A fruitful alliance: the synergy between *Atopobium vaginae* and *Gardnerella vaginalis* in bacterial vaginosis-associated biofilm

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ABSTRACT

Objectives Bacterial vaginosis (BV) is characterised by a change in the microbial composition of the vagina. The BV-associated organisms outnumber the health-associated *Lactobacillus* species and form a polymicrobial biofilm on the vaginal epithelium, possibly explaining the difficulties with antibiotic treatment. A better understanding of vaginal biofilm with emphasis on *Atopobium vaginae* and *Gardnerella vaginalis* may contribute to a better diagnosis and treatment of BV.

Methods To this purpose, we evaluated the association between the presence of both bacteria by fluorescence in situ hybridisation (FISH) and BV by Nugent scoring in 463 vaginal slides of 120 participants participating in a clinical trial in Rwanda.

Results A bacterial biofilm was detected in half of the samples using a universal bacterial probe. The biofilm contained *A. vaginae* in 54.1% and *G. vaginalis* in 82.0% of the samples. *A. vaginae* was accompanied by *G. vaginalis* in 99.5% of samples. The odds of having a high Nugent score above 4 were increased for samples with dispersed *G. vaginalis* and/or *A. vaginae* present (OR 4.5; CI 2 to 10.3). The probability of having a high Nugent score was even higher when a combination of adherent *G. vaginalis* and dispersed *A. vaginae* was visualised (OR 75.6; CI 13.3 to 429.5) and highest when both bacteria were part of the biofilm (OR 119; CI 39.9 to 360.8).

Conclusions Our study, although not comprehensive at studying the polymicrobial biofilm in BV, provided a strong indication towards the importance of *A. vaginae* and the symbiosis of *A. vaginae* and *G. vaginalis* in this biofilm.

Trial registration number NCT01796613.

INTRODUCTION

Bacterial vaginosis (BV) is the most prevalent vaginal disorder in women of reproductive age. It increases the risk of acquisition and transmission of sexually transmitted infections, including HIV, and is associated with preterm birth in pregnant women.1–3 The condition is characterised by a change in the microbial composition of the vagina: the *Lactobacillus* spp., associated with a healthy vaginal microbiome, are outnumbered by micro-aerophilic and anaerobic organisms, including *Gardnerella vaginalis*.3–7 The mere presence of *G. vaginalis*, however, is not sufficient for the diagnosis of BV using traditional diagnostic algorithms (see below) because many women without BV also have *G. vaginalis* in their vaginal microbiome.4 BV is, however, associated with high counts of *G. vaginalis* using molecular methods and/or the presence of a *G. vaginalis*-containing polymicrobial biofilm.3–10 Due to its strong adherence to vaginal epithelial cells and biofilm-forming capacities, it has been suggested that *G. vaginalis* initiates the colonisation of the vaginal epithelium and serves as a scaffolding to which other species subsequently can attach.10–12

One of the species that might attach to the biofilm initiated by *G. vaginalis* could be *Atopobium vaginae*.3–14 Several molecular studies have indicated a probable role for *A. vaginae* in BV14–16 and it has also been suggested that *A. vaginae* plays a major part in the establishment of a biofilm, together with *G. vaginalis*.3–10 Considering it has been found in 80–90% of cases of relapse19 and some strains have been shown in vitro to be metronidazole resistant,18 it could be of importance in the recurrence of BV after standard treatment with metronidazole.

The current gold standard in BV research is the microscopic evaluation and scoring of vaginal slides according to Nugent.19 The diagnosis of BV is based on the absence of lactobacilli and the presence of small Gram-negative to Gram-variable rods (*G. vaginalis* and *Bacteroides* spp. morphotypes) and curved Gram-negative rods (*Mobiluncus* spp. morphotypes). In fact, bacterial biofilm can also be seen with this method in the form of clue cells, which are vaginal epithelial cells covered by layers of adherent Gram-negative and/or Gram-variable cells, that is, biofilms.20 Using Gram staining, it is impossible to distinguish between the different bacterial species in the biofilm. By labelling the cells with a fluorescent probe, using fluorescence in situ hybridisation (FISH), the structure and composition of the biofilm can be studied in more detail.

To study the potential role of *A. vaginae* and the synergy between *A. vaginae* and *G. vaginalis* in the biofilm, we used our newly developed peptide nucleic acid (PNA) *A. vaginae* probe11 together with an existing probe for *G. vaginalis*31 and a universal bacterial probe22 to investigate the composition of vaginal biofilm and its importance in BV.
MATERIALS AND METHODS

Clinical samples

Vaginal sample collection and preparation

Vaginal samples were collected from 120 women participating in a clinical trial at Rinda Ubuzima in Kigali, Rwanda, studying the safety and acceptability of a contraceptive vaginal ring (Nuvaring), including the effect of the vaginal ring on the vaginal microbiome (the Ring Plus study—Clinicaltrials.gov NCT01796613). Participants were between 18 and 33 years old and provided written informed consent for participation in the study. Depending on the group (continuous or intermittent ring use) to which the participant was randomised, a total of four or five samples from the same participant were taken over a period of four menstrual cycles. A total of 463 samples were analysed after Gram stain and after FISH using light microscopy and confocal laser scanning microscopy (CLSM), respectively.

Vaginal sampling was carried out by the study physician during a speculum examination in the Rinda Ubuzima research clinic. A cotton swab was brushed against the lateral walls of the vagina and was transported in its container to the Rinda Ubuzima laboratory within 20 min. Upon arrival in the laboratory, the swab was used to prepare a vaginal slide on a regular glass slide for Gram stain and a second vaginal slide on a Superfrost Plus slide (Menzel-Gläser, Braunschweig, Germany). All slides were air-dried, heat-fixed by passing through a flame twice and then stored in their appropriate boxes until Gram staining and/or shipment for FISH. The first slide was Gram stained and examined on-site in the Rinda Ubuzima laboratory in Kigali. The Superfrost Plus slides were stored and shipped at room temperature to the ITM where they were fixed by passing through a Carnoy solution (6:3:1, ethanol:chloroform:glacial acetic acid).11

Microbiological analysis of the vaginal samples

Pep tide nucleic acid fluorescence in situ hybridisation

PNA FISH was performed as described earlier11 using species-specific probes for A. vaginae (AtoITM1) and G. vaginalis (Gard162) and the broad-range BacUni-1 probe. In 230 samples (49.7%), only dispersed bacteria were read by FISH analysis, excluding 13 missing samples and 51 samples not readable due to the absence of epithelial cells on the slides. In all 463 samples, a positive signal was detected for the universal BacUni-1 probe. In 230 samples (49.7%), only dispersed bacteria were present, while the other 233 slides (50.3%) contained adherent bacteria as well (table 1). A. vaginae and G. vaginalis were part of this biofilm in 126 (54.1%) and 191 (82.0%) samples, respectively. Next, we visualised A. vaginae with FISH microscopy and required 60 women in each group to require 95% power to detect clinically important changes in bacterial counts.23 Data analysis was done using STATA10 (StataCorp LP, Texas, USA). While the samples were collected longitudinally, they were analysed cross-sectionally, with each sample as the unit of analysis. To study the association between the presence and absence of dispersed and/or adherent A. vaginae and adherent G. vaginalis in relation to BV status, we categorised the samples into five categories (table 1) based on combinations of the presence of both bacteria in dispersed and/or adherent form as visualised by FISH. To increase the statistical power, we made the vaginal microbiome status binary: Nugent score 0–3 (reference group) versus Nugent score 4–10 (table 2). A mixed-effects logistic regression model was fitted with BV as the binary outcome (ie, Nugent 0–3 vs Nugent 4–10) and biofilm characteristics as the main dependent variable. The model was adjusted for woman, randomisation group and study visit, because multiple samples per woman at multiple study visits were included in the analysis. ORs are reported with 95% CI and the p values are from χ² tests (table 2).

RESULTS

Characterisation of vaginal samples

In total, 463 of 527 samples from 120 women were available for FISH analysis, excluding 13 missing samples and 51 samples not readable due to the absence of epithelial cells on the slides. In all 463 samples, a positive signal was detected for the universal BacUni-1 probe. In 230 samples (49.7%), only dispersed bacteria were present, while the other 233 slides (50.3%) contained adherent bacteria as well (table 1). A. vaginae and G. vaginalis were part of this biofilm in 126 (54.1%) and 191 (82.0%) samples, respectively. Next, we visualised A. vaginae with FISH

<table>
<thead>
<tr>
<th>Table 1 Gardnerella vaginalis, Atopobium vaginae and G. vaginalis with A. vaginae combinations for samples analysed with fluorescence in situ hybridisation (FISH) by absent, dispersed only and adherent -dispersed category and stratified by Nugent scoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>FISH all bacteria</td>
</tr>
<tr>
<td>Absent</td>
</tr>
<tr>
<td>Dispersed only</td>
</tr>
<tr>
<td>Adherent ± dispersed</td>
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<tr>
<td>FISH A. vaginae (Av)</td>
</tr>
<tr>
<td>Absent</td>
</tr>
<tr>
<td>Dispersed only</td>
</tr>
<tr>
<td>Adherent ± dispersed</td>
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<tr>
<td>FISH G. vaginalis (Gv)</td>
</tr>
<tr>
<td>Absent</td>
</tr>
<tr>
<td>Dispersed only</td>
</tr>
<tr>
<td>Adherent ± dispersed</td>
</tr>
<tr>
<td>FISH Av and Gv combined</td>
</tr>
<tr>
<td>Gv and Av absent</td>
</tr>
<tr>
<td>Gv or Av dispersed only</td>
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<tr>
<td>Gv adherent ± Gv dispersed and Av absent</td>
</tr>
<tr>
<td>Gv adherent ± Gv dispersed and Av dispersed</td>
</tr>
<tr>
<td>Gv and Av adherent ± Gv and Av dispersed</td>
</tr>
</tbody>
</table>

Nugent score

The status of the vaginal microbiome was assessed at the Rinda Ubuzima laboratory by Nugent scoring of a Gram stained vaginal slide.19 A score of 0–3 was considered normal vaginal microbiome; a score of 4–6 intermediate microbiome and a score of 7–10 BV.

Statistical analysis

The clinical study sample size calculation was based on the primary objective to assess the pre–post changes in the vaginal

in 195 (42.1%) samples; in 69 samples (14.9% of the total 463 samples) A. vaginae was present in a dispersed state, whereas in 126 samples (27.2%) the A. vaginae bacteria were seen adherent to epithelial cells (Table 1). For 122 (97.0%) of the samples with adherent A. vaginae, concurrent dispersed A. vaginae bacteria were observed. G. vaginalis was detected by FISH in 291 (62.9%) samples; it was detected as dispersed-only G. vaginalis in 100 samples (21.6% of the total 463 samples) and for the remaining 191 samples (41.3%) G. vaginalis was adherent to the epithelial cells. Furthermore, when combining the results of both bacteria and considering only the 291 G. vaginalis FISH-positive samples, A. vaginae was absent in 98 of the slides (33.7%). On the contrary, only two (0.5%) of the 195 samples showing A. vaginae (dispersed and/or adherent) with FISH were negative for G. vaginalis; this included one sample with adherent A. vaginae.

One-third of the vaginal samples (n=156; 33.7%) was classified as Nugent score 7–10, 10% as Nugent score 4–6 (n=48; 10.4%) and the remaining 259 samples (55.9%) as Nugent 0–3.

The presence of A. vaginae, G. vaginalis, and combinations of both bacteria in dispersed and adherent forms in relation to BV status

The group of FISH samples without A. vaginae and G. vaginalis was used as the reference group (Table 2). Compared with this reference group, the odds of having a Nugent score of 4–10 were increased when one or both bacteria were present in the dispersed state without adhering to the vaginal epithelium (OR 4.5 [CI 2 to 10.3]); it was increased further when G. vaginalis was part of an adherent biofilm on the epithelium (OR 49.2 [CI 15.9 to 151.8]) and even more when dispersed A. vaginae accompanied this G. vaginalis biofilm (OR 75.6 [CI 13.3 to 429.5]); ultimately the OR was highest when A. vaginae was part of the G. vaginalis biofilm as well (OR 119 [CI 39.9 to 360.8]).

**Table 2** Association between the bacterial presence of Atopobium vaginae and Gardnerella vaginalis by fluorescence in situ hybridisation (FISH) and the vaginal microbiome defined by Nugent scoring

<table>
<thead>
<tr>
<th>G. vaginalis and A. vaginae combination</th>
<th>Absent</th>
<th>G. vaginalis (Gv) or A. vaginae (Av) dispersed only</th>
<th>Gv adherent ± Av dispersed and Av absent</th>
<th>Gv adherent ± Av dispersed and Av dispersed only</th>
<th>Gv and Av adherent ± dispersed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total=463</td>
<td>170</td>
<td>101</td>
<td>51</td>
<td>15</td>
<td>126</td>
</tr>
<tr>
<td>Nugent 0–3</td>
<td>153 (90)</td>
<td>72 (71.3)</td>
<td>14 (27.5)</td>
<td>3 (20)</td>
<td>17 (13.5)</td>
</tr>
<tr>
<td>Nugent 4–10</td>
<td>17 (10)</td>
<td>29 (28.7)</td>
<td>37 (72.5)</td>
<td>12 (80)</td>
<td>109 (86.5)</td>
</tr>
<tr>
<td>OR (Cl)*</td>
<td>Reference</td>
<td>4.5 (2 to 10.3)</td>
<td>49.2 (15.9 to 151.8)</td>
<td>75.6 (13.3 to 429.5)</td>
<td>119 (39.9 to 360.8)</td>
</tr>
<tr>
<td>p Value χ² test*</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

*The mixed-effects logistic regression model was adjusted for woman, randomisation group and visit.*

Our study confirms that both A. vaginae and G. vaginalis are important constituents of the vaginal epithelial biofilm.9–11 Adherent A. vaginae and G. vaginalis were visualised in, respectively, 54.1% and 82.0% of samples with bacterial biofilm (detected using the universal BacUni-1 probe), suggesting an important role for both bacteria in this polymicrobial biofilm. Using FISH, we only found two samples containing A. vaginae (dispersed in both, adherent in one) in the absence of G. vaginalis, while more than one-third of the G. vaginalis-positive samples was negative for A. vaginae. This is in accordance with prior reports on the association of A. vaginae with G. vaginalis.9–11 13 16 24 We showed that the presence of both bacteria in the samples, regardless of their existence in a biofilm, was associated with an elevated or high Nugent score indicative for vaginal dysbiosis and BV. The highest probability of having a Nugent score higher than 3 was seen when both A. vaginae and G. vaginalis were part of a biofilm attaching to the vaginal epithelial cells.

The association of G. vaginalis with BV was originally described in 1954 by Gardner and Dukes.23 The involvement of A. vaginae in BV, however, has only been established 10 years ago.13–15 Swidsinski et al. found vaginal biopsies with vaginal biofilm to be positive for G. vaginalis and A. vaginae when using fluorescent probes, although in our hands this A. vaginae probe cross-reacted with other vaginal species as well.11

The presence of A. vaginae in the BV-associated biofilm could have a major impact on treatment. Susceptibility to metronidazole, the standard treatment for BV, varied significantly across various A. vaginae strains in vitro.18 In vivo data are scarce, but Bradshaw et al.17 found that rates of recurrence of BV higher when A. vaginae was present in the vaginal microbiome in addition to G. vaginalis. In another study with topical metronidazole gel by Ferris et al.,13 it was shown that a high concentration of A. vaginae before treatment was associated with complete or partial failure of treatment for BV. In the above studies, no distinction was made between dispersed and biofilm-associated bacteria. Nevertheless, as bacteria in a biofilm are less sensitive to antibiotic treatment26 and considering the evidence from our study that the formation of a bacterial biofilm is more likely to occur when A. vaginae is present in the vaginal microbiome, future design of studies may want to take this distinction into account when treating BV.

Our study has shed new light on the significance of A. vaginae and the synergy between A. vaginae and G. vaginalis in vaginal dysbiosis, using highly specific PNA probes for both bacteria. However, a limitation was that we used multiple samples from the 120 women of the Ring Plus study. Ideally, we should repeat the study in a larger group of women. Furthermore, although we assessed the association between bacterial biofilm and vaginal dysbiosis, more research is needed to

**DISCUSSION**

We set out to study the potential role of A. vaginae in BV and the synergy between A. vaginae and G. vaginalis in the BV-associated biofilm.
unravel the exact mechanisms of biofilm formation in BV, including the role and the importance of both bacteria studied, to finally define improved regimens for treatment of BV.

Moreover, since BV is a polymicrobial condition, new research should study the involvement of other bacteria related to BV.

In conclusion, the presented study uncovered a key piece of the BV puzzle confirming first, the importance of *A. vaginae* in BV-associated biofilm and second, showing the joint presence of *A. vaginae* and *G. vaginalis* in a biofilm. Future studies covering a wide array of BV-associated bacteria may help to further delineate biofilm mechanisms in BV.

**Key messages**

- This study shows that *Atopobium vaginae* is an important constituent of the vaginal biofilm, and is of relevance in the context of bacterial vaginosis (BV).
- We show that *A. vaginae* is almost always accompanied by *Gardnerella vaginalis* in BV, but that *G. vaginalis* can be found without *A. vaginae* in the vaginal microbiome.
- By tackling constituents of the biofilm, the above knowledge can contribute to a more effective and goal-oriented treatment and improve women’s reproductive health.

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**Contributors** All authors were involved in the main study that generated the data. For the present study, LH wrote the first draft of the manuscript. VJ, TC, MV and JvdW revised and edited the text. IDB, TC, LH, VJ and JvdW created the experimental design. SA, LM, VM and LH performed the testing and VJ and LH performed the data analysis. All authors revised and approved the present version of the manuscript.
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Competing interests None declared.

Patient consent Obtained.

Ethics approval The Ring Plus study was approved by the Rwanda National Ethics Committee, Rwanda (Approval number 481/RNEC/2013); the ethics committees of the Institute of Tropical Medicine (ITM), Belgium (Approval number 864/13); the Antwerp University Hospital, Belgium (Approval number 13/7/85) and the University of Liverpool, UK (Approval number RETG000639IREC).

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement The database relevant to the study has been made available to all collaborators.

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REFERENCES
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Objectieven
Bacteriële vaginose (BV) wordt gekenmerkt door een verandering in de samenstelling van de microben in de vagina. De lactobacilli, geassocieerd met een gezond microbioom, worden verdrongen door BV-geassocieerde organismen; deze organismen vormen een polymicrobiële biofilm op het vaginale epitheel, wat de oorzaak kan zijn van de problemen met de behandeling van deze aandoening. Beter inzicht in vaginale biofilm en, meer specifiek in de rol van *Atopobium vaginae* en *Gardnerella vaginalis* hierin, kan bijdragen aan betere manieren om BV te diagnosticeren en behandelen.

Methodes
Daarom evalueerden we de associatie tussen de aanwezigheid van beide bacteriën door middel van fluorescentie in situ hybridisatie (FISH) en het voorkomen van BV op basis van de Nugent score. Hiervoor werden 463 vaginale uitstrijkjes van 120 vrouwen, die deelnamen aan een klinische studie in Rwanda, onderzocht.

Resultaten
We detecteerden een bacteriële biofilm in de helft van de stalen door middel van een universele bacteriële probe. In 54,1% van deze biofilms detecteerden we *A. vaginae* en in 82% van de stalen werd er *G. vaginalis* gevonden. De kans om een Nugent score boven 4 te hebben, was groter voor stalen met planktonisch *G. vaginalis* en/of *A. vaginae* (OR 4,5; CI 2-10,3). De waarschijnlijkheid om een hoge Nugent score te hebben, was nog groter wanneer *G. vaginalis* aangehecht aan de vaginale cellen gecombineerd met planktonisch *A. vaginae* kon gevisualiseerd worden (OR 75,6; CI 13,3-429,5), en was het grootst wanneer beide bacteriën deel uitmaakten van de biofilm (OR 119; CI 39,9-360,8).

Conclusies
Onze studie was niet alomvattend in het bestuderen van de polymicrobiële biofilm in BV, maar gaf wel sterke indicatie omtrent het belang van *A. vaginae* en de symbiose tussen *A. vaginae* en *G. vaginalis* in deze biofilm.

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