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FAM19A4 methylation analysis in self-samples compared with cervical scrapes for detecting cervical (pre)cancer in HPV-positive women

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Background: High-risk human papillomavirus (hrHPV)-positive women require triage to identify those with cervical high-grade intraepithelial neoplasia and cancer (\geq CIN3 (cervical intraepithelial neoplasia grade 3)). FAM19A4 methylation analysis, which detects advanced CIN and cancer, is applicable to different sample types. However, studies comparing the performance of FAM19A4 methylation analysis in hrHPV-positive self-samples and paired physician-taken scrapes are lacking.

Methods: We compared the performance of FAM19A4 methylation analysis (and/or HPV16/18 genotyping) in self-samples and paired physician-taken scrapes for \geq CIN3 detection in hrHPV-positive women ($n = 450, 18\text{--}66$ years).

Results: Overall FAM19A4 methylation levels between sample types were significantly correlated, with strongest correlation in women with \geq CIN3 (Spearman's ρ 0.697, $P < 0.001$). The performance of FAM19A4 methylation analysis and/or HPV16/18 genotyping did not differ significantly between sample types. In women ≥ 30 years, \geq CIN3 sensitivity of FAM19A4 methylation analysis was 78.4% in self-samples and 88.2% in scrapes (ratio 0.89; CI: 0.75–1.05). In women < 30 years, \geq CIN3 sensitivities were 37.5% and 45.8%, respectively (ratio 0.82; CI: 0.55–1.21). In both groups, \geq CIN3 specificity of FAM19A4 methylation analysis was significantly higher in self-samples compared with scrapes.

Conclusions: FAM19A4 methylation analysis in hrHPV-positive self-samples had a slightly lower sensitivity and a higher specificity for \geq CIN3 compared with paired physician-taken scrapes. With a similarly good clinical performance in both sample types, combined FAM19A4 methylation analysis and HPV16/18 genotyping provides a feasible triage strategy for hrHPV-positive women, with direct applicability on self-samples.

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Epidemiological studies have established that a persistent infection with a high-risk type of the human papillomavirus (hrHPV) is a necessary aetiological factor for cervical cancer. Several randomised trials have demonstrated that testing for the presence of hrHPV is a more sensitive screening tool compared with cytology, providing improved detection of cervical intraepithelial neoplasia grade 3 (CIN3) and cervical cancer (Dillner, 2013; Ronco *et al.*, 2014). However, the majority of hrHPV infections is transient, and only upon accumulation of genetic and epigenetic changes in the host and/or viral genomes, progression towards invasive cancer may occur (Snijders *et al.*, 2006; Steenbergen *et al.*, 2014). To avoid unnecessary referral to the gynaecologist of women with transient hrHPV infections, identification of women with lesions reflecting clinically relevant infections with a high risk of progression towards cancer is required. Currently, cytology is the most advocated triage tool for this purpose (Zorzi *et al.*, 2013; Dijkstra *et al.*, 2014). However, cytology triage requires repeat testing to ensure sufficient sensitivity (Rijkaart *et al.*, 2012; Dijkstra *et al.*, 2014) and has a subjective test result (Dijkstra *et al.*, 2014). Moreover, prior knowledge of the hrHPV status influences cytology reading, resulting in an easier classification of abnormal cytology, thus increasing the number of false-positives (Moriarty *et al.*, 2014). Although HPV16/18 genotyping might be a valuable addition to cytology by eliminating the necessity of a repeat test (Cox *et al.*, 2013; Dijkstra *et al.*, 2014), this combination may suffer from non-detection of (pre)cancers associated with non-HPV16/18 hrHPV types.

As gene silencing by promoter hypermethylation has been shown to contribute to cervical carcinogenesis, methylation analysis of cancer-specific genes has been suggested as a valuable, alternative or additive triage tool (Steenbergen *et al.*, 2004; Overmeer *et al.*, 2009; Wilting *et al.*, 2010; Saavedra *et al.*, 2012). Furthermore, in contrast to cytology, DNA methylation analysis detects virtually all cervical carcinomas and is assumed to detect 'advanced' CIN lesions, that is, lesions with a long duration of existence and with many chromosomal aberrations, which have a high risk of short-term progression to cancer (De Strooper *et al.*, 2014; Steenbergen *et al.*, 2014). Gene promoter methylation can be easily accessed by sensitive, quantitative methylation-specific PCR (qMSP) providing an objective test outcome. Previous results in hrHPV-positive cervical scrapes have been promising (Huang *et al.*, 2010; Hesselink *et al.*, 2011, 2014; Eijnsink *et al.*, 2012; Verhoef *et al.*, 2014a), with sensitivities for CIN3 and cervical cancer (\geq CIN3) equalling those of cytology analysis (Hesselink *et al.*, 2011; Verhoef *et al.*, 2014a).

An important development in cervical cancer screening is the use of self-collected cervicovaginal samples for women who do not attend screening (Ogilvie *et al.*, 2005; Snijders *et al.*, 2013; Arbyn *et al.*, 2014). However, as cytology cannot be reliably performed on self-sampled material (Nobbenhuis *et al.*, 2002; Garcia *et al.*, 2003), triage of hrHPV-positive women by cytology still requires a visit to a physician. In contrast, methylation analysis can be performed directly on the self-collected sample (Eijnsink *et al.*, 2011; Hesselink *et al.*, 2014; Verhoef *et al.*, 2014a). Indeed, a prospective trial in non-responders has shown that detection of high-grade CIN with direct *MAL/miR124-2* methylation analysis on hrHPV-positive lavage-collected self-samples is non-inferior to cytology triage on hrHPV-positive physician-taken scrapes, thereby preventing diagnostic delay and loss to follow-up (Verhoef *et al.*, 2014a). Recently, methylation analysis of the *FAM19A4* gene has been shown to yield attractive \geq CIN3 sensitivities and specificities in both hrHPV-positive brush-collected and lavage-collected self-samples (De Strooper *et al.*, 2016) supporting the concept that it serves as a universal triage test for HPV-positive cervicovaginal self-samples collected by different self-collection devices.

Studies evaluating the concordance of methylation analysis between self-collected cervicovaginal samples and physician-taken

cervical scrapes are however limited (Boers *et al.*, 2014; Chang *et al.*, 2015). Such evaluations are crucial to reveal the relative clinical performance for \geq CIN3 detection compared with physician-taken scrapes, as has been assessed for HPV testing (Arbyn *et al.*, 2014). It is well known that each sample type has its own cellular composition with likely a different fraction of indicator cells exfoliated from \geq CIN3, which may affect the performance of molecular reflex tests. The present study compared the clinical performance of *FAM19A4* methylation analysis with and without additional HPV16/18 genotyping, for the detection of \geq CIN3 in a unique cohort of paired self-collected cervicovaginal lavage samples and physician-taken cervical scrapes of hrHPV-positive women.

MATERIALS AND METHODS

Study design, participants and procedures. The present study was conducted as a *post hoc* analysis of data obtained in a prospective observational multicentre cohort study (COMETH), which aimed to compare different triage strategies in hrHPV-positive women (Luttmer *et al.*, 2016). From December 2010 till December 2013, women (age 18–70 years) who visited a gynaecological outpatient clinic in one of six hospitals in the Netherlands were asked to participate in the study. Women could participate in the study regardless of their reason for referral to the gynaecology outpatient clinic. After providing informed consent, participants collected cervicovaginal lavage material (using the Delphi screener; Delphi Bioscience, Scherpenzeel, The Netherlands) for hrHPV testing. Women who met the inclusion criteria and tested hrHPV-positive on the cervicovaginal lavage were invited for a cervical scrape and colposcopy. The cervical scrape was taken by a physician using a Cervex-Brush (Rovers Medical Devices BV, Oss, The Netherlands) or a Medscand Cytobrush Plus (CooperSurgical Inc., Trumbull, CT, USA). Scrape material was stored in 20 ml of Thinprep PreservCyt solution (Hologic, Marlborough, MA, USA) and was evaluated by *FAM19A4* methylation analysis and HPV16/18 genotyping (cytology results on these scrapes have been reported previously; Luttmer *et al.*, 2016). The study was approved by the Medical Ethical Committee of all participating hospitals (METc-VUmc2009/178) and registered as NTR2447. Women with a history of treatment for cervical dysplasia or cervical cancer, current cancer, pregnancy or lactation were excluded from participation (Luttmer *et al.*, 2016).

For logistic reasons, from 141 (31.3%) women, cervicovaginal lavage material was collected by the physician before cervical scraping using a Delphi screener according to the protocol. The remaining 309 (68.7%) women self-collected lavage material at home. In 268 (59.5%) women, the cervical scrape was taken at a minimum of 2 weeks before colposcopy. In 182 (40.4%) women, for logistic reasons, the cervical scrape was taken immediately before colposcopy during the same visit to the gynaecologist.

As shown in Figure 1, in all women who tested both hrHPV-positive on the cervicovaginal lavage and the cervical scrape ($n = 532$), *FAM19A4* methylation analysis was performed on each sample type. All of these women had colposcopy-directed biopsy. Women with invalid test results for *FAM19A4* methylation analysis of the cervicovaginal lavage ($n = 48$; 9.0%) or cervical scrape ($n = 43$; 8.0%) were excluded from analyses. Of these, nine women had an invalid test result in both the lavage and scrape samples. The remaining women comprised the final study population ($n = 450$).

Virtually all women (65 of 66; 98.4%) with histologically confirmed CIN3 and adenocarcinoma *in situ* (AIS) in the biopsy specimen were treated by large loop excision of the transformation zone (LLETZ) or cervical conisation; one woman was followed up

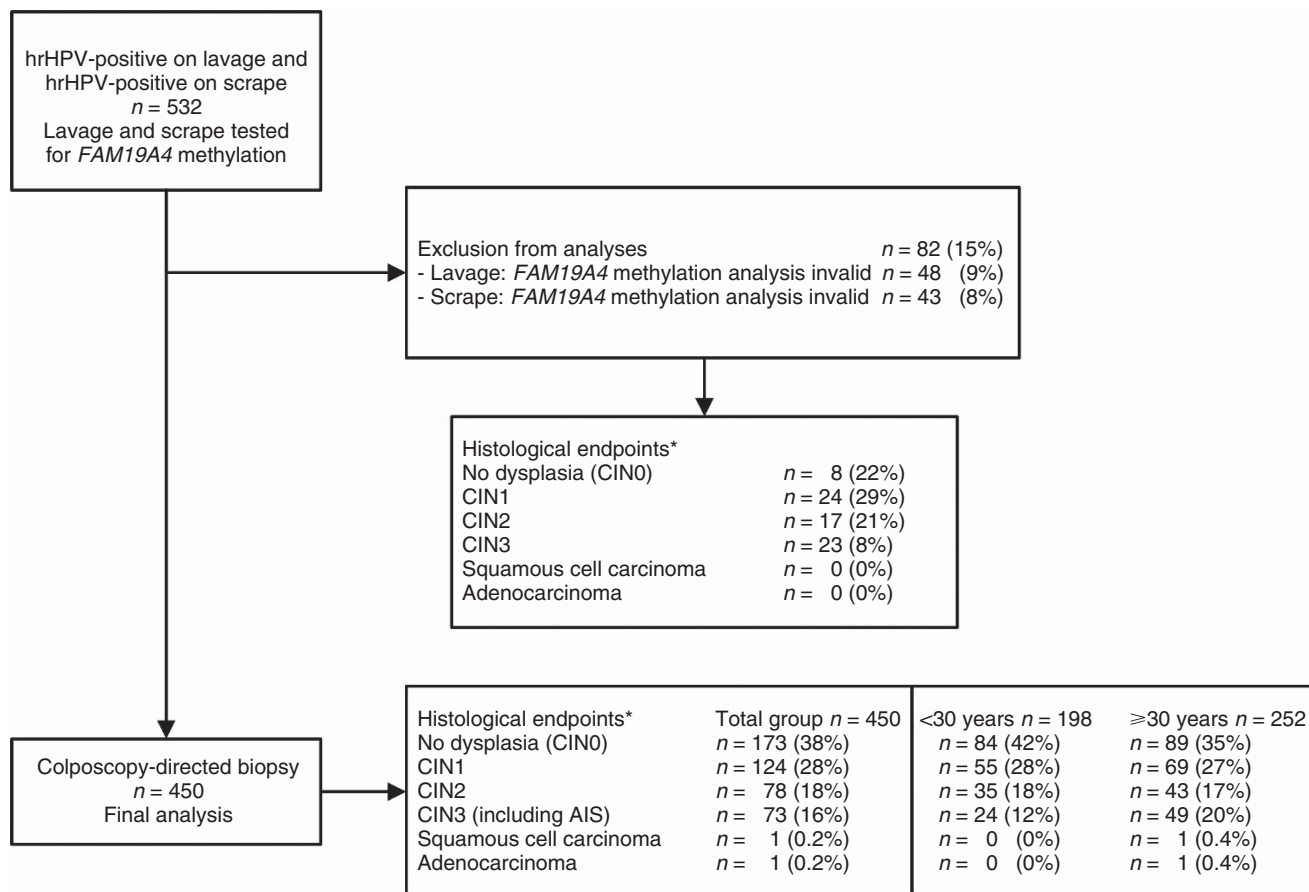


Figure 1. Overview of the study population and histological endpoints. *Histological endpoints were based on the histological outcome of the colposcopy-directed biopsy, or, if classified worse, on the histology result of the specimen excised by LLETZ, conisation or hysterectomy. AIS = adenocarcinoma *in situ*; CIN = cervical intraepithelial neoplasia; hrHPV = high-risk human papillomavirus.

without treatment. Depending on the size of the lesion, also 55 of 85 (64.7%) women with a CIN2 biopsy underwent LLETZ. Of these women, eight (14.5%) were diagnosed with CIN3 in the LLETZ tissue, and categorised accordingly. In addition, one woman with a CIN0 in the biopsy specimen had a CIN3 in the tissue, which was obtained by (diagnostic) LLETZ.

Histological endpoints. In concordance with earlier work (Luttmer *et al*, 2016), we used histologically confirmed \geq CIN3 as primary study end point and \geq CIN2 as a secondary study end point. Unless otherwise specified, histological end points were based on the histological outcome of the colposcopy-directed biopsy, or, if classified worse, on the histology result of the specimen excised by LLETZ, conisation or hysterectomy. In addition, we attempted to provide a rough estimation of the volume of CIN lesions. Therefore, histology results of biopsy specimens and those of the corresponding LLETZ (or conisation/hysterectomy) specimens are presented (Table 1). The presence of \geq CIN3 in the LLETZ (or conisation/hysterectomy) specimen, irrespective of the histological result of the biopsy, was considered indicative of a high-volume \geq CIN3 lesion. The presence of CIN3 in the biopsy specimen, combined with \leq CIN2 in the corresponding LLETZ specimen, was assumed to represent a low-volume CIN3 lesion. Similarly, the presence of CIN2 in the LLETZ specimen combined with \leq CIN2 in the corresponding biopsy specimen was considered to indicate a high-volume CIN2 lesion. The presence of CIN2 in the biopsy with \leq CIN1 in the LLETZ specimen was assumed to represent a low-volume CIN2 lesion. In women who were diagnosed with high-grade CIN on the biopsy specimen and who did not receive LLETZ (according to physician's advice), lesions were classified as low volume.

Table 1. Histology results of biopsy specimens and corresponding LLETZ specimens

Histology biopsy	Histology LLETZ (or conisation or hysterectomy)			
	\geq CIN3	CIN2	\leq CIN1	No LLETZ
\geq CIN3	37 ^{a*}	17 ^b	11 ^b	1 ^b
CIN2	8 ^a	25 ^c	22 ^d	30 ^d
\leq CIN1	1 ^a	1 ^c	3 ^e	294 ^e

Abbreviations: CIN = cervical intraepithelial neoplasia; LLETZ = large loop excision of the transformation zone.
^aHigh-volume \geq CIN3 lesion (*including two carcinomas).
^bLow-volume CIN3 lesion.
^cHigh-volume CIN2 lesion.
^dLow-volume CIN2 lesion.
^e \leq CIN1.

HPV genotyping. DNA was isolated from one-fifth of cervicovaginal lavage specimens and one-tenth of cervical scrape material using the Nucleo-Mag 96 Tissue Kit (Macherey-Nagel, Düren, Germany) and a Microlab Star robotic system (Hamilton, Planegg, Germany) according to the manufacturer's instructions (Hesselink *et al*, 2011). Isolated DNA was subjected to GP5 + /6 + PCR-enzyme immunoassay analysis (EIA Kit HPV GP HR; Diassay BV, Rijswijk, The Netherlands) (Jacobs *et al*, 1997). Subsequent genotyping for the high-risk HPV types 16/18/31/33/35/39/45/51/52/56/58/59/66/68 was performed using a microsphere bead-based assay (Luminex xMAP, Luminex Corp, Austin, TX, USA) as described previously (Schmitt *et al*, 2006).

qMSP analysis. Extracted DNA from hrHPV-positive cervicovaginal lavage specimens and cervical scrapes was treated with bisulphite using the EZ DNA Methylation Kit (Zymo Research, Irvine, CA, USA) as described previously (Overmeer *et al*, 2008, 2009). Bisulphite-converted DNA was used as template for FAM19A4 methylation analysis by qMSP using housekeeping gene β -actin (*ACTB*) as a reference (Steenbergen *et al*, 2013; De Strooper *et al*, 2014). Quantitative methylation-specific PCR analysis was carried out using an ABI 7500 Real-Time PCR-System (Applied Biosystems, Waltham, MA, USA). For each target, quantification cycle (Cq) values were measured at a fixed fluorescence threshold. To assure sample quality, all samples included in the study had a Cq value for *ACTB* <30. In case of poor DNA concentration and an invalid test result, DNA isolation, bisulphite treatment and qMSP were repeated with double sample input if sufficient material was available for analysis. Cq ratios were calculated for each sample using the following formula: $2^{(Cq(ACTB) - Cq(FAM19A4))} \times 100$. For both cervicovaginal lavage specimens and cervical scrapes, assay thresholds, which gave rise to a \geq CIN3 specificity of 70% using a training-validation set approach (De Strooper *et al*, 2014), were chosen to consider a specimen positive for FAM19A4 methylation.

Statistical analysis. The sample size was set such that 90% power was achieved for demonstrating non-inferiority of FAM19A4 methylation analysis in cervicovaginal lavages to FAM19A4 methylation analysis in cervical scrapes using a matched-sample score test (Tang *et al*, 2003; Meijer *et al*, 2009). A minimum of 300 hrHPV-positive women needed to be included at rejection rate α of 0.05. Finally, 450 hrHPV-positive women were included with results for all markers.

For assessing overall genotype concordance, results were either scored as concordant (sample types yielded completely identical genotype results), compatible (one or more of the same genotypes were detected) or discordant (no genotype similarities detected). Paired evaluation of FAM19A4 Cq ratios in cervicovaginal lavages and in cervical scrapes was carried out by Spearman's rank analysis.

The relation of the classification combining histological severity and lesion volume with the percentage of FAM19A4 methylation-positive and/or HPV16/18-positive samples was assessed using Fisher's exact test.

For both cervicovaginal lavages and cervical scrapes, clinical performance of FAM19A4 methylation analysis and the combined use of FAM19A4 methylation analysis and HPV16/18 genotyping was evaluated. Clinical performance indicators were sensitivity, specificity, positive predictive value (PPV) and complemented NPV (1-negative predictive value, a measure of disease risk after a negative result) for \geq CIN3 and \geq CIN2, and referral rate (based on % marker positivity) were calculated. To enable comparisons, relative sensitivity (ratio of the sensitivity of a marker in one sample type to its sensitivity in the other sample type) and relative specificity (ratio of the specificity of a marker in one sample type to its specificity in the other sample type) were calculated with 95% CIs. If the 95% CI of the relative sensitivity or specificity was entirely below or above one, the difference in sensitivity or specificity was considered statistically significant. In case of non-significant differences in sensitivity or specificity, an additional test was performed to evaluate non-inferiority. Non-inferiority was defined as a relative sensitivity or specificity of at least 90% using a matched-sample score test (Tang *et al*, 2003; Meijer *et al*, 2009).

Using logistic regression, we analysed the influence of several factors on the sensitivity and specificity of FAM19A4 methylation analysis in this study population: the age of the participants (<30 years and \geq 30 years), the reason for referral to the gynaecologist (abnormal cytology result or other, non-cervix-related,

gynaecological complaints), the sampling method of the cervicovaginal lavage (collected by the participant at home or by the physician) and the sampling moment of the cervical scrape (during a separate visit 2–3 weeks before colposcopy or combined with the colposcopy procedure). After finding a factor that significantly influenced the performance of the different markers, data were stratified for this factor. *P*-values <0.05 were considered statistically significant. All statistical analyses and computations of graphs were performed in IBM SPSS Statistics 20 (IBM Corporation, Armonk, NY, USA), STATA 11.0 (StataCorp LP, College Station, TX, USA) and Excel.

RESULTS

Study population. The study flowchart and histological end points are shown in Figure 1. The final analysis comprised 450 women (age 18–66 years) who tested hrHPV-positive on both the cervicovaginal lavage material and the cervical scrape, had valid results for FAM19A4 methylation in both sample types and a histological end point. FAM19A4 methylation scored positive in 26.4% (119 of 450) of the cervicovaginal lavage specimens and in 35.8% (161 of 450) of the cervical scrape specimens. Human papillomavirus16 and/or HPV18 was present in 46.4% (209 of 450) of the cervicovaginal lavage specimens and 47.3% (213 of 450) of the cervical scrape specimens. Two women (0.4%) had invasive cervical carcinoma (i.e., one squamous cell carcinoma (SCC) and one adenocarcinoma), 73 women (16.2%) had CIN3 (including one AIS), 78 women (17.3%) had CIN2, 124 (27.6%) had CIN1 and 173 (38.4%) had no CIN. In Table 1, histological results of biopsy specimens and corresponding LLETZ results are presented.

Concordance of HPV genotypes and FAM19A4 methylation analysis. Genotype agreement between the cervical scrape and cervicovaginal lavage was concordant (sample types yielded completely identical genotype results) in 60.7% (273 of 450) and compatible (one or more of the same genotypes were detected) in 28.9% (130 of 450) of cases. In the remaining cases (47 of 450; 10.4%), genotypes were discordant between both sample types. As shown in Table 2, for the majority of hrHPV types, genotype concordance between cervical scrapes and cervicovaginal lavages was substantial to almost perfect (Landis and Koch, 1977), both in the total group and in the strata of histological severity. FAM19A4 Cq ratios in lavage samples were significantly correlated to those in cervical scrapes in the total study population (Spearman's ρ 0.394, $P < 0.001$). In the strata of histological severity, this correlation was found to be strongest in women with \geq CIN3 (Spearman's ρ 0.697, $P < 0.001$), followed by CIN2 (Spearman's ρ 0.255, $P = 0.024$) and \leq CIN1 (Spearman's ρ 0.257, $P < 0.001$). The correlation between methylation Cq ratio in cervical scrapes and lavage samples in the strata of histological severity is presented in Supplementary Figure 1. Both women diagnosed with cervical cancer tested positive for FAM19A4 methylation analysis in both sample types. The woman with an adenocarcinoma tested HPV16-positive, whereas the woman with an SCC harboured HPV39.

Performance of FAM19A4 methylation analysis in total study population. Test specifications of FAM19A4 methylation analysis in cervical scrapes (which were described previously; Luttmmer *et al*, 2016) and in cervicovaginal lavages for detection of \geq CIN3 and \geq CIN2 in the total study population are shown in Table 3 (upper panel). Although the sensitivity of FAM19A4 methylation analysis for the detection of \geq CIN3 was lower in cervicovaginal lavage material (65.3%) compared with that in cervical scrapes (74.7%), this difference was not statistically significant (ratio 0.88; CI: 0.75–1.02). However, statistical non-inferiority (of lavages relative to scrapes) could not be demonstrated ($P = 0.64$). The \geq CIN3 specificity of FAM19A4 methylation analysis was significantly

Table 2. HPV genotype concordance in cervical scrapes and cervicovaginal lavages

HPV genotype	Scrapes		Lavages		Discordant pairs n ^b	Concordance total group κ	≥CIN3 κ	≥CIN2 κ	≤CIN1 κ
	Positive n ^a	Percentage (%) ^a	Positive n ^a	Percentage (%) ^a					
HPV16	175	39	175	39	38	0.822	0.871	0.856	0.789
HPV31	58	13	64	14	32	0.697	0.721	0.655	0.717
HPV56	56	12	51	11	27	0.714	0.654	0.542	0.755
HPV18	52	12	52	12	22	0.761	0.802	0.762	0.760
HPV51	51	11	50	11	19	0.788	0.793	0.843	0.766
HPV66	49	11	64	14	19	0.808	0.517	0.802	0.811
HPV52	46	10	48	11	28	0.667	0.686	0.694	0.653
HPV45	41	9	41	9	24	0.678	0.737	0.765	0.642
HPV59	35	8	38	8	23	0.657	0.661	0.564	0.685
HPV58	25	6	25	6	20	0.576	0.551	0.719	0.490
HPV33	23	5	28	6	11	0.771	0.661	0.759	0.775
HPV35	21	5	31	7	18	0.633	0.786	0.745	0.559
HPV39	20	4	14	3	10	0.695	0.793	0.601	0.753

Abbreviations: CIN = cervical intraepithelial neoplasia; hrHPV = high-risk human papillomavirus; κ = kappa.
^aFrequencies and percentages indicated here include the presence of types both in single and multiple infections; total n = 450 hrHPV-positive women; HPV68 was excluded owing to low frequency (positive n = 4 in scrapes and n = 2 in lavages).
^bNumber of discordant samples between scrape and lavage per single HPV type.

Table 3. Test specifications of FAM19A4 methylation analysis in cervical scrapes and cervicovaginal lavages for detection of ≥CIN3 and ≥CIN2

	Triage marker	n1/N1	Sensitivity (95% CI)	n2/N2	Specificity (95% CI)	PPV (95% CI)	1-NPV (95% CI)	Referral rate (%)
Total group (n = 450)								
≥CIN3	FAM19A4 methylation scrape	56/75	74.7% (64.8–84.5)	270/375	72.0% (67.5–76.5)	34.8% (27.4–42.1)	6.6% (3.7–9.4)	35.8
	FAM19A4 methylation lavage	49/75	65.3% ^a (54.6–76.1)	305/375	81.3% ^b (77.4–85.3)	41.2% (32.3–50.0)	7.9% (5.0–10.8)	26.4
≥CIN2	FAM19A4 methylation scrape	87/153	56.9% (49.0–64.7)	223/297	75.1% (70.2–80.0)	54.0% (46.3–61.7)	22.8% (18.0–27.7)	35.8
	FAM19A4 methylation lavage	68/153	44.4% ^b (36.6–52.3)	246/297	82.8% ^b (78.5–87.1)	57.1% (48.3–66.0)	25.7% (21.0–30.4)	26.4
Subgroup: women ≥ 30 years (n = 252)								
≥CIN3	FAM19A4 methylation scrape	45/51	88.2% (79.4–97.1)	127/201	63.2% (56.5–69.9)	37.8% (29.1–46.5)	4.5% (1.0–8.0)	47.2
	FAM19A4 methylation lavage	40/51	78.4% ^a (67.1–89.7)	147/201	73.1% ^b (67.0–79.3)	42.6% (32.6–52.5)	7.0% (3.0–10.9)	37.3
≥CIN2	FAM19A4 methylation scrape	66/94	70.2% (61.0–79.5)	105/158	66.5% (59.1–73.8)	55.5% (46.5–64.4)	21.1% (14.1–28.0)	47.2
	FAM19A4 methylation lavage	55/94	58.5% ^b (48.6–68.5)	119/158	75.3% ^b (68.6–82.0)	58.5% (48.6–68.5)	24.7% (18.0–31.4)	37.3
Subgroup: women < 30 years (n = 198)								
≥CIN3	FAM19A4 methylation scrape	11/24	45.8% (25.9–65.8)	143/174	82.2% (76.5–87.9)	26.2% (12.9–39.5)	8.3% (4.0–12.7)	21.2
	FAM19A4 methylation lavage	9/24	37.5% ^a (18.1–56.9)	158/174	90.8% ^b (86.5–95.1)	36.0% (17.2–54.8)	8.7% (4.5–12.9)	12.6
≥CIN2	FAM19A4 methylation scrape	21/59	35.6% (23.4–47.8)	118/139	84.9% (78.9–90.8)	50.0% (34.9–65.1)	24.4% (17.6–31.1)	21.2
	FAM19A4 methylation lavage	13/59	22.0% ^b (11.5–32.6)	127/139	91.4% ^c (86.7–96.0)	52.0% (32.4–71.6)	26.6% (20.0–33.2)	12.6

Abbreviations: CI = confidence interval; CIN = cervical intraepithelial neoplasia (grade 2 or 3 or higher); HPV = human papillomavirus; n1 = number of test positive disease cases; N1 = total number of disease cases; n2 = number of test negative non-disease cases; N2 = total number of non-disease cases; 1-NPV = complemented negative predictive value; PPV = positive predictive value.
^aNo significant difference with FAM19A4 methylation in cervical scrape (in the corresponding category); non-inferiority test not significant.
^bSignificant difference with FAM19A4 methylation in cervical scrape (in the corresponding category).
^cNon-inferior to FAM19A4 methylation in cervical scrape (in the corresponding category).

higher in cervicovaginal lavages (81.3%) compared with that in cervical scrapes (72.0%; ratio 1.13; CI: 1.05–1.21). For ≥CIN2 outcome in the total study population (Table 3; upper panel), FAM19A4 methylation analysis had a significantly lower sensitivity in cervicovaginal lavages (44.4%) compared with that in cervical scrapes (56.9%), whereas its specificity in lavages (82.8%) was significantly higher compared with that in scrapes (75.1%; relative specificity 1.10; CI: 1.03–1.18).

Factors influencing the performance of FAM19A4 methylation analysis: age. The performance of FAM19A4 methylation analysis was significantly influenced by the age of the participants in both sample types (Supplementary Tables 1A and B). Neither the reason

for referral of the participant (abnormal cytology result or other, non-cervix-related, gynaecologic complaints) nor the sampling method of the lavage (self-collected by the participant at home or physician-collected) or scrape (during a separate visit 2–3 weeks before colposcopy or combined with the colposcopy procedure) influenced the performance of FAM19A4 methylation analysis significantly (Supplementary Tables 1A and B). Given the influence of age, the performance of FAM19A4 methylation analysis was assessed in subgroups of women 18–30 years (referred to as <30years) and women 30–66 years (referred to as ≥30 years). Sensitivity, specificity, PPV and complemented NPV of FAM19A4 methylation analysis in both sample types and in both age strata are shown in Table 3.

Table 4. Test specifications of FAM19A4 methylation analysis combined with HPV16/18 genotyping in cervical scrapes and cervicovaginal lavages for detection of ≥CIN3 and ≥CIN2

	Triage marker	n1/N1	Sensitivity (95% CI)	n2/N2	Specificity (95% CI)	PPV (95% CI)	1-NPV (95% CI)	Referral rate (%)
Total group (n = 450)								
≥CIN3	FAM19A4 methylation and/or HPV16/18 genotyping scrape	69/75	92.0% (85.9–98.1)	165/375	44.0% (39.0–49.0)	24.7% (19.7–29.8)	3.5% (0.8–6.3)	62.0
	FAM19A4 methylation and/or HPV16/18 genotyping lavage	67/75	89.3% ^a (82.3–96.3)	181/375	48.3% ^a (43.2–53.3)	25.7% (20.4–31.0)	4.2% (1.4–7.1)	58.0
≥CIN2	FAM19A4 methylation and/or HPV16/18 genotyping scrape	117/153	76.5% (69.7–83.2)	135/297	45.5% (39.8–51.1)	41.9% (36.1–47.7%)	21.1% (14.9–27.2)	62.0
	FAM19A4 methylation and/or HPV16/18 genotyping lavage	110/153	71.9% ^b (64.8–79.0)	146/297	49.2% ^a (43.5–54.8)	42.1% (36.2–48.1)	22.8% (16.8–28.7)	58.0
Subgroup: women ≥ 30 years (n = 252)								
≥CIN3	FAM19A4 methylation and/or HPV16/18 genotyping scrape	48/51	94.1% (87.7–100.0)	77/201	38.3% (31.6–45.0)	27.9% (21.2–34.6)	3.8% (0.0–7.9)	68.3
	FAM19A4 methylation and/or HPV16/18 genotyping lavage	47/51	92.2% ^b (84.8–99.5)	88/201	43.8% ^a (36.9–50.6)	29.4% (22.3–36.4)	4.3% (0.2–8.5)	63.5
≥CIN2	FAM19A4 methylation and/or HPV16/18 genotyping scrape	77/94	81.9% (74.1–89.7)	63/158	39.9% (32.2–47.5)	44.8% (37.3–52.2)	21.3% (12.3–30.2)	68.3
	FAM19A4 methylation and/or HPV16/18 genotyping lavage	73/94	77.7% ^b (69.2–86.1)	71/158	44.9% ^b (37.2–52.7)	45.6% (37.9–53.3)	22.8% (14.2–31.4)	63.5
Subgroup: women < 30 years (n = 198)								
≥CIN3	FAM19A4 methylation and/or HPV16/18 genotyping scrape	21/24	87.5% (74.3–100.0)	88/174	50.6% (43.1–58.0)	19.6% (12.1–27.2)	3.3% (0.0–7.0%)	54.0
	FAM19A4 methylation and/or HPV16/18 genotyping lavage	20/24	83.3% ^b (68.4–98.2)	93/174	53.4% ^b (46.0–60.9)	19.8% (12.0–27.6%)	4.1% (0.2–8.1)	51.0
≥CIN2	FAM19A4 methylation and/or HPV16/18 genotyping scrape	40/59	67.8% (55.9–79.7)	72/139	51.8% (43.5–60.1)	37.4% (28.2–46.6)	20.9% (12.5–29.2)	54.0
	FAM19A4 methylation and/or HPV16/18 genotyping lavage	37/59	62.7% ^b (50.4–75.1)	75/139	54.0% ^b (45.7–62.2)	36.6% (27.2–46.0%)	22.7% (14.3–31.0)	51.0

Abbreviations: CI = confidence interval; CIN = cervical intraepithelial neoplasia (grade 2 or 3 or higher); HPV = human papillomavirus; n1 = number of test positive disease cases; N1 = total number of disease cases; n2 = number of test negative non-disease cases; N2 = total number of non-disease cases; 1-NPV = complemented negative predictive value; PPV = positive predictive value.

^aNon-inferior to FAM19A4 methylation and/or HPV16/18 genotyping in cervical scrape (in the corresponding category).

^bNo significant difference with FAM19A4 methylation and/or HPV16/18 genotyping in cervical scrape (in the corresponding category); non-inferiority test not significant.

In women ≥30 years of age (n = 252), 51 ≥CIN3, 43 CIN2 and 158 ≤CIN1 were present (Table 3; middle panel). In this sub-population, the sensitivity of FAM19A4 methylation analysis for ≥CIN3 was lower in cervicovaginal lavages (78.4%) compared with that in cervical scrapes (88.2%). Although this difference was not statistically significant (ratio 0.89; CI: 0.75–1.05), statistical non-inferiority could not be demonstrated (P = 0.56). The specificity of FAM19A4 methylation analysis for ≥CIN3 was significantly higher in lavages (73.1%) compared with that in scrapes (63.2%; ratio 1.16; CI: 1.03–1.30). For detection of ≥CIN2 in women aged ≥30 years, the sensitivity of FAM19A4 methylation analysis in lavages (58.5%) was lower compared with that in scrapes (70.2%; ratio 0.83; CI: 0.70–0.999), and its specificity in lavages (75.3%) was higher compared with that in scrapes (66.5%; ratio 1.13; CI: 1.01–1.28).

In the subgroup of women <30 years of age (n = 198), 24 ≥CIN3, 35 CIN2 and 139 ≤CIN1 were present (Table 3, lower panel). The sensitivity of FAM19A4 methylation analysis for ≥CIN3 in lavages did not differ significantly from its sensitivity in scrapes (37.5% vs 45.8%; ratio 0.82; CI: 0.55–1.21), but statistical non-inferiority could not be established (P = 0.69). The specificity of FAM19A4 methylation analysis for ≥CIN3 in lavages (90.8%) was significantly higher compared with that in scrapes (82.2%; ratio 1.10; CI: 1.02–1.20). The sensitivity of FAM19A4 methylation for ≥CIN2 in lavages was significantly lower in lavages (22.0%) compared with that in scrapes (35.6%; ratio 0.62; CI: 0.40–0.96), whereas the ≥CIN2 specificity of this marker in lavages (91.4%) was non-inferior to its specificity in scrapes (84.9%; ratio 1.08; CI: 0.99–1.17; non-inferiority test: P = 0.01).

The performance of FAM19A4 methylation analysis combined with HPV16/18 genotyping. Table 4 presents the clinical

performance of FAM19A4 methylation analysis combined with HPV16/18 genotyping for ≥CIN3 and ≥CIN2 in both sample types. Compared with FAM19A4 methylation analysis alone (Table 3), the combined marker panel (Table 4) reached significantly higher ≥CIN3 and ≥CIN2 sensitivities, at significantly lower specificities in both sample types and in both age categories. In contrast to FAM19A4 methylation analysis alone, the performance of combined FAM19A4 methylation analysis and HPV16/18 genotyping did not differ significantly between cervicovaginal lavages and cervical scrapes (Table 4).

FAM19A4 methylation analysis in relation to histological severity. In an attempt to evaluate FAM19A4 methylation analysis in relation to lesion severity and volume, participants were stratified on the basis of a combination of histological severity and volume of the CIN lesion (Table 1). FAM19A4 methylation positivity rates in cervicovaginal lavages and cervical scrapes, in relation to this combined classification, are presented in Table 5. In both cervicovaginal lavage samples and cervical scrapes, the percentage of FAM19A4 methylation-positive cases increased with the lesion severity and volume (P < 0.001 for both sample types; Table 5). A similar increase in positivity rate was observed when combining FAM19A4 methylation analysis and HPV16/18 genotyping, yet at overall higher positivity rates for each volume category (Table 5).

DISCUSSION

This study compared the performance of FAM19A4 methylation analysis in large series of paired self-collected cervicovaginal lavage samples and physician-taken cervical scrapes for the detection of

Table 5. FAM19A4 methylation results in cervicovaginal lavages and cervical scrapes in relation to histological results of the biopsy and LLETZ specimen

Histology and lesion volume	FAM19A4 methylation analysis				FAM19A4 methylation analysis and/or HPV16/18 genotyping			
	Lavage		Scrape		Lavage		Scrape	
	Positive n/ total n	Percentage	Positive n/ total n	Percentage	Positive n/ total n	Percentage	Positive n/ total n	Percentage
High-volume \geq CIN3 ^a	35/46	76.1	41/46	89.1	45/46	97.8%	45/46	97.8
Low-volume CIN3 ^b	14/29	48.3	15/29	51.7	22/29	75.9	24/29	82.8
High-volume CIN2 ^c	8/26	30.8	12/26	46.2	15/26	57.7	17/26	65.4
Low-volume CIN2 ^d	11/52	21.2	19/52	36.5	28/52	53.8	31/52	59.6
\leq CIN1 ^e	51/297	17.2	74/297	24.9	151/297	50.8	162/297	54.5

Abbreviations: CIN = cervical intraepithelial neoplasia; HPV = human papillomavirus; LLETZ = large loop excision of the transformation zone. Fisher's exact test $P < 0.001$ for both FAM19A4 methylation analysis and the combination of FAM19A4 methylation analysis and HPV16/18 genotyping, in both lavages and scrapes.

^aLLETZ (or conisation/hysterectomy) specimen \geq CIN3 (including two carcinomas).

^bBiopsy specimen CIN3, LLETZ specimen \leq CIN2.

^cBiopsy specimen \leq CIN2, LLETZ specimen CIN2.

^dBiopsy specimen CIN2, LLETZ specimen \leq CIN1.

^eBoth biopsy specimen and LLETZ specimen (if available) \leq CIN1.

\geq CIN3 in hrHPV-positive women from a gynaecologic outpatient population. FAM19A4 methylation analysis on self-collected lavage material had a slightly lower sensitivity and a significantly higher specificity compared with FAM19A4 methylation analysis on physician-taken scrapes.

This study is the first large prospective multicentre cohort study comparing the performance of methylation marker analysis in hrHPV-positive cervicovaginal lavage samples to cervical scrapes from the same women. The required number of participants with and without \geq CIN3 lesions in this study was calculated in advance to allow comparison of sensitivity and specificity in both sample types. Until now, limited data comparing methylation marker performance in paired samples were available. The methylation markers studied by Boers *et al* (2014) (*C13ORF18*, *EPB41L3*, *JAM3* and *TERT*) (Boers *et al*, 2014) and Chang *et al* (2015) (*PAX1*, *SOX1* and *ZNF582*) have shown moderate to good concordance in self-samples and cervical scrapes, yet these studies were performed on very small study populations with limited controls and require confirmation from other prospective studies.

In the current study, the differences in clinical performance between the two sample types can most likely be attributed to a different cellular composition and proportion of hypermethylation-positive cervical indicator cells. During cervical scrape collection, a physician will target the transformation zone of the cervix, contributing to a likely large number of cervical indicator cells. In case of self-collection by a lavage device, a more random distribution of vaginal and cervical indicator cells can be expected. Consequently, the lower fraction of hypermethylated indicator cells in self-collected lavages might explain the slightly lower sensitivity and higher specificity of FAM19A4 methylation analysis.

Our previous studies have shown that FAM19A4 methylation analysis and cytology on HPV-positive cervical scrapes have a similar \geq CIN3 sensitivity (De Strooper *et al*, 2014; Luttmmer *et al*, 2016). However, FAM19A4 methylation analysis has proven to be more sensitive for the detection of CIN3 lesions with a longer duration of existence (the so-called advanced lesions) and cervical carcinoma (Luttmmer *et al*, 2016). An advantage of the present study is the availability of both biopsy and LLETZ histological results from all participants with a high-grade lesion enabling a semiquantitative assessment of lesion volume. We showed that in both hrHPV-positive cervicovaginal lavages and cervical scrapes, FAM19A4 methylation-positivity increases with the volume of high-grade CIN lesions. These results support the concept that FAM19A4 methylation analysis has a preference for detecting

the larger, probably more advanced CIN lesions (De Strooper *et al*, 2014). Of note, combined FAM19A4 methylation analysis and HPV16/18 genotyping detected all but one high-volume \geq CIN3 lesions in both cervical scrapes and cervicovaginal lavages.

As expected, and found previously (Verhoef *et al*, 2014b; De Strooper *et al*, 2016), the addition of HPV16/18 genotyping to FAM19A4 methylation analysis yielded a significant increase in sensitivity at the cost of a marked decrease in specificity. Of interest, whereas FAM19A4 methylation analysis alone was found to be slightly less sensitive and more specific in the cervicovaginal lavages compared with the cervical scrapes, no significant differences were found for the marker combining FAM19A4 methylation analysis and HPV16/18 genotyping. Thus, the combination of FAM19A4 methylation analysis with HPV16/18 genotyping might be a safe alternative triage strategy that performs similarly on both sample types.

In line with earlier studies (Luttmmer *et al*, 2016), our data showed a significant influence of age on FAM19A4 methylation positivity in both cervical scrapes and cervicovaginal lavage material. Accordingly, in young women, FAM19A4 methylation analysis results in quite low \geq CIN2/3 sensitivities of only 37.5–45.8%, at relatively high specificities of 82.2–90.0%. In young women, hrHPV prevalence is known to be high, but the majority of infections are transient and most lesions, also a substantial part of CIN3 lesions, tend to regress spontaneously (Winer *et al*, 2003; Insinga *et al*, 2010; Jaisamrarn *et al*, 2013), contributing to a very low cancer incidence in this age category (Benard *et al*, 2012). As FAM19A4 methylation analysis has previously shown to preferably detect advanced CIN lesions and cervical cancer (De Strooper *et al*, 2014; Steenbergen *et al*, 2014), this lower sensitivity has the clinical benefit that it could protect young women from overtreatment. This is particularly relevant for women in their reproductive age as treatment may lead to adverse pregnancy outcome.

Owing to the selection of an outpatient population, the translation of our results into screening settings should be handled with care. Further confirmation in population-based screening trials is required as the percentage of HPV-positive women with \geq CIN3 lesions in a screening population is lower compared with that in a gynaecologic referral population. Another limitation of our study is the relatively large number of samples with an invalid test result for FAM19A4 methylation analysis of 8% in the cervical scrapes and 9% in the cervicovaginal lavage samples. These invalid test results on the cervical scrapes might result from cautious scraping during colposcopy to prevent bleeding and thus poor

visualisation, leading to low DNA concentrations (Overmeer *et al*, 2011). Indeed, 88.4% of the invalid results were found in scrapes that were collected directly before colposcopy, a procedure that is not likely to be applied in a routine cervical screening setting. Also in self-samples, the number of cells can be limited or the sample can be of poor quality, for example, by collection or storage failures. This problem can be circumvented by using a larger fraction of the scrape or self-sample in the DNA isolation procedure, or by decreasing the elution volume during isolation. Given the study setting aiming to evaluate different triage strategies, leftover sample material was not always sufficient to perform repeat methylation analysis. In routine setting, this limitation will likely not be applicable, as also supported by the limited occurrence of methylation-invalid samples in a randomised controlled trial in screening setting (Verhoef *et al*, 2014a).

In conclusion, *FAM19A4* methylation marker analysis in hrHPV-positive self-collected lavage samples had a slightly lower sensitivity and a higher specificity for \geq CIN3 compared with *FAM19A4* methylation analysis in paired physician-taken scrapes. Combined *FAM19A4* methylation analysis and HPV16/18 genotyping revealed a similarly good clinical performance, which was similar in both sample types. Therefore, this combination could provide a feasible triage strategy for hrHPV-positive women, with the advantage of direct applicability on self-collected material.

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CONFLICT OF INTEREST

JB has played an advisory role for Merck and Roche, has been on the speakers bureau of Qiagen and has received a travel reimbursement from DDL Diagnostic Laboratory. PJFS has been on the speakers bureau of Roche, Qiagen, Abbott, Gen-Probe and Seegene. PJFS is consultant for Crucell Holland BV. TJMH, RHMV and WAH have been principal investigators of a GlaxoSmithKline sponsored study. WGVQ is a minority shareholder of Diassay BV and obtained grants from GlaxoSmithKline. DAMH has been on the speakers bureau of Hologic/Gen-Probe and serves occasionally on the scientific advisory boards of AMGEN and Pfizer. CJLMM has been on the sponsored speakers bureau of GlaxoSmithKline, Qiagen, Merck, Roche, Menarini and Seegene, and served on the scientific advisory board of GlaxoSmithKline, Qiagen, Merck and Roche. CJLMM has been consultant for Qiagen and Gentcel and is a minority shareholder of Diassay BV. Formerly, CJLMM was a minority shareholder of Delphi Biosciences. CJLMM, PJFS, RDMS

and DAMH have minority stake in Self-screen BV, a spin-off company of VU University Medical Center Amsterdam, which holds patents related to the present work. RL, LMADS, MGD, FJvK, LR, WMvB, GCMG, JWMS and DKEvD do not have any conflict of interest to declare.

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