The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/112878

Please be advised that this information was generated on 2019-04-18 and may be subject to change.
Isolation and Functional Characterization of Two Distinct Sexual-Stage-Specific Promoters of the Human Malaria Parasite *Plasmodium falciparum*

KOEN J. DECHERING, ANITA M. KAAN, WILFRED MBACHAM, WIJNAND ELING, RUUD N. H. KONINGS, AND HENDRIK G. STUNNENBERG

Department of Molecular Biology, University of Nijmegen, 6525 ED Nijmegen, and Department of Medical Parasitology, University of Nijmegen, 6500 HB Nijmegen, The Netherlands, and Department of Tropical Public Health, Harvard School of Public Health, Boston, Massachusetts 02115

Received 10 July 1998/Returned for modification 23 September 1998/Accepted 11 November 1998

Transmission of malaria depends on the successful development of the sexual stages of the parasite within the midgut of the mosquito vector. The differentiation process leading to the production of the sexual stages is delineated by several developmental switches. Arresting the progression through this sexual differentiation pathway would effectively block the spread of the disease. The successful development of such transmission-blocking agents is hampered by the lack of a detailed understanding of the program of gene expression that governs sexual differentiation of the parasite. Here we describe the isolation and functional characterization of the *Plasmodium falciparum* *pfs16* and *pfs25* promoters, whose activation marks the developmental switches executed during the sexual differentiation process. We have studied the differential activation of the *pfs16* and *pfs25* promoters during intraerythrocytic development by transfection of *P. falciparum* and during gametogenesis and early sporogonic development by transfection of the related malarial parasite *P. gallinaceum*. Our data indicate that the promoter of the *pfs16* gene is activated at the onset of gametocytogenesis, while the activity of the *pfs25* promoter is induced following the transition to the mosquito vector. Both promoters have unusual DNA compositions and are extremely A/T rich. We have identified the regions in the *pfs16* and *pfs25* promoters that are essential for high transcriptional activity. Furthermore, we have identified a DNA-binding protein, termed PAF-1, which activates *pfs25* transcription in the mosquito midgut. The data presented here shed the first light on the details of processes of gene regulation in the important human pathogen *P. falciparum*.

*Plasmodium falciparum* is one of the major debilitating and life-threatening parasitic pathogens of humans. Half of the world’s population lives in areas endemic for malaria, and 2 million to 3 million people are killed annually. Despite years of intensive research, an effective vaccine is still not available and the parasite displays a growing resistance to the currently available drugs. New ways of combating the disease should be equipped to invade the midgut of the mosquito vector. One approach to control malaria is to prevent sexual development of the parasite and thus transmission to the mosquito (1, 25). Research efforts directed toward such a goal will greatly benefit from a detailed understanding of the gene-regulatory events underlying sexual development.

The process of sexual differentiation is governed by several developmental switches that direct the parasite through a complex series of morphological changes (Fig. 1). First, a subpopulation of asexually reproducing parasites commits to sexual differentiation and undergoes gametocytogenesis, the formation of male and female sex cells. The sexually committed parasites are marked by the expression of the *pfs16* gene, which is the earliest event in the sexual differentiation process described to date (13). A second developmental switch defines the sex of the developing gametocyte (39). The next developmental switch is executed following transmission of mature gametocytes to the mosquito midgut. Here, the gametocytes form gametes that fertilize and produce a motile ookinete. This ookinete penetrates the peritrophic membrane surrounding the blood meal and initiates sporogonic development, which leads to the production of new infectious sporozoites. The processes of gametogenesis and fertilization are completed within the 15 to 20 min following the arrival of the gametocytes in the mosquito midgut (1). The onset of gametogenesis is marked by the induction of the *pfs25* gene (13, 18), which encodes a membrane protein containing several epidermal growth factor-like domains (27). It has been proposed that *Pfs25* is involved in a receptor-ligand interaction required for invasion of the midgut epithelium (40). Antibodies raised against *Pfs25* potently block transmission of *P. falciparum* to...
the mosquito, and the protein is a leading candidate for a transmission-blocking vaccine (26).

The significance of the pfs16 and pfs25 genes as specific markers for two important developmental switches executed by the malaria parasite prompted us to investigate the transcriptional regulation of these genes in greater detail. Therefore, we have isolated the promoters of the P. falciparum pfs16 and pfs25 genes. To study the differential activities of these promoters during intraerythrocytic development of the parasite, we have exploited transient transfections of P. falciparum (10, 47). In addition, we have studied the activities of the pfs16 and pfs25 promoters in the parasite stages that develop within the mosquito midgut, using transfections of the related parasite P. gallinaceum. Our data show that the pfs16 and pfs25 promoters exhibit unusual DNA compositions that are extremely biased toward A and T nucleotides. We have identified the regions in these promoters that are essential for high transcriptional activity. Furthermore, we show that distinct mechanisms control the activities of these promoters during development of the parasite. The pfs16 promoter is induced at the very onset of gametocytogenesis and remains active following transmission of the parasite to the mosquito midgut. The activity of the pfs25 promoter is restricted to the parasite stages that develop within the mosquito midgut. We show that the induction of the pfs25 gene partially relies on a DNA-binding protein, termed PAF-1, which activates pfs25 transcription within the mosquito midgut.

MATERIALS AND METHODS

Transfection vectors. Transfection vectors pHRPCAT, pA0, and pHLL were kindly provided by Y. Wu (Oxford University, Oxford, England). Plasmids pHLL and pA0 are derivatives of pHRPCAT and PSOCS2, respectively (47), in which cat (chloramphenical acetyltransferase) reporter genes have been replaced by luciferase reporter genes. A general-purpose transfection vector was constructed by substituting the hrp3 (histidine-rich protein 3 gene) promoter from plasmid pHRPCAT with a KpnI/NsiI restriction fragment containing the polylinker of pZERO (InVitrogen). The resulting plasmid was designated pCAT-L.

Isolation of the pfs16 5' flanking sequences and pfs16 plasmid construction. P. falciparum NF54 genomic DNA was digested with EcoRI and additionally sheared by sonication to an average fragment size of 2 kbp. The fragment ends
were made blunt ended with T4 polymerase and introduced in a lambda ZAPII vector (Stratagene) with the aid of EcoRI linkers. The library was propagated in Escherichia coli XL-1 Blue cells (Stratagene) and screened with a pfs25-specific CDNA insert. The positive clones were further characterized. Plasmid DNAs were purified in the laboratory of the author, and plasmids were rescued from the phages by an in vivo excision protocol (Stratagene). A plasmid with an insert of 1.461 bp that hybridized to the pfs25 probe was isolated. From this plasmid, the pfs25 upstream region was amplified by PCR using primers P5pfs25 (ggctcgagACCATGTTGGTTGAGG) and P6pfs25 (GGATTACATTATATGCTATGTTGG) (lowercase indicates nucleotides not present in the pfs25 sequence that introduce restriction sites) and introduced into a pGEM-T vector (Promega) to yield plasmid pK6.3. The pfs25 upstream region was introduced in transcription vector pCAT-L by cloning a XhoI/SphI fragment of pK6.3 in the EcoRV/SphI-digested pCAT-L vector after blunting the XhoI end with Klenow polymerase. A set of 5' deletions of the pfs25 upstream region in plasmid pCAT-L6.1 was generated. First, one of the two BamHI sites present in pCAT-L6.1 was eliminated by digesting the plasmid with Smal/XhoI and blunting of the fragment ends with Klenow polymerase. Religation of the plasmid then resulted in plasmid pCAT-L6.1ΔSmal/XhoI. Subsequently, this plasmid was digested with KpnI and BamHI. Exonuclease III and S1 nuclease treatment followed by religation of the plasmids then generated a series of incrementing 5' deletions of the pfs25 upstream region. 3' deletion mutants of the pfs25 promoter were generated by cloning the products of a partial SphI/EcoRI digest of the pfs25 promoter region of plasmid pCAT-L6.ΔSmal/XhoI in an EcoRI/EcoRV-digested pCAT-L vector.

A plasmid containing a luciferase reporter gene under control of the pfs25 promoter was generated by cloning a NotI/HindIII fragment containing the luciferase gene in plasmid pRL-CMV in the plasmid pNeo2. To visualize the developmental-stage-specific activity of the pfs25 promoter, a green fluorescent protein (GFP) reporter gene was introduced in plasmid pUC16.1. To this end, a XbaI/SphI fragment of plasmid pENGFPM2 (kind gift of R. B. Cormack, Stanford University, Stanford, Calif.) containing the coding region of GFPmut2 was cloned in plBluescript KS- (Stratagene), and an 81-bp restriction site was introduced in the gfp gene by PCR with GFP primer TATA and EcoRI linkers and introduced in EcoRI-digested plBluescript KS- vector (Stratagene). Fragments were excised from the vector with EcoRI, gel purified, and labeled by filling in the overhanging ends with Klenow polymerase in the presence of [γ-32P]dATP. Ten femtomoles of end-labeled probe, combined with nuclear extract from infected Hep-2 cells (position 71 100 bp KC3-I MEM EDTA-1 mM dithiothreitol-1 μg of poly(dA-dT) - poly(dA-dT)-4% Ficoll for 15 min at room temperature. Binding reactions were supplemented with specific competitor DNA fragments as indicated in the figure legends and analyzed on a 6% polyacrylamide gel with 0.25× TBE (1× TBE is 0.1 M Tris Base, 0.1 M boric acid, and 2 mM EDTA).

Nucleotide sequence accession numbers. Sequence data have been submitted to the GenBank database under accession no. AF033459 (pfs16) and AF030628 (pfs25).

RESULTS

Structure of the pfs16 and pfs25 upstream regions. To assess whether the developmental regulation of Pfs16 and Pfs25 expression is mediated by DNA elements located upstream of the respective genes, and to enable a subsequent characterization of the elements controlling the expression, we set out to isolate the pfs16 and pfs25 upstream regions. For the pfs16 gene, a 1.5-kb-long fragment was obtained. Sequence analysis revealed that this plasmid contains 710 bp upstream of the ATG start codon of the pfs16 gene. The sequence of the pfs25 5' flanking region was determined from a 3.5-kb genomic HindIII fragment which contains 1,006 nucleotides upstream of the ATG translational start codon. Inspection of the pfs16 and pfs25 upstream regions reveals that both are extremely AT-rich (Fig. 2). The AT content of the pfs25 upstream region is 85% and reaches 90% in the pfs25 5' flanking sequence. In both promoters, the AT richness is characterized by a striking abundance of long homopolymeric (dA-dT) and alternating poly(dA-dT) stretches, a common feature of P. falciparum intergenic regions (12). Further comparison of the two sequences did not reveal any other regions of homology. Comparison of the pfs16 upstream region with sequences in the EMBL database of eukaryotic promoter elements (8) revealed two elements with homology to the binding site of the yeast MATα2 transcription factor (Fig. 2A). This homebox protein binds as a homodimer to two indirectly repeated half sites separated by a 13-nucleotide spacer (46). The elements found in the pfs16 upstream region have an analogous structure with the exception that the repeated sequences are in a direct orientation. The pfs25 upstream region contains numerous TATA boxes, as does the pfs16 upstream region, and a CAAT box (position −571 in Fig. 2B). No additional elements that relate
sequences present in the EPD database were found in the pfs16 and pfs25 upstream regions.

Determination of the transcription initiation sites of the pfs16 and pfs25 genes. As an initial step in the characterization of the pfs16 and pfs25 promoters, we mapped the transcription initiation sites of the respective genes. The initiation site of the pfs16 gene was analyzed by RNase protection. As shown in Fig. 3, hybridization of a pfs16-specific probe to RNA of gametocytes and gametes results in the protection of fragments that cluster in a discrete region that spans approximately 10 nucleotides and that is located 175 nucleotides upstream of the ATG translation initiation codon. The protected fragments most likely represent a single transcription initiation site, as the observed minor heterogeneity is frequently associated with this type of experimental approach. No protection of the probe was found when an RNA preparation of the schizont stages was used, which is in agreement with the observation that these stages do not express the pfs16 mRNA (13).

Determination of the transcription initiation sites of the pfs16 and pfs25 genes. As an initial step in the characterization of the pfs16 and pfs25 promoters, we mapped the transcription initiation sites of the respective genes. The initiation site of the pfs16 gene was analyzed by RNase protection. As shown in Fig. 3, hybridization of a pfs16-specific probe to RNA of gametocytes and gametes results in the protection of fragments that cluster in a discrete region that spans approximately 10 nucleotides and that is located 175 nucleotides upstream of the ATG translation initiation codon. The protected fragments most likely represent a single transcription initiation site, as the observed minor heterogeneity is frequently associated with this type of experimental approach. No protection of the probe was found when an RNA preparation of the schizont stages was used, which is in agreement with the observation that these stages do not express the pfs16 mRNA (13).

To analyze the transcriptional start sites of the pfs25 gene, we used a RACE procedure. The sequences of the amplified products recovered were colinear with the genomic sequence and heterogeneous in their 5’ ends. Figure 2b shows a compilation of the transcription initiation sites on the basis of the 10 independent RACE products analyzed. The initiation sites cluster in an 18-nucleotide region located 267 nucleotides upstream of the ATG translation initiation codon. Of the 10 RACE products, 5 indicated initiation at position 2267.

The pfs16 and pfs25 upstream regions contain differentially regulated promoters. We assessed whether the extremely A/T rich pfs16 and pfs25 upstream regions contain functional promoters. To this end, these sequences were fused to cat reporter genes, the resulting plasmids were introduced into blood- and mosquito-stage parasites by transfection, and CAT activities were determined. As a control, we tested the activity of the hrp3 promoter, which has been described previously (47). For

FIG. 2. (A) Nucleotide sequence of the pfs16 upstream region. Numbering is with respect to the ATG translation initiation codon, which is italicized. The transcription start site as determined by RNase protection is indicated with an arrow. The starting positions of deletion mutants used in transfection studies are indicated in bold and above the sequence. Sequence elements with homology to the binding site of the yeast MATa2 homeobox transcription factor are in bold and overlined. The starting positions of deletion mutants of plasmid pFS25LUC are indicated in bold and above the sequence. Sequence elements with homology to the binding site of the yeast MATa2 homeobox transcription factor are in bold and overlined. (B) Nucleotide sequence of the pfs25 upstream region. Numbering is with respect to the ATG translation initiation codon (italicized). Arrows indicate positions of the transcription initiation sites. The starting positions of deletion mutants of plasmid pFS25LUC are indicated in bold and above the sequence. The AAGGAATA sequences that serve as the recognition sites for the PAF-1 transcription factor identified in this work are underlined and in bold. A CCAAT box is overlined.

FIG. 3. Analysis of the transcription initiation site of the pfs16 gene. RNase protection was performed on RNA of the different developmental stages of P. falciparum and on yeast RNA as indicated. An arrow indicates the position of the major protected fragment. The letters G, A, T, and C indicate the products of a sequencing reaction that was run along the protected fragments for size determination. Note that the sequence depicted in the figure does not contain a single cytosine base.
transfection of the blood stages of the parasite, preparations of *P. falciparum* were used. As the mosquito stages of *P. falciparum* are neither transflectable nor viable in an in vitro culture, we used *P. gallinaceum* parasites for the transfection of the mosquito stages (45). The data presented in Figure 4A show that the three promoters show distinct patterns of transcriptional activities. Whereas the *pfs16* upstream sequence drives the expression of the *cat* reporter gene in both the mosquito- and blood-stage preparations, the activity of the *pfs25* promoter is restricted to mosquito-stage parasites. Conversely, the activity of the *hrp3* promoter peaks in blood-stage parasites but is not detectable in mosquito stages. A quantitative comparison of the activities of the *pfs16* and *pfs25* promoters in mosquito-stage parasites showed that the *pfs25* promoter exhibits an activity approximately fivefold higher than the transcriptional activity of the *pfs16* promoter (Fig. 4B). Thus, the transcriptional activities of the *pfs16* and *pfs25* promoters in mosquito-stage parasites showed that the *pfs25* promoter marks the transition of the parasite to the mosquito midgut whereas transcription from the *pfs16* promoter is activated in the blood stages of the parasite.

The activity of the *pfs16* promoter is restricted to the sexual stages. At the onset of gametocytogenesis, biochemical differentiation precedes morphological differentiation. Initially, sexually committed ring stages are morphologically indistinguishable from asexual ring-stage parasites (Fig. 1) (32). However, they are marked by the induction of the transcriptional activity of the *pfs16* gene, which is the earliest event in the sexual differentiation process described to date (13). Following the accumulation of the *pfs16* mRNA, the sexually committed ring stages transform into the readily recognizable stage II gametocytes (20). Our data indicate that the *pfs16* promoter can drive the expression of a reporter gene in transfection of an asynchronous culture of the blood stages of the parasite (Fig. 4A). Such a culture contains both asexual and sexual parasites, and the experiment depicted in Fig. 4A does not clarify which of the subpopulations is responsible for the *pfs16*-driven expression of the reporter gene. To corroborate and extent the notion that the activity of the *pfs16* gene is restricted to parasites undergoing sexual development, we analyzed the activity of the *pfs16* promoter in cultures undergoing sexual differentiation. Given the finding that the transcriptional activity of the *hrp3* gene is restricted to asexual parasites (43) and that the *hrp3* promoter is silent in the mosquito stages (Fig. 4A), we used the *hrp3* promoter as a specific marker for the asexual population of parasites. *P. falciparum* blood-stage parasite cultures were transfected with *hrp3* and *pfs25* promoter-reporter constructs, and gametocytogenesis was induced by omitting the supply of fresh erythrocytes (36). Figure 5A shows the parasitemias during the course of the experiment together with the temporal activities of the *hrp3* and *pfs16* promoters. The asexual parasitemia initially rises and eventually shows a slight decline. The high asexual parasitemia at day 2 triggers gametocytogenesis, as demonstrated by the appearance of stage 2 gametocytes at day 4. The pattern of activity of the *hrp3* promoter parallels the asexual parasitemia and persists throughout the course of the experiment. The activity of the *pfs16* promoter coincides with the appearance of sexually committed ring-stage parasites in the culture. Thereafter, higher levels of reporter enzyme, driven by the *pfs16* promoter, accompany the increase in numbers of gametocytes.

To assess whether the developing gametocytes are indeed responsible for the observed activity of the *pfs16* promoter,
transfected cultures were treated with pyrimethamine, which eliminates asexual parasites and sexually committed ring stages but leaves gametocytes that have passed developmental stage I unaffected (36). As a consequence, the activity of the pfs16 promoter is slightly reduced but still persists at a high level (Fig. 5B). By contrast, the pyrimethamine treatment completely abrogates the asexual parasitemia and the activity of the hrp3 promoter. The sharp contrast in the effect of pyrimethamine on the activities of the pfs16 and hrp3 promoters clearly indicates that these reside in different subpopulations of the culture. The pyrimethamine treatment completely abolishes the hrp3-driven expression of the reporter gene, indicating that the activity of the hrp3 promoter is restricted to asexual parasites. The activity of the pfs16 promoter persists at a high level, indicating that this promoter is active in the developing gametocytes.

Transcriptional activity of the pfs16 promoter continues in the parasite stages that invade the mosquito midgut. The functional roles of the Pfs16 protein in the sexual differentiation process and the penetration of the mosquito midgut remain elusive. Moreover, data on the expression pattern of Pfs16 are ambiguous. Some studies have reported that Pfs16 is synthesized by gametes and is present on the outer membrane of the gametes (31, 33). Other studies have, however, failed to detect the protein in the gametes and have shown that Pfs16 apparently associated with the gamete membrane is in fact attached to remainders of the parasitophorous vacuole membrane of the gametocytes (2, 6). These remainders eventually are completely shed from the surface of the gamete. Nuclear run-on analysis has shown that the pfs16 gene is transcriptionally active in gametes (13). Furthermore, our data show that the pfs16 promoter is active in the parasite stages that develop within the mosquito midgut (Fig. 4). To specify the pattern of the activity of the pfs16 promoter in the mosquito stages, we visualized this activity by using the gene encoding the GFP of the jellyfish Aequorea victoria as a reporter. Figure 6 shows the GFP expression pattern in the developing midgut stages. The pfs16 promoter drives GFP expression both in unfertilized gametes and in the developing and mature ookinetes. As the morphological differentiation of ookinetes preceded the appearance of the GFP signal, we conclude that the ookinetes were actively synthesizing the GFP protein and did not show fluorescence as a result of an accumulated pool of GFP originating from the gametes. These results lend support to the notion that the pfs16 gene is transcriptionally active in the mosquito stages of the parasite and demonstrate that the pfs16 promoter can drive the expression of foreign genes in the parasite stages that are involved in the invasion of the mosquito midgut epithelium.

Deletion mapping of the psf16 and psf25 promoters. To gain insight in the DNA elements involved in the expression of the pfs16 and psf25 genes, plasmids in which the reporter genes were placed under the control of a series of truncated promoter fragments were transfected to P. gallinaceum mosquito-stage parasites. The data presented in Figure 7 indicate that the transcriptional activity of the pfs16 promoter relies on different components. The -247 to +1 region of the promoter is the shortest region tested here that drives transcription of
FIG. 6. GFP expression driven by the pfs16 promoter in P. gallinaceum mosquito midgut stages. Fluorescence (left) and light transmission (right) images are shown. Gametocytes ingested by a mosquito transform into gametes (A [female gamete]) that fertilize and develop into invasive ookinetes (C) via the intermediate retort stages (B). Parasites that had successfully been transfected with plasmid pGFPp16.2 show a bright fluorescence signal (left).

the reporter gene. Deletion of the sequences between −247 and −209 from this promoter abrogates its activity. The apparent importance of this region for high transcriptional activity and its close proximity to the start site of transcription suggest that this region constitutes the pfs16 core promoter. The region immediately upstream of these sequences, from −247 to −388, is silent with respect to the modulation of transcriptional activity. The sequences upstream of position −388 contribute to the overall efficacy of the promoter but do not contain dominant negative or positive transcriptional control elements. Finally, the results suggest the presence of an activator sequence in the region between nucleotides +1 and −93. However, as this region is located downstream of the transcriptional start site, its deletion affects the transcribed RNA. Hence, the observed lowered CAT activity may be due to a decreased stability or translation efficiency of the mRNA.

The transfection data do not support a functional role for the two elements with homology to the DNA recognition site of the yeast MATα2 repressor that are present in the pfs16 promoter (Fig. 2A). Deletion of either one of these elements does not affect the activity of the promoter (compare the transcriptional activities of exo6 and exo7 and of pCAT-L16.2 and pCAT-L16.3 in Fig. 7). In addition, mutations in the single MAT-like element present in plasmid exo7 do not affect the transcriptional activity of this plasmid in transfections of blood- or mosquito-stage parasites (data not shown).

Mutational analysis of the pfs25 promoter was performed on truncated versions of plasmid pPFS25LUC, which contains a luciferase gene under control of the pfs25 promoter and pfs25 3′ processing signals. The structures of the deletion mutants are schematically depicted in Fig. 7 together with the luciferase activities obtained after transfection of P. gallinaceum mosquito-stage parasites. Deletion from positions −1006 to −959 reduces the activity of the pfs25 promoter to 60% of the activity of the full-length promoter. Further deletions up to position −542 marginally affect the transcriptional activity. The most dramatic effects on the activity of the promoter are seen with next two extended deletions: deletion of the region between positions −542 and −484 results in a 10-fold reduction of the activity of the promoter activity, and further deletion up to position −386 fully abolishes the activity of the promoter. In conclusion, the region between −484 and +1 is the shortest region tested here that drives transcription of the reporter gene. Equipping this region with the region between −484 and −542 potently activates transcription. Finally, the regions upstream of position −542 contribute to an efficient activity of the pfs25 promoter.

The pfs25 upstream region is the target of protein-DNA interactions. To gain insight in the possible trans-acting factors that play a role in the regulation of transcription of the pfs16 and pfs25 genes, we performed a series of EMSAs. Restriction fragments derived from the pfs16 and pfs25 upstream regions were scanned for the presence of binding sites for proteins present in a nuclear extract of P. gallinaceum gametes. Pilot experiments failed to reveal any specific interactions between DNA-binding proteins and the pfs25 promoter. By contrast, three of the four pfs25-specific probes tested yielded DNA-protein complexes when incubated with a nuclear extract, as shown in Fig. 8A and B. Probe C forms a single complex, indicating a single interaction with a DNA-binding protein. Probes B and D form multiple complexes, revealing a more complex set of interactions on these probes.

A cross-competition experiment with probe C as the radiolabeled probe reveals that a 100-fold molar excess of probe B disrupts the interaction of probe C with the nuclear factor, whereas probes A and D cannot prevent the interaction between probe C and the nuclear factor (Fig. 8C). Furthermore, a 100-fold molar excess of probe C prevents the formation of a DNA-protein complex on probe B, whereas probes A and D have no effect on complex formation (Fig. 8C). These observations suggest that the nuclear factor that binds to probe C does not have a preference for generally A/T-rich DNA but obeys more specific sequence constraints that are shared by probe B. Close inspection of the sequences of probes B and C reveals that they indeed share a DNA element, AAGGAATA,
that is found neither in probes A and D or in other regions of the pfs25 promoter.

AAGGAATA recruits a mosquito-stage-specific transcription factor. To test whether the AAGGAATA element constitutes a functional promoter element, a mutant version of this element was tested in transfection studies and EMSAs. The data presented in Fig. 9A show that oligonucleotide TFB25, which contains the AAGGAATA sequence, recruits a DNA-binding protein when incubated with a nuclear extract derived from P. gallinaceum gametes. The interaction can be disrupted by the addition of a 100-fold molar excess of the unlabeled oligonucleotide but not by the addition of an oligonucleotide containing a mutated version of this sequence motif. Accordingly, oligonucleotide TFB25 can compete for the interaction
between probe C and the DNA-binding protein, whereas the mutant oligonucleotide cannot (Fig. 9C). These results indicate that AAGGAATA sequence serves as the recognition site for a DNA-binding protein, which we named PAF-1 (pfs25-activating factor 1 [see below]).

We assessed whether PAF-1 is a developmental-stage-specific protein. To this end, the radiolabeled oligonucleotide TFB25 was incubated with nuclear extracts derived from either *P. gallinaceum* or *P. falciparum* gametes or from an asynchronous *P. falciparum* blood-stage parasite culture that contained both asexual parasites and gametocytes. The results shown in Fig. 9A indicate that extracts derived from *P. falciparum* or *P. gallinaceum* gametes contain a DNA-binding protein that specifically interacts with the TFB25 oligonucleotide. In contrast, no PAF-1-like activity is present in the nuclear extract derived from *P. falciparum* blood-stage parasites. As a control on the activity of the blood-stage extract, it was incubated with radiolabeled probe KAHRP, which resulted in the formation of two DNA-protein complexes as described previously (Fig. 9B) (30). We conclude, therefore, that the AAGGAATA sequence comprises a cis-acting element involved in the activation of the pfs25 promoter. The correlation between a decline in promoter activity and a decreased affinity for PAF-1 upon mutation of the AAGGAATA sequence indicates that PAF-1 is a transcriptional activator that is recruited to the promoter by the AAGGAATA sequence.

**DISCUSSION**

Sexual differentiation is an obligate part of the life cycle of malaria parasites. It requires a series of developmental decisions to be made during progression from the asexually replicating parasites in the bloodstream of the vertebrate host to the highly specialized cells that invade the mosquito midgut. First, a subpopulation of asexual parasites commits to sexual differentiation; second, the sex of the developing gametocytes is determined; finally, gametogenesis is induced when the ar-
rival of the gametocytes in the mosquito midgut is sensed. A complex network of gene-regulatory events governs the transitions through the sexual differentiation process, as indicated by developmental-stage-specific expression of the pfs16 and pfs25 genes. This paper links the regulatory events operating on the pfs16 and pfs25 promoters to two important developmental switches exhibited by the parasite. Activation of the pfs16 promoter marks commitment to sexual differentiation, whereas the induction of the pfs25 promoter is indicative for the transition to the mosquito midgut. In addition, our data show that the hrp3 gene, which is expressed in asexual parasites, is shut off when parasites commit to sexual differentiation.

A functional analysis of the mechanisms of gene expression underlying sexual development of the malaria parasite has for long been impeded by the lack of a transfection protocol and by the laborious culture of the sexual stages. Recently, transfection methods for the blood stages of *P. falciparum* have been described (14, 47). However, the in vitro culture and transfection of the mosquito stages of *P. falciparum* is still not feasible. An alternative is offered by the avian malaria parasite *P. gallinaceum*, which has been proven to be a versatile model system for the study of sexual differentiation of malaria parasites (16, 45). As *P. falciparum* and *P. gallinaceum* are very closely related and are thought to have arisen by lateral transfer between the human and the avian host (41), one might assume that the elements that control gene expression are conserved and interchangeable. Functional conservation has been observed for the *P. falciparum* hrp3 and the *P. berghei* dhfr promoters in *P. knowlesi* (42), for the *P. chabaudi* dhfr promoter in *P. falciparum* (10), and for the *P. falciparum* hsp86 and *pcna* promoters in *P. gallinaceum* (11a). *P. gallinaceum* possesses a close homologue of the Pfs25 protein, termed Pgs25 (28). The regions flanking the pfs25 gene have not been cloned, and a direct comparison of the pfs25 and pgs25 promoters awaits the isolation of the latter sequence. Nonetheless, the results presented here corroborate the notion that the factors required for basal and activated transcription indeed are conserved between the *Plasmodium* species. Accordingly, the PAF-1 DNA-binding activity was observed in nuclear extracts derived both from *P. gallinaceum* and from *P. falciparum* gametes.

Gene regulation is atypical in many parasitic protozoa. Genes of the Kinetoplastida (e.g., *Leishmania* and *Trypanosoma* species) seem to be transcribed by a class I RNA polymerase and produce long polycistronic RNA precursors, which are processed into mature RNAs via trans-splicing (35). There is no evidence for polycistronic transcription, trans-splicing, or extensive posttranscriptional regulation of gene expression within the phylum of the Apicomplexa (e.g., *Plasmodium* spp. and *Toxoplasma* spp.). Nevertheless, the structure of the gene promoters of organisms of the latter phylum is atypical. Although the deletion mapping of the pfs16 and pfs25 promoters suggests that these promoters resemble typical eukaryotic poly...
merase II-transcribed promoters, with a core promoter region and more distally located enhancers, the primary structure of the pfs16 and pfs25 promoters is atypical. The extreme A/T richness seems to preclude the assignment of a functional TATA box. Accordingly, analysis of promoters of apicomplexan parasites has revealed that a TATA box is not a conserved promoter element in these organisms (4, 11). Conversely, a repeated (A/T)GAGACG element, which acts as a selector of the transcriptional start site, has been identified as a critical element of many Toxoplasma gondii promoters (4). This element is absent in the pfs16 and pfs25 promoter regions.

Our data furthermore indicate that the few elements that do bear homology to known eukaryotic promoter elements, such as the MATa2-like elements in the pfs16 promoter and the CCAAT box in the pfs25 promoter, are not essential for a high transcriptional activity. That P. falciparum promoters are functionally distinct from other eukaryotic promoters is further substantiated by the observation that the pfs16, pfs25, and hrp3 promoters do not function in transfections of mammalian cells (11a). Conversely, viral promoters such as the simian virus 40 promoter do not operate in P. falciparum (22).

Although we failed to identify specific cis- and trans-acting factors operating on the pfs16 promoter, our data show that its mode of action is developmental stage specific. The activity of the pfs16 promoter persists during pyrimethamine treatment, demonstrating that the gametocytes are responsible for the observed activity of the pfs16 promoter in transfections of blood-stage parasites. The pfs16-driven signal of the reporter gene appears at the time at which sexually committed ring-stage parasites appear in the culture, indicating that the pfs16 promoter is induced at the very onset of sexual differentiation. Accordingly, elimination of the sexually committed ring-stage parasites from the culture, a consequence of the pyrimethamine treatment, lowers the level at which the reporter enzyme accumulates. Our results indicate that the hrp3 promoter is silent during gametocytogenesis, as its activity is not observed under pyrimethamine pressure. These results extend the notion that the commitment to sexual differentiation involves the switching to an alternate program of gene expression (1). Asexual genes such as the hrp3 gene are shut off during gametocytogenesis, whereas specific sex genes, such as pfs16, are turned on. The exact nature of the signal that triggers a parasite to commit to sexual development is unknown (1), although it is well documented that the parasite density is an important determinant (5, 7). Our data substantiate the previous finding that the pfs16 gene is activated in sexually committed parasites at the very onset of the sexual differentiation process (13) and indicate that the activation of this gene is immediately downstream of the trigger that activates gametocytogenesis. The early expression of Pfs16 suggests that this protein plays an important role during gametocytogenesis.

Gametocytogenesis ultimately leads to the production of mature gametocytes, which circulate in the bloodstream and remain infective to the mosquito for several weeks (38). Once gametocytes are ingested by a mosquito, their entrance in the midgut induces an array of mutual responses. The drop in temperature following transmission to the poikilothermic mosquito activates gametocytes to produce male and female gametates, a process which is further enhanced by a specific factor in the mosquito midgut (15), recently identified as xanthurenic acid (3). The arrival of the parasites in the mosquito midgut triggers the immune response of the mosquito (37) and induces the expression of mosquito trypsin that help to digest the blood meal (34). The trypsins together with the immune factors provide a hostile environment to the parasite, and ookinetes that do not succeed in penetrating the midgut epithelium are rapidly degraded (17). The key to the escape route through the midgut epithelium is provided by the Pfs25 protein, which appears on the surface of the zygote within 30 min following the arrival of the blood meal in the midgut (18). Antibodies against this protein completely block penetration of the epithelium, suggesting a requirement for this molecule for penetration (40). The pfs25 promoter described here fulfills the need for an immediate expression of the Pfs25 protein. Our data indicate, in agreement with previous data (13), that the pfs25 promoter is silent during asexual growth and gametocytogenesis but activated during gametogenesis. The activation relies in part on the DNA-binding protein PAF-1, which is specific for the mosquito stages of the parasite. Hence, expression of PAF-1 is part of the response of the parasite to the dramatic change in environment following transmission. The recognition site for PAF-1 is novel and is not found in the database of eukaryotic promoter elements (8). Interestingly, the recognition site for PAF-1 is also present in the P. falciparum hsp86 promoter, but absent in the hrp3 promoter. Accordingly, the hrp3 promoter is active following transmission to the mosquito (11a), whereas the hrp3 promoter is not (Fig. 4).

The data presented in this paper constitute the first detailed description of cis- and trans-acting elements in Plasmodium. Future analysis of the details of the transcriptional activation of the pfs16 and pfs25 promoters will yield further insight in the mechanisms underlying the sexual differentiation process and might provide new targets for transmission-blocking agents. In addition, the promoters identified and characterized in this study allow the expression of foreign genes in the parasite stages that invade the mosquito midgut and hence provide invaluable tools for the study of parasite-vector interactions.

ACKNOWLEDGMENTS

We gratefully acknowledge Yimin Wu for supplying plasmids pHR-PCAT, pHLL, and pAO, Brendan Cormack for providing GFP plasmids, and David Kaslow for the gift of pNF4.13. We thank Jeffrey VanWye for communicating unpublished results on GFP expression in Plasmodium and Patrick van den Boogaard for expert technical assistance.

This investigation received financial support from the Netherlands Ministry for Development Cooperation (grant NL002701), from the UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases, and from the Commission of the European Community for Life Sciences and Technologies for Developing Countries. K.J.D. is grateful to the Harald Quintus Bosz Foundation and the Netherlands Organization for the Advancement of Pure Research (NWO) for gifts that covered travel expenses.

REFERENCES


29. Kaushal, D. C., R. Carter, R. J. Howard, and F. M. McAuliffe.


