the compared region with *rgp-1* or Rgp.

^d % Sim., percent similarity of the compared region with Rgp-1.

^e NA, not available.

product. The complete 3' end of the *prpR1* coding region has not been reported. The *agp* gene, flanking DNA, and gene product were also highly homologous to *rgp-1* and Rgp-1, with the exception of an apparent deletion which effectively combined two repeated regions into one sequence. The *prtH* gene overlapped with and extended beyond the *rgp-1* gene, and the DNA homology continued throughout the available sequence 3' of *rgp-1*. However, the alignment was affected by several single-base insertions in *prtH* relative to *rgp-1*. Finally, *cpGR*, although not homologous to *prtP*, was highly homologous to *rgp-1* and the other proteinase genes (Table 1). Remarkably, the available DNA sequence following the putative stop codon of *cpGR* could encode an additional 61 amino acids that would be identical to the corresponding residues in Rgp-1. All in all, none of these previously described genes were directly analogous to *prtP* but could each be variants of a single, distinct genetic locus.

Figure 3 shows a detailed comparison of PrtP with Rgp-1 and HagA. Only Rgp-1 was included from the group of pro-

teinases described above, because it encompassed most of the predicted coding regions of the other proteinases and all of the sequences homologous to PrtP (see Fig. 5A). Large regions of PrtP and Rgp-1 were highly homologous, but no homology was detected in the N-terminal segments of the proteins. The homology between PrtP and the product of the *hagA* gene (14) was also limited to the C-terminal portion of PrtP (Fig. 3).

PrtP may be cleaved prior to or during release from the cell. Proteinases with Lys-X (KGP) or Arg-X and Lys-X specificity isolated from culture supernatants of strains HG66 and ATCC 33277 (8, 41) consist of associated peptides or apparent auto-degradation products with N-terminal sequences homologous to PrtP sequences starting at amino acids 229, 738, 1157, and 1292 (Fig. 3 and 4A). Rgp-1 recovered from culture supernatants of strain HG66 also appears to have been cleaved (39, 41) (shown in Fig. 3). Each of the putative cleavage sites in PrtP and Rgp-1 is preceded by an Arg or Lys residue. No other consensus pattern was noted by alignment of the cleavage sites.

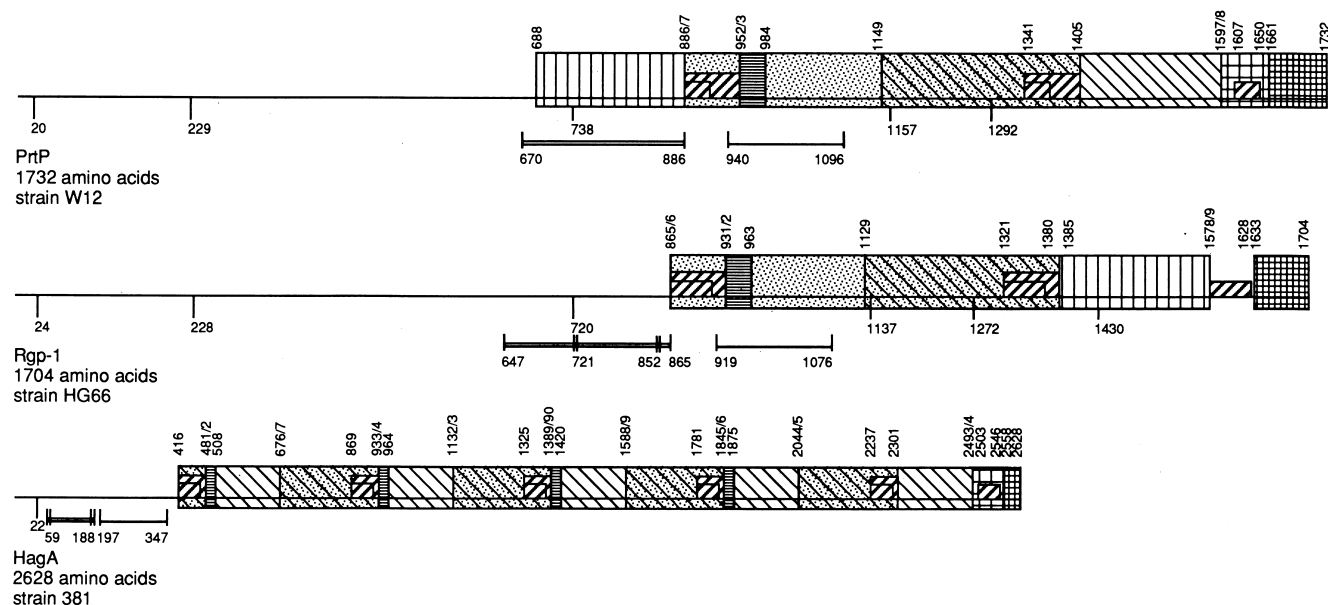


FIG. 3. Comparison of PrtP with Rgp-1 and HagA. Each protein is represented in linear fashion; HagA is shown in half-scale. Putative cleavage sites in PrtP and Rgp-1 are shown below each protein. Sequences homologous to repeat 2 of PrtP are shown as small, internal hatched boxes. Regions of 90% or greater identity between PrtP and Rgp-1 or HagA are shown by identical boxes; regions of 50 to 60% identity are similarly underlined. The horizontally striped box represents a region encompassing the Pro-Asn tandem repeat and is substituted after repeat 2 in all but one of the large repeated regions comprising most of HagA.

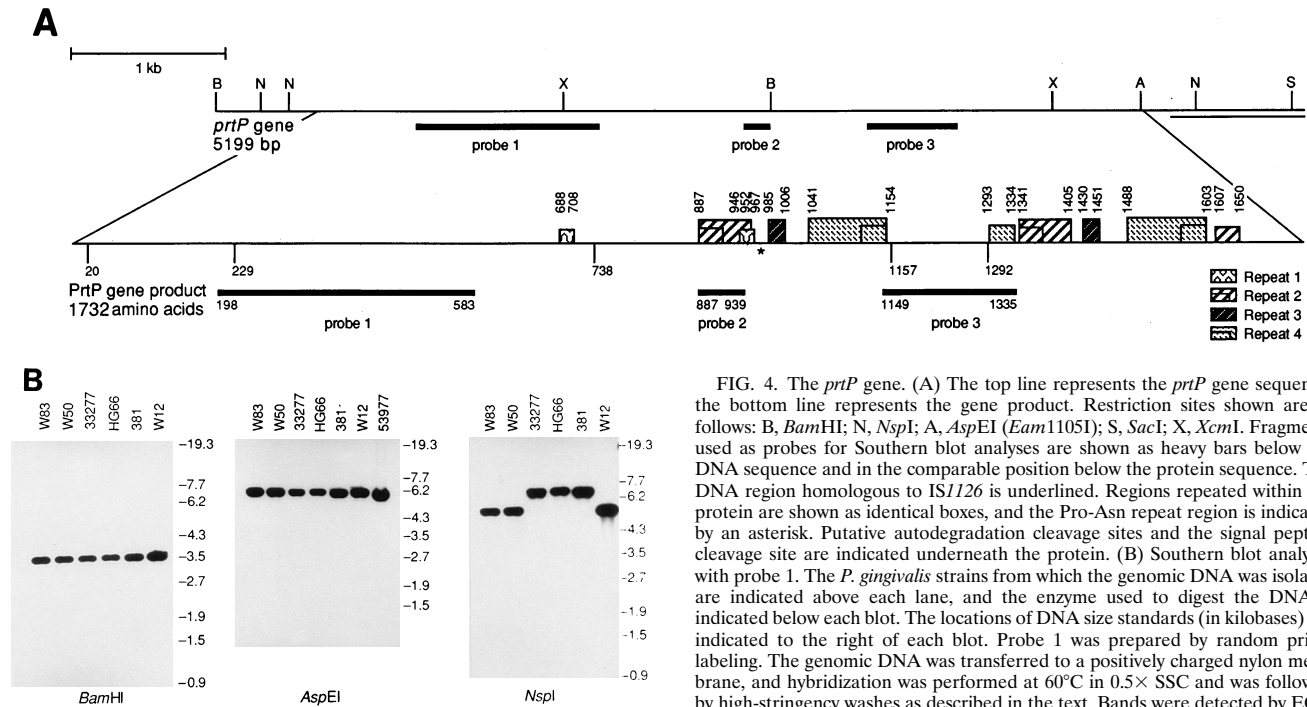


FIG. 4. The *prtP* gene. (A) The top line represents the *prtP* gene sequence; the bottom line represents the gene product. Restriction sites shown are as follows: B, *Bam*HI; N, *Nsp*I; A, *Asp*EI (*Eam*1105I); S, *Sac*I; X, *Xcm*I. Fragments used as probes for Southern blot analyses are shown as heavy bars below the DNA sequence and in the comparable position below the protein sequence. The DNA region homologous to *IS1126* is underlined. Regions repeated within the protein are shown as identical boxes, and the Pro-Asn repeat region is indicated by an asterisk. Putative autodegradation cleavage sites and the signal peptide cleavage site are indicated underneath the protein. (B) Southern blot analyses with probe 1. The *P. gingivalis* strains from which the genomic DNA was isolated are indicated above each lane, and the enzyme used to digest the DNA is indicated below each blot. The locations of DNA size standards (in kilobases) are indicated to the right of each blot. Probe 1 was prepared by random prime labeling. The genomic DNA was transferred to a positively charged nylon membrane, and hybridization was performed at 60°C in 0.5× SSC and was followed by high-stringency washes as described in the text. Bands were detected by ECL.

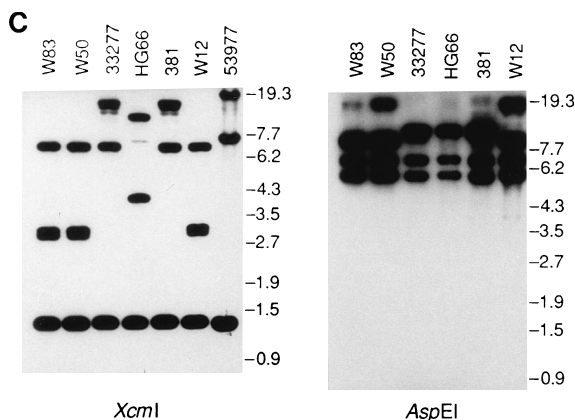
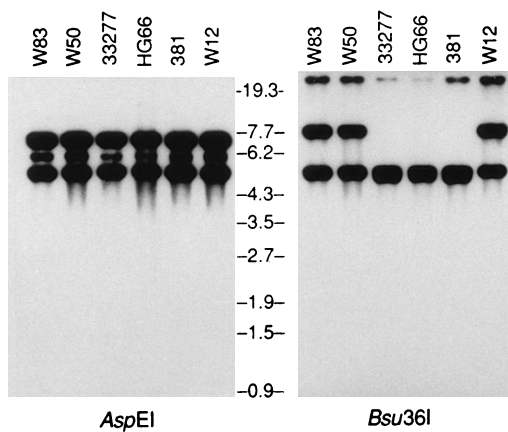
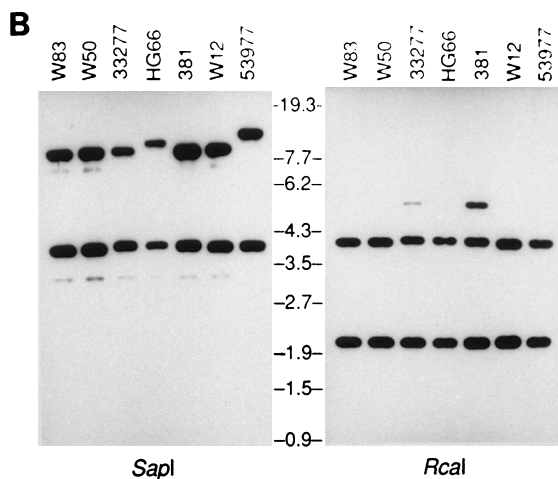
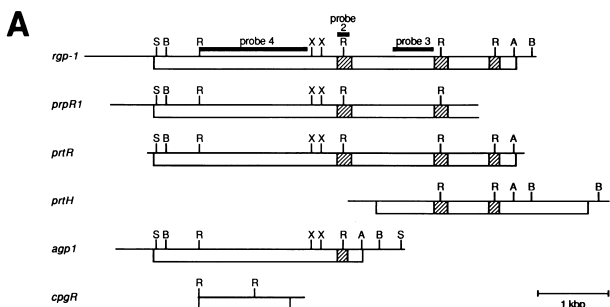
The *prtP* gene is present in single copy in the genomes of seven *P. gingivalis* strains. Cells of all *P. gingivalis* strains tested reacted with anti-porphyrin-2 IgGs (data not shown). A 1.16-kb *Hind*III fragment unique to *prtP* (Fig. 4A, probe 1) was used to probe genomic DNA of seven *P. gingivalis* strains (Fig. 4B; some data not shown for strain ATCC 53977). Digests of genomic DNA from all seven strains examined exhibited only one band. The size of the *Nsp*I band detected in DNA from strains ATCC 33277, HG66, 381, and ATCC 53977 varied from the predicted size (Fig. 4B and data not shown). The 3' *Nsp*I site delineating the band detected in strain W12 was located within the sequence homologous to the insertion element *IS1126* (Fig. 4A); this sequence apparently was not immediately adjacent to *prtP* in the differing strains, i.e., the insertion element did not transpose to the same location in all strains (data not shown).

Analysis of the homologous Arg-X proteinase genes. The data in Table 1 suggested that the six described genes represent identical loci. A probe specific for the region of these genes which was not homologous to *prtP* or *hagA* was used in Southern blot analyses to test this hypothesis (probe 4, Fig. 5A). Probe 4 hybridized with two major bands in the genomic DNA of all seven *P. gingivalis* strains examined; there is a doublet at approximately 6.0 kb for DNA of strains ATCC-33277, HG66, and 381 digested with *Bsu*36I (Fig. 5B). A minor third band was also detected in most analyses but could not be correlated with any of the genes described. The *agp* gene was not detected in any of the genomes, including that of strain 381 from which it was originally cloned—note the absence of a 3.5-kb *Sap*I fragment or a 3.0-kb *Bsu*36I fragment detected with probe 4. There was also no evidence of the *cpgR* gene, on the basis of the absence of a 0.8-kb *Rca*I fragment which should hybridize to probe 4 (data not shown). However, one of the major bands detected in all seven genomes with this probe was consistent with the size predicted for *rgp-1*, *ppr1*, or *prtR*—for example, the 2.0-kb *Rca*I fragment (Fig. 5B and data not shown). If *ppr1* and *prtR* are separate loci from *rgp-1*, then

digests with enzymes that cleave no more than once within the coding region might be used to illustrate the differing loci, particularly in strain W50. However, an additional strongly hybridizing locus was not detected when the genomic DNA was digested with *Asp*EI or *Sap*I (Fig. 5B).

The *prtH* gene would not be detected by probe 4, but it does have a region in common with *prtP*, the *rgp-1*-like genes, and *hagA*. Probe 3 (Fig. 4A and 5A) was used to determine the number of times the common sequence appears in the *P. gingivalis* genome. Digestion of the genomic DNAs with *Asp*EI or *Xcm*I resulted in three or four bands that hybridized with probe 3, depending on the strain analyzed (Fig. 5C). The *Asp*EI bands detected at 7.0 and 6.0 kb corresponded to the *rgp-1*-like and *prtP* loci, respectively, on the basis of bands of a similar size hybridizing with probes to the respective 5' regions (probes 1 and 4, Fig. 4B and 5B). The 1.35-kb *Xcm*I band that hybridized to probe 3 was indicative of the *hagA* gene (Fig. 5C; restriction data not shown), so the *prtP*, *rgp-1*, and *hagA* genes were each identified. This analysis revealed some heterogeneity in the *prtP* gene from various strains (Fig. 5C). The fourth band detected in several *P. gingivalis* strains could indicate the presence of *prtH*. When genomic DNA was digested with *Asp*EI, the fourth band identified with probe 3 was not the same size as a band detected with probe 4, nor was the approximately 5-kb band that hybridized to probe 4 detected with probe 3 (Fig. 5B and C).

A repeat region present in *prtP* is present in multiple copies in the *P. gingivalis* genome. The PrtP gene product contained several repeated regions (Fig. 2B). Repeat 2, beginning with YTY... , was also present three times in Rgp-1 (39) and six times in HagA (Fig. 3). A nucleotide probe encoding a portion of copy 1 of PrtP repeat 2 (Fig. 4A and 5A, probe 2) was used in Southern blot analyses of seven *P. gingivalis* strains; blots were treated with high-stringency washes (0.2× SSC, 60°C) (Fig. 6). A minimum of 19 to 23 bands were detected, depending on which strain genome was examined. At least three of the bands must represent multiple copies of the repeat present in



prtP, *hagA*, and the *rgp-1*-like genes. For example, the 1.35-kb *XcmI* band was from all six copies present in the *hagA* gene, and the 6.0- and 7.0-kb *AspEI* bands represent the repeat 2 copies in *prtP* and *rgp-1*, respectively (14) (Fig. 4 and 5). Strains W50 and W83 had very similar but not identical patterns in these analyses, and strains ATCC 33277 and 381 showed identical patterns. Also, the 5-kb band detected with probe 4 in *AspEI*-digested DNA (Fig. 5B) was not detected with the probe to the repeat region (Fig. 6).

DISCUSSION

Workers in this laboratory have purified a proteinase, porphypain, from detergent extracts of *P. gingivalis* cells (6). The previous biochemical characterization of porphypain supports the presence of two types of active sites in a single proteinase (6). Determination of whether these are separate sites, are conformational variants of one active site, or are present in two separate proteins (as suggested in reference 42) awaits expression of the proteinase as a recombinant. This report describes the cloning and sequencing of *prtP*, the gene encoding porphypain. The *prtP* gene as cloned did not express an active proteinase in *E. coli*. A region that is highly homologous to the insertion element IS1126 (31) was found 3' to *prtP* in strain W12. It is missing a segment encoding part of the predicted transposase and thus would be inactive alone, but since there are multiple copies of IS1126 throughout the *P. gingivalis* genome (reference 31 and data not shown), it could serve as one end of a composite transposon or be transactivated. Genes proximal to an insertion element can be subjected to transposition or deletion; however, a single copy of *prtP* was detected in all seven *P. gingivalis* strains examined—ATCC 33277, 381, W50, W83, W12, HG66, and ATCC 53977.

The active site(s) of porphypain has not yet been identified, and no cysteine proteinase active site motifs were detected in PrtP. As has been previously suggested for Rgp-1 (5, 39), PrtP may belong to a new class of cysteine proteinases, in keeping with its unusual stimulation by derivatives of glycine, inhibition by EDTA, and activation by reducing agents in an unusual order of preference (6). Four repeated sequences and a Pro-Asn tandem repeat were identified in the C-terminal three-fifths of the *prtP* gene product; the significance of these motifs is unclear, but they may be functionally or structurally important. For example, a Pro-X motif in the *E. coli* TonB protein has been implicated in crossing the periplasmic space, although it apparently is not essential for protein function (27). On the basis of Southern blot analyses, at least 20 copies of sequences homologous to those encoding repeat 2 (shown in Fig. 2) were present in each of the seven *P. gingivalis* genomes examined, further suggesting that this peptide region may be structurally or functionally important.

The latter analysis fortuitously provided a means of comparing genomes. The pattern of bands observed in the Southern

FIG. 5. Analyses of *rgp-1*-like genes. (A) The DNA sequences of each gene shown in Table 1 are represented linearly and aligned to indicate homology. The boxes represent the predicted translation products; the hatched boxes represent repeat 2 as identified in PrtP. Selected restriction sites are shown above each gene—S, *SapI*; B, *Bsu36I*; R, *RcaI* (*BspHI*); X, *XcmI*; A, *AspEI* (*Eam1105I*). The regions corresponding to DNA probes are shown by heavy bars above *rgp-1*. Probes 2 and 3 are the same as probes 2 and 3 shown in Fig. 4A. (B and C) Southern blot analyses with probes 4 and 3, respectively. The *P. gingivalis* strains from which genomic DNA was obtained are indicated above each lane, and the enzyme with which the DNA was digested is indicated below each blot. The locations of DNA size standards (in kilobases) are indicated between the blots. Experimental conditions were as described for Fig. 4B. Probe 4 was prepared by random prime labeling, and probe 3 was prepared by PCR labeling.

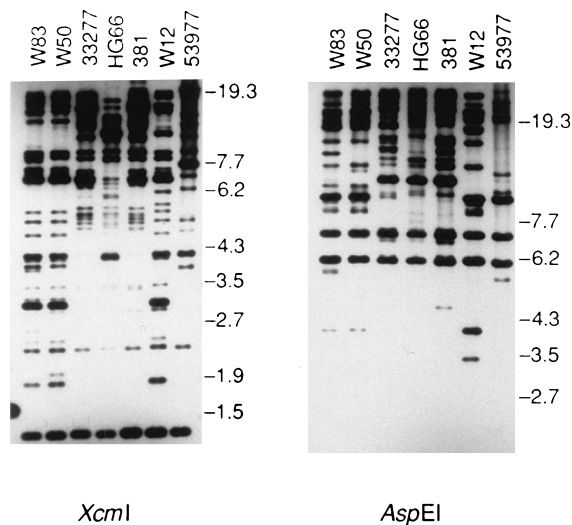


FIG. 6. Southern blot analyses with probe 2. Genomic DNA was digested with *XcmI* or *AspEI* (*Eam1105I*) as indicated. The locations of DNA size standards (in kilobases) are indicated to the right of each blot. Experimental conditions were as described for Fig. 4B. Probe 2 was prepared by labeling during PCR amplification.

blot analyses with a probe corresponding to repeat 2 was very similar for strains W50 and W83 but not identical; these strains were previously indistinguishable when analyzed by multilocus enzyme electrophoresis, DNA fingerprinting, and arbitrarily primed PCR (4, 28, 29). Strains ATCC 33277 and 381 showed an identical banding pattern in the Southern blot analyses, which supports previous analyses characterizing the relatedness of the strains (4, 28, 29) and the suggestion that strain ATCC 33277 is actually a derivative of strain 381 (29).

The *prtP* gene had regions of homology with several other *P. gingivalis* genes, although no homology was detected between *prtP* and the *P. gingivalis* proteinase genes *ipr* (not *trp* as stated in the work of Potempa et al. [42]), *prtT*, and *prtC* (3, 19, 30) or between the respective protein products at 80% similarity over 20 amino acids or 65% similarity over 100 amino acids. Most of *hagA*, which encodes a hemagglutinin and was cloned from strain 381 (14), was highly homologous to the C-terminal portion of *prtP*, by virtue of four and one-half copies of a large DNA segment encompassing the *prtP* repeat 2 sequence. Southern blot analyses were consistent with the presence of *hagA* in the seven strains examined. Five genes encoding Arg-X active proteinases previously identified in *P. gingivalis* were also found to be partially homologous to *prtP*: *rgp-1*, *prpR1*, *prtR*, *prtH*, and *agp* (1, 9, 20, 36, 39). None of these genes had homology to the 5' end of *prtP*, nor was there homology between the corresponding protein regions. Conversely, and consistent with their differing specificities (5, 6), *PrtP* was not homologous to the N-terminal region of *Rgp-1*, which is thought to include the proteinase active site (39). Pike et al. (41) have suggested that the C-terminal moiety of *Rgp-1* acts as a hemagglutinin, and there is some evidence suggesting that an extracellular form of *PrtP* participates in hemagglutination (data not shown). The amino acid sequence found in *HagA* and in the C-terminal halves of both *PrtP* and *Rgp-1* could be functionally important in hemagglutination, but further evidence is needed to confirm this theory.

Another *P. gingivalis* proteinase, KGP, could be a variant of *PrtP* (41). KGP was isolated from culture supernatants of strain HG66 and appears to be a high-molecular-mass complex

of a 60-kDa proteinase and a purported hemagglutinin; the latter was suggested on the basis of similarity with *Rgp-1* (41). The reported N-terminal sequences of the KGP components (41) were highly homologous to sequences in *PrtP*. KGP reportedly cleaves after lysine and not arginine, but porphypain apparently has both Arg-X and Lys-X specificity (6, 41). Therefore, *prtP* has not been named *kgp* as suggested by Potempa et al. (42), because the specificity of the enzyme is in question. Neither recombinant proteinase has been characterized to date. It is possible that *kgp* and *prtP* will prove to be separate genes, although it seems more likely that the differences in detected activities are due to strain variations or differing assay conditions.

A comparison of the genes associated with Arg-X active proteinases—*rgp-1*, *prpR1*, *prtR*, *agp*, and *prtH*, along with *cpgR*—showed that they are highly homologous to one another. During preparation of the manuscript, Potempa et al. (42) also reported a comparison of these nucleotide sequences. The data in this report show that these genes, with the possible exception of *prtH*, are probably derived from one *P. gingivalis* genomic locus. The *prpR1* and *prtR* genes both were cloned from strain W50 (1, 20), and the *rgp-1* gene of strain W50 reportedly encodes only two conservative amino acid changes relative to *Rgp-1* of strain HG66 (39). However, only one locus consistent with the restriction maps of these genes was detected in the genomes of strain W50 and the other six strains examined. In addition, the *agp* gene, which is essentially identical to *rgp-1* except for a large deletion between two repeated regions (36), was not detected in any of the *P. gingivalis* genomes examined by Southern blot analyses—DNA fragments were of the size consistent with the presence of the purportedly missing sequence. It is possible that recombination between the repeated regions occurred prior to or during cloning. Even though it should have been detected, the *cpgR* gene also was not found in Southern blot analyses. Finally, the presence or absence of the *prtH* gene as a separate locus was not clearly discerned by the Southern blot analyses used in this study; four loci with sequences homologous to *prtH*, *rgp-1*, *hagA*, and *prtP* were detected in several *P. gingivalis* strains.

Although a second locus homologous to the 5' one-third of *rgp-1*, *prpR1*, and *prtR* was detected, it did not have a restriction pattern comparable to those of the reported proteinase genes. In our analyses and those of other groups (1, 34), the second locus did not appear to be adjacent to sequences present in the 3' portion of the *rgp-1*-like genes. A weakly hybridizing third band was frequently detected in Southern blot analyses, but it too did not match the restriction patterns of the reported proteinase genes.

In conclusion, the *prtP* gene encoding porphypain, a unique proteinase of *P. gingivalis*, has been cloned and sequenced. The *prtP* gene encodes a protein with a unique N-terminal region but with large C-terminal regions of homology to several reported proteinases of *P. gingivalis* and *HagA*, a *P. gingivalis* hemagglutinin. In addition to the characterization of *prtP*, this report details the relationships of the group of homologous Arg-X active proteinase genes cloned from various strains of *P. gingivalis* and suggests that the genes represent variants of a single genetic locus.

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REFERENCES

1. Aduse-Opoku, J., J. Muir, J. M. Slaney, M. Rangarajan, and M. A. Curtis. 1995. Characterization, genetic analysis, and expression of a protease antigen (PrpR1) of *Porphyromonas gingivalis* W50. *Infect. Immun.* **63**:4744-4754.
2. Bedi, G. S., and T. Williams. 1994. Purification and characterization of a collagen-degrading protease from *Porphyromonas gingivalis*. *J. Biol. Chem.* **269**:599-606.
3. Bourgeau, G., H. Lapointe, P. Pélouin, and D. Mayrand. 1992. Cloning, expression, and sequencing of a protease gene (*ptr*) from *Porphyromonas gingivalis* W83 in *Escherichia coli*. *Infect. Immun.* **60**:3186-3192.
4. Chen, C., and J. Slots. 1994. Clonal analysis of *Porphyromonas gingivalis* by the arbitrarily primed polymerase chain reaction. *Oral Microbiol. Immunol.* **9**:99-103.
5. Chen, Z., J. Potempa, A. Polanowski, M. Wikstrom, and J. Travis. 1992. Purification and characterization of a 50-kDa cysteine proteinase (gingipain) from *Porphyromonas gingivalis*. *J. Biol. Chem.* **267**:18896-18901.
6. Ciborowski, P., M. Nishikata, R. D. Allen, and M. S. Lantz. 1994. Purification and characterization of two forms of a high-molecular-weight cysteine proteinase (porphypain) from *Porphyromonas gingivalis*. *J. Bacteriol.* **176**:4549-4557.
7. Curtis, M. A., M. Ramakrishnan, and J. M. Slaney. 1993. Characterization of the trypsin-like enzymes of *Porphyromonas gingivalis* W83 using a radio-labelled active-site-directed inhibitor. *J. Gen. Microbiol.* **139**:949-955.
8. DeCarlo, A. Personal communication.
- 8a. Duncan, M. Personal communication.
9. Fletcher, H. M., H. A. Schenkein, and F. L. Macrina. 1994. Cloning and characterization of a new protease gene (*prtH*) from *Porphyromonas gingivalis*. *Infect. Immun.* **62**:4279-4286.
10. Fujimura, S., and T. Nakamura. 1990. Purification and characterization of a 43-kDa protease of *Bacteroides gingivalis*. *Oral Microbiol. Immunol.* **5**:360-362.
11. Fujimura, S., Y. Shibata, and T. Nakamura. 1992. Comparative studies of three proteases of *Porphyromonas gingivalis*. *Oral Microbiol. Immunol.* **7**:212-217.
12. Gharbia, S. E., and H. N. Shah. 1995. Molecular analysis of surface-associated enzymes of *Porphyromonas gingivalis*. *Clin. Infect. Dis.* **20**(Suppl. 2): S160-S166.
13. Grant, D. A., I. B. Stern, and M. A. Listgarten. 1988. Periodontics, 6th ed., p. 348-375. The C. V. Mosby Co., St. Louis.
14. Han, N., J. Whitlock, and A. Progulsk-Fox. Unpublished data.
15. Holt, S. C., and T. E. Bramanti. 1991. Factors in virulence expression and their role in periodontal disease pathogenesis. *Crit. Rev. Oral Biol. Med.* **2**:177-281.
16. Hunter, W. M. 1978. Radioimmunoassay, p. 14.1-14.40. In D. M. Weir (ed.), *Handbook of experimental immunology*. Blackwell Scientific Publications, Ltd., Oxford.
17. Huynh, T., R. A. Young, and R. Davis. 1985. Construction and screening of cDNA libraries in λ gt11 and λ gt11. p. 56-110. In D. M. Glover (ed.), *DNA cloning*, vol. I. IRL Press Ltd., Oxford.
18. Kadowaki, T., M. Yoneda, K. Okamoto, K. Maeda, and K. Yamamoto. 1994. Purification and characterization of a novel arginine-specific cysteine proteinase (argingipain) involved in the pathogenesis of periodontal disease from the culture supernatant of *Porphyromonas gingivalis*. *J. Biol. Chem.* **269**:21371-21378.
19. Kato, T., N. Takahashi, and H. K. Kuramitsu. 1992. Sequence analysis and characterization of the *Porphyromonas gingivalis* *prtC* gene, which expresses a novel collagenase activity. *J. Bacteriol.* **174**:3889-3895.
20. Kirszbaum, L., C. Sotiropoulos, C. Jackson, S. Cleal, N. Slakeski, and E. C. Reynolds. 1995. Complete nucleotide sequence of a gene *prtR* of *Porphyromonas gingivalis* W50 encoding a 132 kDa protein that contains an arginine-specific thiol endopeptidase domain and a haemagglutinin domain. *Biochem. Biophys. Res. Commun.* **207**:424-431.
21. Lantz, M. S. Are bacterial proteases important virulence factors? *J. Periodontal Res.*, in press.
22. Lantz, M. S., R. D. Allen, P. Ciborowski, and S. C. Holt. 1993. Purification and immunolocalization of a cysteine protease from *Porphyromonas gingivalis*. *J. Periodontol. Res.* **28**:467-469.
23. Lantz, M. S., R. D. Allen, L. W. Duck, J. L. Blume, L. M. Switalski, and M. Hook. 1991. Identification of *Porphyromonas gingivalis* components that mediate its interactions with fibronectin. *J. Bacteriol.* **173**:4263-4270.
24. Lantz, M. S., R. D. Allen, T. A. Vail, L. M. Switalski, and M. Hook. 1991. Specific cell components of *Bacteroides gingivalis* mediate binding and degradation of human fibrinogen. *J. Bacteriol.* **173**:495-504.
25. Lantz, M. S., R. W. Rowland, L. M. Switalski, and M. Hook. 1986. Interactions of *Bacteroides gingivalis* with fibrinogen. *Infect. Immun.* **54**:654-658.
26. Lantz, M. S., L. M. Switalski, K. S. Kornman, and M. Hook. 1985. *Bacteroides intermedius* binds fibrinogen. *J. Bacteriol.* **163**:623-628.
27. Larsen, R. A., G. A. Wood, and K. Postle. 1993. The conserved proline-rich motif is not essential for energy transduction by *Escherichia coli* TonB protein. *Mol. Microbiol.* **10**:943-953.
28. Loos, B. G., D. W. Dyer, T. S. Whittam, and R. K. Selander. 1993. Genetic structure of populations of *Porphyromonas gingivalis* associated with periodontitis and other oral infections. *Infect. Immun.* **61**:204-212.
29. Loos, B. G., D. Mayrand, R. J. Genco, and D. P. Dickinson. 1990. Genetic heterogeneity of *Porphyromonas (Bacteroides) gingivalis* by genomic DNA fingerprinting. *J. Dent. Res.* **69**:1488-1493.
30. Madden, T. E., V. L. Clark, and H. K. Kuramitsu. 1995. Revised sequence of the *Porphyromonas gingivalis* PrT cysteine protease/hemagglutinin gene: homology with streptococcal pyrogenic exotoxin B/streptococcal proteinase. *Infect. Immun.* **63**:238-247.
31. Maley, J., and I. S. Roberts. 1994. Characterisation of IS1126 from *Porphyromonas gingivalis* W83: a new member of the IS4 family of insertion sequence elements. *FEMS Microbiol. Lett.* **123**:219-224.
32. Mayrand, D., and S. C. Holt. 1988. Biology of asaccharolytic black-pigmented *Bacteroides* species. *Microbiol. Rev.* **52**:134-152.
33. McKee, R. A., S. Adams, J. A. Matthews, C. J. Smith, and H. Smith. 1986. Molecular cloning of two cysteine proteinases from paw-paw (*Carica papaya*). *Biochem. J.* **237**:105-110.
34. Nakayama, K., T. Kadowaki, K. Okamoto, and K. Yamamoto. 1995. Construction and characterization of arginine-specific cysteine proteinase (argingipain)-deficient mutants of *Porphyromonas gingivalis*. *J. Biol. Chem.* **270**:23619-23626.
35. Nishikata, M., and F. Yoshimura. 1991. Characterization of *Porphyromonas (Bacteroides) gingivalis* hemagglutinin as a protease. *Biochem. Biophys. Res. Commun.* **178**:336-342.
36. Okamoto, K., Y. Misumi, T. Kadowaki, M. Yoneda, K. Yamamoto, and Y. Ikehara. 1995. Structural characterization of argingipain, a novel arginine-specific cysteine proteinase as a major periodontal pathogenic factor from *Porphyromonas gingivalis*. *Arch. Biochem. Biophys.* **316**:917-925.
37. Ootogoto, J.-I., and H. K. Kuramitsu. 1993. Isolation and characterization of the *Porphyromonas gingivalis* *prtT* gene, coding for protease activity. *Infect. Immun.* **61**:117-123.
38. Park, Y., and B. C. McBride. 1992. Cloning of a *Porphyromonas (Bacteroides) gingivalis* protease gene and characterization of its product. *FEMS Microbiol. Lett.* **92**:273-278.
39. Pavloff, N., J. Potempa, R. N. Pike, V. Prochazka, M. C. Kiefer, J. Travis, and P. J. Barr. 1995. Molecular cloning and structural characterization of the Arg-gingipain proteinase of *Porphyromonas gingivalis*. *J. Biol. Chem.* **270**:1007-1010.
40. Perlman, D., and H. O. Halvorson. 1983. A putative signal peptidase recognition site and sequence in eukaryotic and prokaryotic signal peptides. *J. Mol. Biol.* **167**:391-409.
41. Pike, R., W. McGraw, J. Potempa, and J. Travis. 1994. Lysine- and arginine-specific proteinases from *Porphyromonas gingivalis*. *J. Biol. Chem.* **269**:406-411.
42. Potempa, J., N. Pavloff, and J. Travis. 1995. *Porphyromonas gingivalis*: a protease/gene accounting audit. *Trends Microbiol.* **3**:430-434.
43. Sambrook, J., E. F. Fritsch, and T. Maniatis. 1989. *Molecular cloning: a laboratory manual*, 2nd ed. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y.
44. Scott, C. F., E. J. Whitaker, B. F. Hammond, and R. W. Colman. 1993. Purification and characterization of a potent 70-kDa thiol lysyl-proteinase (lys-gingivain) from *Porphyromonas gingivalis* that cleaves kininogens and fibrinogen. *J. Biol. Chem.* **268**:7935-7942.
45. Shah, H. N., S. E. Gharbia, D. Kowlessur, E. Wilkie, and K. Brocklehurst. 1991. Gingivain; a cysteine proteinase isolated from *Porphyromonas gingivalis*. *Microb. Ecol. Health Dis.* **4**:319-328.
46. Syed, S. A., and W. J. Loesche. 1978. Bacteriology of human experimental gingivitis: effect of plaque age. *Infect. Immun.* **21**:821-829.
47. von Heijne, G. 1983. Patterns of amino acids near signal sequence cleavage sites. *Eur. J. Biochem.* **133**:17-21.
48. von Heijne, G. 1986. A new method for predicting signal sequence cleavage sites. *Nucleic Acids Res.* **14**:4683-4690.
49. Yanisch-Perron, C., J. Vieira, and J. Messing. 1985. Improved M13 phage cloning vectors and host strains: nucleotide sequences of the M13mp18 and pUC19 vectors. *Gene* **33**:103-119.