The potential of RNA as a target for national screening of pre-cancer

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Abstract

Whole national screening of pre-cancer is done only in some few countries, dominated by The Netherlands, Denmark, UK, Norway and Finland. These national screenings are done combining national cancer registry, national public health and national medical bodies or hospitals. Until some few years ago national screening was only done using morphological or visual methods or technology. Today a number of molecular methods have been implemented to serve these national screening programs. Based on all the discussions within this review, it is clear that the main driving engine and the cause of cervical pre-cancer and the main cause of invasive cervical cancer is the expression of E6 and E7 oncoproteins from HPV 16, 18, 31, 33 and 45. However, the main challenge is the role of morphology or imaging-based diagnosis in the original definition of pre-cancer disease. This definition is not based on the cause of cervical pre-cancer but based on a complex, subjective, morphological observations. The difference between these two definitions are discussed in this review. The unique discovery done while validating the first standardized detection technology used against mRNA, confirmed that the presence of both abnormal E6 and/or E7 mRNA and protein is the cause of cervical pre-cancer or severe neoplasia and the main cause of invasive cervical cancer. This confirmation was evident even though all these studies were disturbed by the above defined biases from morphology or imaging-based diagnosis. The use of the screening target that cause stable and high expression of the most carcinogenic compounds ever discovered, must cause a more accurate screening program. A number of studies have proved that the detection of E6/E7 mRNA followed-up by indirect or direct treatment in a well-organized national screening program, would reduce the incidence of cervical cancer. This review discusses the main studies involved in the scientific, clinical evaluation and how this unique technology could be used as a new medical gold standard for national screening of cervical pre-cancer.

Introduction

The diagnosis or screening of cervical pre-cancer and invasive cervical cancer has for the last 80 years relied on the histology, colposcopy and the Pap methods including cytological identification of abnormal cells.1-7 In addition the colposcopy has also been being involved making the gynecologists and pathologists working together.4-6 Before treatment or interventions in the cervix based on cytology or colposcopy, histology has to be used as the gold standard in order to confirm the presence of histological CIN2+.8,9 Therefore, an abnormal pap smear has only being an indicator that a disease process is present and further tests are required to make the complete diagnosis.2 However, the main problem with these morphological tests have been its subjective nature, loss of repeatability, lack of fellow standards, lack of internal controls and the high number of false negatives and positives.10 In the accuracy evaluation of cervical cytology few studies of initial screening were unaffected by workup bias, but the few that were provided estimates of the specificity of Pap smear screening of 97 to 100 percent and sensitivity of 29 to 56 percent, indicating sensitivity estimates much lower than those generally believed to be true. The evidence regarding the accuracy of the newer technologies on cervical cytology screening is insufficient for several reasons. Most effect on sensitivity are based on surrogate reference standard (cytology) and the assess of the effects of thin-layer cytology or computer rescreening on specificity.10 Another main problem with these morphological tests is the inability to include them in complete performance evaluation.10 The third main problem with cytology is the lack of clinical sensitivity towards invasive cervical cancer. Even in the countries where a more complete national screening program is done, cytology is able to miss around 50% of the cancer positive samples.11-13 Another significant problem with cytology is the relative high number of women that still become positive (4-7%) without improving the discovery of invasive cervical cancer (ICC) in a national screening program. However, the major problem for all women may be the need for follow-up on the majority of cytological diagnosis for months or years without any diagnostic conclusion.

The Cancer Registry of Norway (CRN) is responsible for several registers of premalignant lesions and cancers as well as the screening program for cervical cancer. The register of pre-malignant cervical lesion treatment, and the Cytology Register have been linked by the use of the Norwegian person identification number (PIN). This PIN is a unique 11 digital-number given to each Norwegian citizen, and is used in all official register. The database of CRN uses a reporting system that is based on pathology, autopsy and cytology reports, clinical records and death certificates. One record is the result of accumulated reports on one person for each disease. The registration of Invasive Cervical Cancer (ICC) is practically 100% complete in Norway. Virtually all PAP smears are registered into the Cytology Register. The use of a unique personal identification number given to all Norwegian residents in all these registers made it possible to compare all cases with a CIN 2/3/ACIS (N=8586) with ICC (N=777) in the period 2000-2002. All Pap smears since
1992 were used to characterize detection mode and screening history. The report from this follow-up was conducted by Nygård and colleagues.11,12,14 Fifty-five percent of the women diagnosed with CIN2/3/ACIS had an adequate screening history. Of women diagnosed with ICC, 45% in stage I and 10.5% in stage IV had an adequate history. Women with ICC stage II-IV, 40.9% had no Pap smear within 24 months of diagnosis while 5.7% had a normal Pap smear. For women with CIN2 or CIN3, more than 30% had an abnormal Pap smear. Again, the Pap smear sensitivity varied greatly, with estimates from 11-99 for detecting CIN2 or worse lesions, with meta-analyses reporting a mean sensitivity of 50%.15,16 Data suggest that the Pap test is unable to discriminate between histologic diseased and non-diseased individuals with concurrently high sensitivity and specificity. It is very clear that a Pap smear in an asymptomatic woman is a screening procedure, not a preventive act. The important for pap is the regular use often enough to establish high enough accuracy. This may also create the main bias behind the so-called cytological screening success. However, the cost of this lack of objective clinical accuracy is around 35 000 women (CRN) every year strongly exposed to unnecessary psychological stress. Increasing number of cytological examinations would naturally give a higher number of possible examinations; including colposcopy examinations and histology of biopsies. It is also very likely that most of the cytological success may be related to a much higher random number of biopsies followed by histological examination. It may also happen that a higher frequency of cytological examinations causes a higher number of colposcopy examination including Pap diagnosis. This higher number of morphological or image analysis cause a higher frequent disturbances or lesions of the transformation zone. Lesions in the cervix may cause a higher number of HPV infections in the basal cell layer and thereby cause more production of E6 and E7 oncoproteins following presence of an abnormal E6/E7 mRNA and cervical pre-cancer.

Within the area of cervical cancer prevention, a wide range of molecular methods and HPV biomarkers have been introduced during the last 30 or so years. Common for most of these biomarkers (e.g. HPV-DNA tests) is a low positive predictive value for histological CIN2+ in screening (typically below 10%) making it unlikely to treat women solely on this diagnosis.17-20 However, due to very high clinical sensitivity based on possible biased presence of both carcinogenic and natural HPV infection, these HPV DNA based methods are selected and FDA approved, despite the high number of false positives and the lack of targeting true pre-cancer. A recent very large study in US on 256 648 women confirmed this bias made HPV DNA test (HC2) (Qigen, Hilden, Germany), missing 19% of the invasive cancer cases in the first run or at baseline.21 More than 80% of women within a country may have been infected by natural HPV infections and only a fraction of these women should have been included in the statistical risk of developing several pre-cancer. Despite this fact, 15% of the cytological normal cases from the above large study, were identified to have high-risk Human Papillomavirus (hrHPV) infection using the HC2. Recently, in China, a similar study showed that more than 19% of the women in the big cities were positive by high-risk HPV by the gold standard HPV DNA test; HC2.22 All FDA approved HPV tests have been validated against this HC2 test. Recently, a national screening related study in Norway has presented related results, showing that COBAS 4800 HPV DNA test missed 40% of the HPV 16 infections in histological normal/CIN1 cases.23 The medical opinion still demand that all studies should involve morphological methods. Therefore, all studies involving objective molecular methods have to undergo verification bias from morphology. Comparing morphological and very subjective diagnosis with accurate molecular test targeting the cause of cervical pre-cancer, had to fail. Another challenge was the selection of HPV DNA tests targeting many HPV DNA types not able to separate between transient and transforming infection. This caused another verification bias creating a lot of positive results from HPV DNA infections that did not cause transforming infection of true cervical pre-cancer. A third challenge include the use of gold-standard histology done on tissue that was not representative for the whole risk area of the cervix. This also produced another bias when possible accurate molecular test targeting the cause of disease was evaluated. The bias or noise from morphological methods are included or have to be included, in most studies that involve validation of new molecular methods. Therefore, it has been nearly impossible to perform studies and present data, using objective and very accurate molecular methods, without verification bias. The cause of cervical pre-cancer or severe neoplasia/dysplasia is identified based on accurate analytical performance, but cannot and should not always confirm subjective morphological diagnosis. This may be the main reason for confusions involved when opinion leaders worldwide discuss screening strategies in order to improve primary screening of cervical cancer. The use of the suggested gold standard method presented in this review used in a primary screening setting, would give a direct same day follow-up treatment based on accurate identification of the cause of pre-cancer. The methods discussed in this review are used for direct detection of cervical pre-cancer. The methods are based on the direct identification of E6/E7 abnormal modified mRNA (include human RNA sequences) from the carcinogenic methods directly on extracted mRNA from collected cervical cells. A standardized method that is able to fulfill this demand are PreTect HPV mRNA products (PreTect AS, Klokkarstua, Norway).23,24 The combined name used in this review is E6/E7 mRNA technology.

The true invasive potential for CIN3 is in fact smaller than 50% according to 30 years follow-up of CIN3, studies done by McCredie and colleagues.45,46 Histology is the gold standard morphological method to detect CIN3 but not persistent CIN3. On the other hand, mRNA tests are based on an oncological biomarker profile indicating the presence of pre-cancerous lesions by a high positive predictive value,37,47-49 even though it cannot directly confirm persistent pre-cancer (Figures 1 and 2). Likely, the female immune system will remove more than 50% of these severe neoplasia or severe oncogene expression before it become an invasive cancer (Figure 1). Therefore, methods directly targeting oncogene activity and not only a risk, should have a clinical sensitivity between 50-70% against CIN2+ and not higher. The high positive predictive value demonstrated by the E6 mRNA technology makes it possible for clinicians to use this method exclusively when deciding which women should be treated to avoid progression towards invasive cervical cancer.41,50,51 E6/E7 mRNA technology identifies the presence of the well-known oncogenic activity involved in the cervical cancer carcinogenesis. HPV DNA based PCR methods are only targeting small fragments of the HPV DNA and they do not distinguish between transforming and transient infections (Figures 1 and 2). The HPV DNA based PCR methods may not distinguish between the driver and the passenger HPV’s with regards to the viral type. Therefore, Matsuura and Sugase concluded that only the seven HPV types (Type 16, 18, 31, 33, 35, 52 and 67) may be the true carcinogenic types.52 HPV 31, 33, 35, 52 and 67 may be highly prevalent in female populations, diagnosed to be cytological normal or histological CIN2+. However, when women with invasive cer-
Cervical cancer are evaluated for HPV types by PCR in countries with high prevalence of e.g. HPV 35,52 or 66 in the normal population, the prevalence of the same types are dramatically reduced or gone in women with true invasive cancer.\textsuperscript{53,54} It means that even among these seven carcinogenic HPV types there may be transforming infections that is not involved in driving carcinogenic process all the whole way from CIN2+ cases into invasive cervical cancer (Figure 1).\textsuperscript{55}

**Short introduction to morphological methods for national screening of cervical cancer**

Cervical smears or epithelial cells from the transformation zone are normally collected by a gynecologist or a physician using different kinds of brush or swabs. However, nurse or normal health personal also collects more and more samples and self-sampling equipment has been introduced to the market (CRN). Most of the swabs used for this collection have not been developed for this purpose. However, several of the brush types have been developed for better collection of cells from the cervix area.\textsuperscript{56,57} Evaluation of cervical cytology accuracy the initial few screening studies were unaffected by workup bias, but few provided estimates of the specificity and sensitivity of Pap smear screening as 97 to 100 and 29 to 56 percent respectively, indicating much lower sensitivity estimates.
than those generally believed to be true.

After a collection of the cells have been transferred to a microscope glass, conventional techniques or liquid based techniques are used. The cell smear that has been prepared is examined through a microscope using what we call a morphological examination or cytology. The cell smear may also be examined using automatic image analyses. The evaluation is typically following the recommendations from Bethesda, with more or less defined matrix or cell morphology given the diagnosis: ASCUS-L, LSIL, ASCUS-H, AGUS, MSIL, HSIL and Cancer. Normally, there are many more kinds of defined diagnosis that may be used. ASCUS and LSIL normally have to be repeated until a normal diagnosis or ASCUS-H, AGUS, MSIL or HSIL are discovered.

When HSIL or ASCUS-H is discovered by a cytologist, the gynecologist normally takes 4 biopsies from the transformation zone following guidelines from a colposcopy. The biopsies are sent to the pathological department fixed by formaldehyde or some other fixative. Thin sections of the tissue are placed on an object glass and stained before the pathologist is performing histological diagnosis: CIN0, CIN1, CIN2, CIN3, Cancer In-situ and Invasive Cancer. Following examination, many more kinds of defined diagnosis may normally be given by pathologists. Anything similar to CIN2 or more severe are than sent to the gynecology oncologists for treatment including LEEP or LETZ conization.

Short introduction to the molecular methods for national screening of cervical cancer

There are many molecular methods and in particular many commercial molecular methods available for detection of HPV DNA, p16INK4a or similar markers. There are also some few commercial molecular methods that identify E6/E7 proteins or mRNA. Some in-situ methods are also available. The main HPV assays may be divided into target amplification methods including consensus or type-specific primers, HPV mRNA amplification including E6/E7 targeting primer-sets and probes or signal amplification methods. The main commercial HPV assays are: The hybridization full genome method HC2 including CareHPV test (High-risk types not type-differentiating; Qiagen, Gaithersburg), The PCR L1 based method Amplicor HPV test (High-risk types and not type-differentiating; Roche, Branchburg), The hybridization L1 based Cervista HPV HR test (High-risk types not type differentiating; Hologic, Madison), the reverse line-blot hybridization on PCR products L1 based CLART test (Differentiate 13 or more high-risk types; Genomica, Coslada), the reverse line-blot hybridization on PCR products L1 based INNO-LiPa HPV Genotyping (Differentiate 13 or more high-risk types; Innogenetics, Gant), the reverse line-blot hybridization on PCR products L1 based Linear Array HPV Genotyping test (Differentiate 13 or more high-risk types; Roche, Branchburg), the reverse line-blot hybridization on PCR products L1 based E1 based Infiniti HPV-HR QUAD test (Differentiate 13 or more high-risk types; Digene, Hilden), microarray on PCR products E1 based PapilloCheck (Differentiate 13 or more high-risk types; Greiner Bio-one, Frickenhausen), hybridization Cervista HPV16/17 also targets E6 and E7 test (Hologic, Madison), real-time PCR COBAS 4800 HPV test (specific genotyping information for HPV types 16 and 18, while concurrently detecting 12 other high-risk HPV genotypes as a pooled results; Roche, Pleasanton), real-time PCR Real Time High Risk (HR) HPV test (Differentiate 14 high-risk types with current distinction of HPV-16 and HPV-18 from 12 other HPV genotypes; Abbott, Des Plaines), transcription mediated amplifica-

Figure 2. Description of cervical carcinogenesis with HPV infection or persistent oncogene expression.
tion APTIMA HPV (AHPV) ASSAY targeting E6/E7 mRNA (14 high-risk types as a group, not type differentiating; Hologic, San Diego, Madison), transcription mediated amplification AHPV-GT assay targeting E6/E7 mRNA (type-specific detection of HPV type 16 and for combined detection of HPV types 18 and 45; Hologic, San Diego, Madison), real-time Nucleic Acid Sequence Based Amplification (NASBA) E6/E7 mRNA based PreTect HPV-Proofer assay detecting E6/E7 mRNA (type-specific differentiation of HPV 16, 18, 31, 33 and 45 including human mRNA control detection; PreTect AS, Klokkarstua), real-time Nucleic Acid Sequence Based Amplification (NASBA) E6/E7 mRNA based PreTect SEE assay (type-specific differentiation of HPV 16, 18 and 45 including human mRNA control detection; PreTect AS, Klokkarstua).

The main challenge with nearly all the commercial HPV DNA detection methods is the dependency of the consensus primer. These consensus primer-sets have a lower analytical sensitivity compared to a direct typing real-time PCR method (Figure 3). Due to the low analytical sensitivity of these consensus primer-sets, the analytical sensitivity of these PCR methods may not be higher than HC2 or other similar hybridization methods. This may cause a problem when large numbers of histological or cytological normal samples are analyzed. Another challenge for the consensus primer’s used in PCR is the lack of analytical specificity. Therefore, consensus PCR done in samples with two or more infections may completely miss one or two of the types due to the combination of low analytical sensitivity and specificity. Even a rather high number of HPV 16 (14-40%) or invasive cervical cancer cases (19%) may be missed due to this challenge.

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with the AHPV technology is the detection of HPV E6/E7 DNA in addition to HPV E6/E7 mRNA. According to the Getman and colleagues that has developed this AHPV technology, the AHPV or the AHPV-GT will detect all HPV DNA copies in cervical samples containing 600,000 or one million Siha like cancer cells. According to experienced cytologists (personal communication), normal cytological samples collected from women in a screening program contain between 1-10 million cells. Therefore, the AHPV-GT technology will detect HPV E6/E7 DNA in the same way as HPV E6/E7 mRNA in typical female screening population.

In the next generation of commercial methods envisage provide same day sampling, diagnosis and treatment in addition to more conventional physician-gynecologist-cytologist-labtest-oncologist road. This kind of same day services are normally called point-of-care diagnosis and treatment.

The rest of the document discuss the key characteristics of the E6/E7 mRNA technology and the role of oncogene expression from abnormal HPV genomes as the cause of cervical pre-cancer, the main cause of cervical cancer, and the basis for the assessment of E6/E7 mRNA and E6/E7 oncogenic proteins in the cervical mucosa. In addition, a high number of peer-review articles and clinical data are available that supports or evaluate the use of PreTect HPV mRNA products in the diagnostics of pre-cancer lesions and cervical cancer.

### Key biological properties of the E6/E7 mRNA technology

#### Introduction and summary

The main HPV assays may be divided into target amplification methods including consensus or type-specific primers, HPV mRNA amplification including E6/E7 targeting primer-sets and probes or signal amplification methods. The first standardized E6/E7 mRNA method detects the presence of E6 and E7 proteins following the expression of abnormal E6/E7 mRNA from the five carcinogenic HPV types. The E6/E7 mRNA method detects an abnormal presence of E6/E7 mRNA in the cervical mucosa samples that has been shown to be related to the loss of transcriptional regulation (discussed below). This has been documented in more than 5000 international peer-review articles (Pubmed Search) since 1985 giving the following key properties of the E6 and E7 proteins:

1. **The E6 protein from carcinogenic HPV (but not from none-carcinogenic HPV)** produce three nuclear localization signals making it operational both in cytoplasm and in the nucleus
2. **The expression of the E6 protein alone immortalize several human cells**
3. **E6 activate vascular endothelial growth factor promoter and fibroblast growth factor –binding protein mediating angiogenesis**
4. **E6 induce over-expression of 16ink4a and p27kip1 to enter S phase (only in carcinogenic HPV types)**
5. **Both E6 and E7 cause via anaphase bridges telomerase activity and chromosomal instability**
6. **E6 from the carcinogenic HPV types inhibits onco-suppressive functions of p53 thereby preventing cell cycles arrest or apoptosis induction. E6 can compete with p53, repress p53 and inhibit p53 translocation**
7. **E6 degrade p53 together with ubiquitin ligase, E6-AP and together with E6-AP the E6 protein bind to several kinases of the SRC family**
8. **E6 is involved in the deregulation of transcription and DNA replication**
9. **Carcinogenic E6 protein binds to PDZ motifs causing regulation of cell adhesion, apicobasal polarity, and proliferation. This binding also causes unblocking of bDig/APC tumor suppressor functions**
10. **E6 binds to interferon regulatory factor, calcium-binding protein E6-BP. E6 inhibit insulin signaling, Jak-STAT pathway and p63 pathway**

Clinical experience indicates that any malignant growth is preceded by specific pre-cancer or pre-cancerous lesions (Figure 3). Dysplasia became one of the key morphological criteria of the concept of pre-cancer. The term dysplasia became widespread in both practical morphology and therapy. In the cervical epithelium, dysplasia is characterized by abnormal cell composition and architecture. The cells become heteromorphic demonstrated with wide variation in the size and shape. The nuclei become hyperchromatic and oversized relative to the normal nuclei. This phenomenon is called dyskaryosis. The number of mitotic figures increases and they are found in unusual sites of the epithelial layer. In cervical dysplasia, mitoses can be detected in any (including surface) layer of the multilayered epithelium as against basal cells only in the norm. However, atypical mitoses are not commonly observed. Dysplasia is also characterized by abnormal architecture as a loss of the normal epithelial structure, polarity, and sometimes histotypic or organotypic pattern: the vertical anisomorphism of cells is lost in the multilayered squamous epithelium and the layer is replaced with basal cells instead of progressive differentiation of the basal elements into squamous cells (Kos’s diagnostics Cytology). Strong evidence has shown that E6 and E7 proteins cause abnormal cellular changes on the molecular level which may or may not correlate with morphological dysplasia or neoplasia criteria of the concept of pre-cancer. A study performed in Africa, which included histology...
and cytology from all the women, showed that more than 50% of the histological negative women still had expression of E6/E7 mRNA.\(^37\) However, all clinical studies always include a rather high number of HPV DNA or RNA positive cases without any morphological positive diagnosis. The papillomavirus type DNA may be present in a clinical sample with dysplasia, neoplasia or CIN2+ without being the cause of further on-going pre-cancer or persistent CIN2+ or invasive cancer.\(^52\) This means that HPV 52, HPV 35 or HPV 31 may be present in a clinical sample claimed by morphological analyses to have pre-cancer but may never cause persist oncogenic expression until presence of invasive cervical cancer. The detection of HPV DNA by PCR in clinical samples with neoplasia or dysplasia morphology not able to progress into persistent CIN2+ or invasive cervical cancer, may cause too many false-positives within a typical nationwide screening set or program.

**Definition of and comparison between CIN and Presence of E6/E7 mRNA expression as detected using pathological methods or E6/E7 mRNA technology**

Definition of Cervical Intraepithelial Neoplasia (CIN): All precancerous intraepithelial abnormalities of the uterine cervix that are capable of progression to invasive cancer, albeit with a low frequency for the better differentiated (low-grade) lesions and a higher frequency for poorly differentiated (high-grade) lesions.\(^147-151\)

Definition of Presence of E6/E7 mRNA expression in cervical mucosa: Precancerous abnormalities are present in the uterine cervix that is capable of progression to invasive cancer.

**Similarities** between pathology and E6/E7 mRNA technology: i) Both can identify abnormal cervical cells; ii) Both can identify cervical pre-cancer; iii) Both are related to hyperchromatic and oversized nuclei relative to the normal nuclei; iv) Both identify mitosis.

**Differences** between pathology and E6/E7 mRNA technology: i) E6/E7 mRNA technology cannot identify the location of the oncogene expression in the epithelial cell layers; ii) More than one morphological lesion will often be present making diagnosis very subjective. The E6 and E7 is present or not present and the difference is not subjective.\(^40,44\) iii) E6/E7 mRNA technology may be optimal for detection of molecular oncology in completely normal samples, while morphological methods may be dependent upon the collection of biopsies in order to detect any oncological activity.\(^17,40\) iv) Morphological methods are dependent on subjective counting of number of cell abnormalities (Koss’s Diagnostic Cytology). E6/E7 mRNA technology may only be used as a qualitative method;\(^40,152\) v) 250 different kinds of morphological diagnoses have been observed by histological examination. Many different kinds of morphological diagnosis have also been observed by cytological examination. Molecular diagnosis is either positive or negative and there is now room for questions;\(^11,12,153\) vi) E6/E7 mRNA technology has undergone complete performance evaluation showing robustness, sensitivity and specificity.\(^38,40\) Cytology can undergo complete performance control but only against another morphological methods. The typical high number of ASCUS/LSIL cases including a number of undefined diagnosis definitions may cause problems when cytology is correlated with the type-specific PCR or the E6/E7 mRNA technology; vii) More than 70% of the following morphological diagnosis may be negative with E6 mRNA technology: ASCUS, hyperplasia, metaplasia, condyloma, HPV-changes, LSIL or CIN1 diagnosis;\(^42,144,152,154\) viii) More than half of the cases with moderate cervical intraepithelial neoplasia are always negative with E6 mRNA Technology.\(^154,155\) It means that it is difficult to understand how cells with neoplasia and dysplasia that do not supporting expression of E6/E7 mRNA is able to progress to invasive cervical cancer.

**Function and importance of the different E6/E7 mRNA transcripts and their expression**

**Function and importance of the different E6/E7 mRNA transcripts**

HPV E6 and E7 expression is primarily regulated at the transcriptional or post-transcriptional level. For example, for HPV 16, the E6 Open Reading Frame (ORF) encodes at least three distinct variants of the E6 protein, which all may have different roles in the viral life cycle. These transcripts are either unspliced (full-length E6-E7 transcript) or spliced transcripts: E6*I is spliced from nucleotide 226 to 409 and E6*II from nucleotide 226 to 526, all being transcribed from the p97 promoter.\(^27\) The detection of HPV 16 E6*I/E6*II representing the way the RT-PCR can detect the full-length transcript may serve to identify transcription patterns indicative of cervical disease progression and help physicians to decide clinical management.\(^34\) Taken together, these studies point to the full-length transcript as being the transcript important for the carcinogenic process.

The importance of E6/E7 mRNA expression

The role of E6/E7 mRNA expression in the natural lifecycle of human papillomavirus is very clear:

In a normal HPV infection at the lower layers of the cervical epithelium, the E6/E7 transcripts or full-length transcripts are transcribed from the p97 promoter. However, when the infected cells move up to the surface (terminal differentiation) of the cervical epithelium the p97 promoter will be more and more down regulated and finally turn off. Therefore, the transcripts that are transcribed from this promoter in cells with normal HPV infections cannot be detected in the upper layers of the stratified squamous epithelium.\(^141\) With other words: This totally turn off the transcription of E6 and E7 mRNA in the upper layers of the stratified squamous epithelia (The upper part of the spinous layer, the granular layer and the cornified layer).\(^123\) A normal papillomavirus infection regulate down the p97 promoter in order to increase the transcription from the p670 promoter preparing the ground for viral particle production. During the terminal differentiation an increased level of E1 and E2 are produced turning down the activity of the p97 switching to the p670. The p670 promoter produces transcripts that are spliced out in order to preferential expression L1/L2 transcripts and proteins.\(^58\) The viral early promoter, which controls E6 and E7 expression, is thought to be constitutively active during differentiation (in the lower parts of epithelia) in order to maintain the cells in a “pseudo” S phase state necessary for high-level replication of
viral episome. In cervical pre-cancer cases (without normal HPV infection) this regulation and the regulation of mRNA splicing is lost and all cells coming to the cornified layer will be transcribe from the p97 promoter giving full-length E6 transcripts in addition to different variants as well as full-length E6 and E7 proteins.

Therefore, the detecting of E6/E7 mRNA in the cervical mucosa tells us the following (Figure 1): i) Something is wrong with the normal HPV life cycle; ii) There must be a lack of transcriptional control; iii) This lack of transcriptional control is most likely related to integration of HPV by deletion of whole or parts of the E1 and E2 genes; iv) The splicing of HPV mRNA is probably not regulated anymore giving a possible stable production of full-length E6 mRNA as well as full-length E6 proteins. This is in particular the case detected by the HPV 16 primer-sets and probes, walking over the area between the E6 and E7 genes, that can only detect full-length HPV 16 E6/E7 mRNA; v) Stable expression of E6/E7 mRNA giving stable expression of E7 and full-length E6 proteins is by a molecular oncological definition, the cause of cervical pre-cancer (First Author definition); vi) Stable expression of E6/E7 mRNA giving stable expression of E7 and full-length E6 proteins is also the main cause of invasive cervical cancer and metastasis; vii) The only possible cure of this irreversible lack of regulation and uncontrolled oncogene activity is the removal of the pre-cancer cells by treatment or by the natural immune system.

This should be a strong indication that E6/E7 cannot be detected in factual normal smear samples. In fact, we have at least two studies showing that the E6/E7 expression is totally absent in factual CIN1 cases diagnosed by a panel of experienced pathologists.

One option is the level of E6/E7 mRNA expression. In samples with a malignant progression the loss of regulation of E6/E7 protein or mRNA expression due to integration or instability is the real problem, proved in a high number of scientific studies. Loss of regulation may not give different defined levels of mRNA expression that correlate with different level of malignancy detected or different stages of carcinogenesis. We believe that integration or loss of regulation is resulting in any level of expression throughout the stratified squamous epithelial, and is visible on the surface of the epithelium following the differentiation. Even a very low level of mRNA expression will cause high production of full-length E6 and E7 proteins. We do not know about any method that always detects a level less than 20 mRNA copies per cell, when the method is positive in a routine screening setting. The E6/E7 mRNA technology has documented a PPV for CIN2+ higher than 50% in clinical studies even with strong bias from cytology or histology. This indicates that it is very likely that E6/E7 mRNA technology when positive is detecting underlying pre-cancer in the majority of cases. This also indicates that assays (typical HPV DNA assay’s) detecting more than 70-80%, positivity rate (or sensitivity) towards CIN2+ cases will have an increased level of false positive or may not reflect the true oncological state of the lesion.

Evaluation of different transcripts from HPV 16 discovered in clinical samples

Design of E6/E7 mRNA technology

The E6/E7 mRNA technology detects the presence of E6 and E7 proteins following the expression of abnormal E6/E7 mRNA from the five carcinogenic HPV types. E6/E7 mRNA technology detects an abnormal presence of E6/E7 mRNA in the cervical mucosa samples that has been shown to be related to the loss of transcriptional regulation (discussed below). Normally human papillomaviruses do not express the E6/E7 mRNA in the three upper layers of the epithelium. It is only when something goes wrong with the human papillomavirus that it is able to express E6/E7 mRNA in the upper layer of epithelial cells. It is only these kinds of infections that is defined as transforming infection and will be persistent transforming infection if the human immune system is not able to remove the transformed cells.

Design of the primer-set and probes

The sequences and positions of the primers and molecular beacons within the E6/E7 sequences and targets are patented but it is still all business secrets. However, the discussion below presents evidence related to the selection of correct transcripts for optimal cervical cancer screening. As a positive reaction control for the different primer-sets, artificial oligos were designed based on the primer and probe sequences.

HPV 16 transcripts in relation to the physical state of HPV in SCC

Karlsen and Molden (not published) were also interested in the aspect of transcript patterns in relation to the physical state of HPV in SCC determined by in situ hybridization (ISH). The physical state of HPV identified as viral integration (I) (n=50) or as viral integration/episomal (I/E) (n=64) has been described previously.161 In addition, two samples were not positive for HPV 16 DNA by ISH. The transcripts detected by the use of primer-set E6/E7 (E6/E7 mRNA technology), E6*I/II, and E1 are present in almost all the SCCs, integrated as well as integrated together with epimodal states of the virus. The transcripts detected by the use of the E2 primer-set, was detected in 72% of the lesions where the virus was found to be integrated in the human genome, while it was detected in 97% of the lesions which contained both integrated and episomal forms of the virus. The E1*E4*L1 and E1*E4E5 transcripts were detected in roughly half the SCCs with only integrated viral DNA in contrast to nearly all SCC with episomal DNA as well and hence support the current understanding about disruption within the E2 gene region upon viral integration in SCCs.162 We would not expect to detect these transcripts when integration has occurred in the E1-E2 gene region.162 However, we cannot be sure that these samples are not containing small amounts of episomal forms of DNA as well, due potential lack of analytical sensitivity by the ISH method.

Cellular aspects of tumor progression

Precancerous and early cancerous lesions are of clear interest. Clinical experience indicates that any malignant growth is
preceded by specific changes. However, there is no common view of ‘precancer’; some propose a narrow definition, while others tend to broaden it. Finally, in addition to the concept of cancer progressive development, the concept of its de novo development exists. Dysplasia became one of the key morphological criteria of this concept. This term became widespread in both practical morphology and therapy. At the same time, the limits of the term are getting more and more fuzzy, which necessitates the definition of ‘dysplasia’. Metaplasia is the replacement of one distinctive tissue with another one that differs morphologically and functionally. During metaplasia, the epithelium loses the organotypic form and function, while the histotypic type and function are preserved. These changes in tissue differentiation rely on pluripotent basal cells, which are sources of any epithelium development. Morphological evaluation of metaplastic changes should consider not only the histotypic and structural properties, but also the cytological properties of tissue elements. Dysplasia is an abnormal differentiation giving rise to cells with pathological properties. Metaplasia and dysplasia can develop independently; however, it is very important that dysplasia can develop on the background of metaplasia. The relationships between metaplasia, atypical hyperplasia, and dysplasia remain controversial, which leads to terminological confusion and complicates the interpretation of data. Dysplasia should be considered only as controlled and reversible precancerous abnormalities of epithelial differentiation resulting from the proliferation of cambial elements (undifferentiated pluripotent cells of the basal layer) to atypical cells with no polarity and affected histological structure without the membrane invasion. In the cervical epithelium, dysplasia is characterized by abnormal cell composition and architectonics. The cells become heteromorphic and demonstrate wide variation in the size and shape. The nuclei become hyperchromatic and oversized relative to the normal nuclei. This phenomenon is called dyskaryosis. The number of mitotic figures increases and they are found in unusual sites of the epithelial layer. In cervical dysplasia, mitoses can be detected in any (including surface) layer of the multilayered epithelium as against basal cells only in the norm. However, atypical mitoses are not commonly observed. Dysplasia is also characterized by abnormal architectonics as a loss of the normal epithelial structure, polarity, and sometimes histotypic or organotypic pattern: the vertical anisomorphy of cells is lost in the multilayered squamous epithelium and the layer is replaced with basal cells instead of progressive differentiation of the basal elements into squamous cells. Dysplasia of the cervical multilayered squamous epithelium features limited numbers of proliferation foci with affected vertical anisomorphy of cells in the layer, basal cell hyperplasia, nuclear polymorphism and hyperchromatism, enlarged nuclei, higher nuclear/cytoplasmatic ratio, hyper- and parakeratotic lesions, and high mitotic activity. At the same time, the pathological elements to different extents replace the epithelial layer usually not reaching the surface layers. Different stages (grades) of dysplasia are recognized according to the degree of epithelial proliferation and structural and cellular atypia, affecting the cell organization. The most significant morphological features of dysplasia include nuclei polymorphism and abnormal mitoses. The limits between different grades of dysplasia and preinvasive cancer or sometimes invasive cancer are not always clearly defined by morphological analysis. Adequate identification of dysplasia and its grade is of principal clinical significance and largely determines the risk of malignant transformation and treatment approach. The probability of malignant transformation of the regenerating, hyperplastic, or metaplastic epithelium is low. The risk of transformation increases in the case of dysplasia, and severe dysplasia demonstrating cellular changes similar to cancerous ones appears to correspond to the highest risk. The progress of the recent years in studying cervical carcinogenesis is primarily due to the elucidation of the role of papillomaviruses. The integration event invariably results in the expression of two viral proteins, E6 and E7. These two proteins are capable of transforming cells individually and cooperate to immortalize primary human epithelial cells. In vitro tissue culture studies indicate that HPV E6 and E7 are oncogenes, and that their oncogenicity is due in part to their capacity to inactivate cellular tumor suppressor genes. The behavior of E6 and E7 in vitro and the genetic evidence from analysis of human cancers suggest that the E6 and E7 genes play a significant role in the development of cervical cancer. Aneuploidy, the most frequent form of genomic instability in human carcinomas, develops as early as in nonmalignant cervical precursor lesions. In addition, cervical neoplasia is frequently associated with abnormal multipolar mitotic figures, suggesting disturbances of the cell-division process as a mechanism for chromosome segregation defects. Spindle poles are formed by centrosomes, and the high-risk HPV E6 and E7 oncoproteins can each induce abnormal centrosome numbers. These two HPV oncoproteins, however, induce centrosome abnormalities through fundamentally different mechanisms and, presumably, with different functional consequences. High-risk HPV E7, which targets the pRB tumor suppressor pathway, can provoke abnormal centrosome duplication in phenotypically normal cells. On the contrary, cells expressing the HPV E6 oncoprotein, which inactivates p53, accumulate abnormal numbers of centrosomes in parallel with multinucleation and nuclear atypia. These two pathways are not mutually exclusive, since co-expression of HPV E6 and E7 has synergistic effects on centrosome abnormalities and chromosomal instability. Taken together, these findings support the general model in which chromosomal instability arises as a direct consequence of oncogenic insults and can develop at early stages of tumor progression. In summary E6-E7 gene products submerge control of the cell cycle and mitotic spindle pole formation through complex interactions with various cellular protein complexes and induce severe chromosomal instability. The E6 and E7 activity should therefore not cause normal differentiation, morphology, metaplasia, hyperplasia or atypical hyperplasia. The activity of other markers like Ki67, p14 or p16 may cause metaplasia, hyperplasia or atypical hyperplasia. However, the activity of E6/E7 should cause nuclear polymorphism, nuclear hyperchromatism, enlarged nucleic, cellular atypia, abnormal cell organization, abnormal epithelium organization, higher nuclear/cytoplasmatic ratio, hyper- and parakeratotic lesions, high mitotic activity and abnormal mitoses. In fact, these kind of changes should very much be linked to the typical definition of severe dysplasia or severe dyskaryosis and should cover broad range of cervical pre-cancer behavior and characteristics. Cells having this kind of E6/E7 activity can only be removed by the immune system or by surgery. The very presence of E6/E7 mRNA in the mucosa or in cells collected at the upper epithelium layer is linked to integration of the carcinogenic HPV and loss of E6/E7 expression regulation including ongoing activity from promoter p97. It is logical that no presence of E6/E7 mRNA in the upper epithelium layer or in the mucosa would not cause any translation of the E6 and E7 proteins, making the presence of cellular abnormalities unlikely. It is quite obvious that both the E6/E7 full-length mRNA and the E6 and E7 proteins are involved in the cervical carcinogenesis and therefore are the main cause and engine behind invasive cervical cancer.
The potential of E6/E7 mRNA technology for national screening of cervical cancer

Some possible definitions

There is no doubt that colposcopy, histology and cytology has been very valuable morphological examination methods in order to define cervical dysplasia, neoplasia, pre-cancer, cancer in-situ and invasive cancer. However, many studies have shown that subjective morphological examination even including automatic or manual image analyses are disturbed by the complexity of a cell smear or a tissue including thousands of different matrices, networks, structures caused by millions of different cells. The results are that national cancer registry may operate with more than 250 kinds of different histological or cytological diagnosis given by very different pathologists before it is sorted into more Bethesda like defined diagnosis.12-14,193

HPV DNA based amplification and detection methods have increased the possibility to detect any potential pre-cancer like morphology, even though these methods is not able to separate between natural HPV infection and transforming/carcinogenic HPV infection. Natural HPV infections are not directly related to the development or the presence of cervical pre-cancer. Therefore, the HPV DNA methods detecting 14 or more HPV types containing mostly natural HPV infections, make many more women positive than the cytological method, making many more unnecessary women the idea that they may have cervical pre-cancer. It is obvious that even the detection of natural HPV 16 or 18 infection, is not the same as the detection of a cervical pre-cancer causing, is also producing false-positives. Only using cytology as the national screening test in Norway produced 17000 women every year with a not relevant risk of developing cervical cancer (The Norwegian Cancer Registry). The repeat use of a very sensitive HPV DNA method mostly detecting natural HPV infection, have to increase the number of women with not relevant positive diagnosis without any transforming/carcinogenic HPV infection.

An ideal gold standard method for the identification of cervical pre-cancer or cancer may be defined with the following number of properties: i) The method must identify the cause of the disease and not a risk of the disease. ii) The method must identify the true pre-cancer or neoplasia that progress to invasive cervical cancer if the immune system is not working. iii) The method must create a minimum number of false positives and negatives. iv) The method must give a simple yes or no conclusive diagnosis with highest possible analytical performance (in order to be used in national screening settings). v) The method should be able to be used in a national screening setting that causes the highest possible coverage rate. vi) The sample collection method used related to the method should be possible to be done by normal health personal or the woman herself. vii) The method must be accurate enough to cause the same day treatment.

How these properties are working related to different screening strategies are discussed below.

1. Morphological examinations are not able to identify the cause of the disease but maybe the results of a disease. Morphological methods may miss more than 50% of invasive cervical cancer. The HPV DNA methods cannot identify the cause but only the risk of developing the disease. Many enough false-positives detected by the HPV DNA increase the likelihood of detecting invasive cervical cancer. However, the first time HPV DNA methods is used it is not able to detect more than 90% of the women with invasive cervical cancer. The PreTect HPV mRNA product, PreTect HPV-Proofer identifies the cause of cervical pre-cancer and the main cause of invasive cervical cancer. The detection of similar or more numbers of invasive cervical cancer cases than a typical consensus PCR or Hybridization method targeting only five HPV types compared with 14 or more HPV-types, teach that PreTect HPV-Proofer identifies more specific cancer markers (Table 1). It also teaches that the standard DNA methods use a lot of biomarkers that is not related to the main cause of invasive cervical cancer. Table 1 also confirm that it is very likely that PreTect HPV-Proofer detect the real disease markers with very few false negatives making it very likely that the PreTect HPV-Proofer detect the cause of cervical pre-cancer.

2. Morphological examinations are not able to identify the true pre-cancer or neoplasia disease directly making it necessary to repeat the test many times within time intervals.12-14,193 The HPV DNA methods can only identity the presence of an HPV type that may have a risk of developing severe neoplasia or true pre-cancer.194,202 PreTect HPV-Proofer identify the cause of pre-cancer or severe neoplasia and progress to invasive cervical cancer, if the immune system is suppressed.37,41,44 The E6/E7 mRNA technology may detect a minimum number of false negative and positives. The HPV DNA methods always create a high number of false positives but with less false negatives. However, it has been shown by Castle’s research group that some HPV 16, 18 or 45 infections are not detected with the consensus PCR methods.203-205 The E6/E7 mRNA technology may detect a minimum number of false negative and positives. But, because it is difficult to perform a study without verification

Table 1. E6/E7 mRNA technology has similar sensitivity as DNA test against samples positive for Invasive cervical cancer.

<table>
<thead>
<tr>
<th>Study</th>
<th>N.</th>
<th>PreTect HPV-Proofer, %</th>
<th>DNA-tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lie AK et al. (2005) DNA versus RNA based methods for HPV detecting cervical neoplasia. Gyn Oncol Vol 97, Issue 3, June 2005, 508-915</td>
<td>20</td>
<td>100</td>
<td>90% (hc2)</td>
</tr>
<tr>
<td>Basu et al. Human papillomavirus Genotype Distribution in Cervical Cancer in India: Results from a Multi-center study, Asian Pacific J. Cancer, 10, 2009, 27-34.</td>
<td>278 DNA</td>
<td>83</td>
<td>83% (My09/11)</td>
</tr>
<tr>
<td></td>
<td>276 RNA</td>
<td></td>
<td></td>
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</tbody>
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bias and with proper treatment of all PreTect HPV-Proofer positive it is difficult to confirm these minimum numbers. It may be claimed that the E6/E7 mRNA technology may miss some few cancer’s or samples with true pre-cancer cells since it is not detecting HPV 35, 52 or 58 However, it has been proved that morphological and DNA methods may also miss some cancer’s and true pre-cancer cells.

4. Morphological examinations including ASCUS, LSIL or CIN 1 can never produce a simple yes or no conclusion. Most of the morphological methods produce conclusions that just demands coming back for a new evaluation. Even several ASCUS diagnoses may not cause a simple yes or no conclusion. The analytical performance of morphological diagnosis cannot be fully defined. The HPV DNA methods may not come up with a yes or no diagnosis as long as they are not performing type-specific analyses. Including a HPV-DNA type-specific diagnosis it may still not tell the clinicians what to do with HPV 35, 52, 58, 66, 67, 56, etc.

When these HPV types are discovered in Europe it may only contain HPV DNA that do not support stable production of oncogenic E6 and E7. The HPV DNA type-specific diagnosis is not telling the clinicians if this infection is a transforming or transient infection.

5. The use of morphological methods demands large cytological laboratories with intra and inter control quality system connected to a very well-organized national screening system that is able to follow-up all women carefully and repeat the cytological examinations several times. The HPV DNA methods will also create many positive women that have to be followed-up for several times before treatment. The most problematic example is the use of HC2 in China creating a positivity rate of more than 19% in a normal population.

6. Samples collected for morphological methods have to be done by a professional medical person. With the rather large number of self-collected samples methods it has been proved that PCR-based DNA technology methods can be used.

7. Most positive morphological diagnosis cannot be used for direct treatment. The same is the case for all the HPV DNA based results. However, the PreTect technology identify the cause of pre-cancer and have the potential to be used as test and treat.

Recent evaluation and meta-analyses of the accuracy of mRNA tests used in screening settings compared with the definition of diagnostic gold standard

Two studies have evaluated the use of PreTect HPV-Proofer and Nuclisens Easy Q HPV in different studies. Verdoodt and colleagues concluded that the HPV assays for detecting of 5 hrHPV types may reduce the over-diagnosis of women who have minor cytologic abnormalities. However, given the lower sensitivity, women with negative mRNA test results cannot be considered free of CIN2+ and require further surveillance. Orégoni and colleagues (2015) concluded the following: Compared to hrHPV-DNA testing, which actually represents the most validated alternative to cytology in screening settings, mRNA tests present the valuable improvement of a better specificity, and consequently, higher positive predictive value (PPV) towards high-grade cervical lesions (CIN2+).

HPV E6/E7 mRNA testing may serve as a more specific discriminator between transient cervical dysplasia and potentially progressive lesions. According, testing for high-risk HPV E6/E7 mRNA might reduce the psychological burden associated with HPV-DNA testing.

It is very clear that the main engine behind the progression to cervical pre-cancer and invasive cervical cancer is stable expression of E6 and E7 full-length proteins followed by the stable presence of full-length E6/E7 mRNA. It is also very clear that histological defined CIN2+ or cytological HSIL is a typical definition of cervical tissue with severe dysplasia/neoplasia or pre-cancer. However, it is very well known that the female immune system is able to both remove cells with stable expression of E6/E7 proteins and to remove CIN2+ or HSIL like cells from the transformation zone. Very large follow-up studies have shown that 50% of cervical pre-cancer cells may not progress to invasive cervical cancer weather they are defined as CIN2+, HSIL or with E6/E7 expression. Luckily, many women have an immune system that is able to remove these pre-cancer-like cells. The question is whether it is possible to claim that CIN2+ or HSIL like cells without detectable E6/E7 expression is pre-cancer like cells in the same way as cells with E6 and E7 expression without detectable CIN2+ or HSIL like cells. It may be claimed that women with E6/E7 expression from carcinogenic HPV types without detectable CIN2+ or HSIL like cells may have more carcinogenic pre-cancer cells than in women with CIN2+ or HSIL without detectable E6/E7 from the carcinogenic HPV types. The CIN2+ or HSIL diagnosis is a subjective morphological diagnosis that is not covered by any analytical performance evaluation and is very dependent upon how skilled and well experienced the histologists are. In addition, the histological examination is dependent upon a more complex collection of representative biopsies by a medical person and only one or 10 pre-cancer cells may not be enough for making a diagnosis. The molecular test is only dependent upon a simple collection of cervical samples using a Cervex brush. The histological examination does not include an objective control of sample (detection of human mRNA) in the same way as included in the PreTect HPV-mRNA products. Key statistical properties of E6/E7 mRNA technology

E6/E7 mRNA technology detects the presence or absence of E6/E7 mRNA and the active molecular oncogenes (E6 and E7) followed by the expression of E6/E7 mRNA from for the HPV-types 16, 18, 31, 33, and 45 or only HPV-types 16,18 and 45. The key statistical properties of E6/E7 mRNA technology are as follows: i) High positive predictive value towards CIN2+ (30-50%); ii) High sensitivity towards cervical cancer (comparable to HPV-DNA detection methods, typically ≥90%); iii) High specificity in a screening population (comparable or slightly better than cytology).

This chapter gives an overview of these key statistical properties of the E6/E7 mRNA technology and discusses, in addition, the same characteristics of cytology and HPV-DNA testing technologies. The calculations are based on the clinical and scientific documentation, experience and knowledge behind cytology, HPV-DNA and E6/E7 mRNA technologies.

The key statistical properties have to be estimated using three different scenarios in order to evaluate the predictive accuracy.

i) When measuring PPV it is important to focus on pre-cancerous lesions which may be identified or verified by independent technologies such as histology. Although many direct prognostic markers have been identified to date, most of these did not make it into actual clinical decision algorithms. The biomarker has to match the current clinical diagnostic gold standard without any verification bias.

ii) Since only a minority of histologically confirmed CIN2+ progress to invasive cervical cancer, real sensitivity must be measured against invasive cervical cancer. This was also concluded about in the recent study done in USA against...
more than 250,000 women having undergone Pap or HPV DNA testing one year before a colposcopy directed biopsy was evaluated. The conclusion was: Since most CIN3 did not progress to cancer, it is of more concern that approximately 19% of women with biopsy-documented cancer in the study tested negative for HPV.

iii) Specificity indicates the volume of false positives. Since invasive cervical cancer and also pre-cancerous lesions are rare in a population, correct screening program specificity can only be measured in a screening population supposed to be normal.

Negative predictive value (NPV) is a statistical property that is independent of technology due to the low number of annual invasive cervical cancer cases.

Positive predictive value towards CIN2+

In diagnostics, it is important to have a high positive predictive value. In cervical cancer prevention, the different technologies available have quite dissimilar PPV’s for detecting a histologically confirmed CIN2+ condition. The discussion below is based on overview of results from the literature. To be able to estimate the actual incident level of CIN2+ in a population, the sensitivity of cytology towards CIN2+ is important. However, there are very few studies which are properly designed for measuring this sensitivity. Meta-analysis indicates the sensitivity of cytology at about 50%.15,16

PPV of cytology

Cervical cytology is based on a range of different diagnosis, of which the most common ones are normal, ASCUS, LSIL, HSIL, and invasive cervical cancer (ICC). Therefore, the PPV of cytology will, of course, differ depending on the cut-offs used. In the United States about 6%, or about 3.5 million of 55 million yearly Pap smears, are classified as abnormal.16 The majority of these women are referred to colposcopy and biopsy. We have not found documentation on how many women that are treated by conization each year in the United States that are based on identified CIN2+ histology. However, based on numbers from Norway,11,12,14,15 we estimated that less than 1% of the women screened are treated by conization annually. This indicates an overall PPV of less than 17% for cytology (PPV = 1% / 6%

PPV of HPV-DNA testing technologies

HPV-DNA testing technology is acknowledged to have higher sensitivity than cytology, but at the same time finds many more women as positives. Scientific studies indicate that the positivity rate of HPV-DNA testing technology is about 3 times higher than the rate of abnormal cytology in a screening population. Thus, since the rate of abnormal cytology is about 6% in USA it can be expected that about 18% of the women undergoing screening annually will be positive with an HPV-DNA testing technology. The higher sensitivity of HPV-DNA testing technology is estimated to 90-95%,219 resulting in considerably more women being found as histologically confirmed CIN2+ compared to cytology; roughly estimated to 1.9% of the women screened (i.e. 95% of 2%). Many opinion leaders advocate the use of cytology to limit the number of HPV-positive women referred to colposcopy and for collection of biopsies.220 This implies that the estimated sensitivity increase of HPV-DNA testing technologies will be counteracted by the subsequent cytology analysis. These observations indicate an overall PPV of 5% [PPV = (1.9% × 50%) / 18%] for HPV-DNA testing technologies.

Recently, an HPV-mRNA assay has been introduced (APTIMA HPV, Hologic, San Diego, Madison). Published studies indicate that the properties of this assay are quite similar to the HPV-DNA testing technologies already present in the market, with a possible slight reduction in the positivity rate. Since the positivity rate is similar to the HPV-DNA testing technologies, cytology is still needed in order to reduce the number of referrals to colposcopy and biopsy. This implies that this HPV-RNA assay may have similar or possibly a slightly increased PPV compared to HPV-DNA testing technologies. However, there is no evidence that the PPV of this HPV-RNA detection technology will approach the PPV of cytology.

PPV of E6/E7 mRNA technology

Studies show that E6/E7 mRNA technology has a higher sensitivity than cytology and finds a number of positive women that is about 25% less than those found to be abnormal by cytology, i.e. it can be estimated that E6/E7 mRNA technology will be positive in about 4.5% of the women undergoing screening annually in the United States. Based on the sensitivity of cytology in the United States, which is estimated at 50%, and the expected treatment rate of 1% (see paragraph on “PPV of cytology”), we expect that about 2% of the women have an incident underlying CIN2+ abnormality. Since the number of E6/E7 mRNA technology positive women are comparable to the number of women referred to colposcopy and biopsy today, no cytology triage is needed. Thus, the increased sensitivity is not altered by a cytology triage step as is the case for HPV-DNA testing technologies. Studies show that E6/E7 mRNA technology has a sensitivity of 70-80% towards CIN2+. This indicates that about 1.4-1.6% of these women will be found by E6/E7 mRNA technology, indicating a PPV of 31% (PPV = 1.4% / 4.5%). However, existing primary screening studies indicate an even higher PPV of about 50%. One explanation may be that the expected sensitivity of on-time cytology is even less than 50%, probably approaching 30%. It is only repeating cytology than may have a clinical sensitivity high enough to be defended used in national screening services.12

Sensitivity towards cervical cancer in screening algorithms

The aims of all cervical cancer screening programs are to reduce the incident of invasive cervical cancer and at the same time reduce the number of deaths caused by invasive cervical cancer. Since the disease is invasive cervical cancer, all preventive diagnostics, should first of all be evaluated towards confirmed invasive cervical cancer cases.

Traditionally the cervical cancer prevention programs have transformed the main aims into the pseudo endpoint of detecting pre-cancerous lesions defined as histologically confirmed CIN2+. However, previous and recent studies have shown that only very few CIN2 cases will ever develop into invasive cervical cancer and that only 30% of the CIN3 cases will ever develop into invasive cervical cancer.45,46 Since almost all CIN2+ cases are treated there is today a huge overtreatment in connection with existing screening programs. This overtreatment does not contribute to the above-mentioned main aims of the cervical cancer prevention programs.

Since only a minority of the histologically confirmed CIN2+ cases progress to invasive cervical cancer, it is obvious that at any time a significant proportion of these cases are regressing to a normal condition. If all CIN2+ cases would eventually develop into invasive cervical cancer, diagnostic sensitivity could be measured towards this pseudo endpoint. Since this obviously is not the case, it is not correct to measure diagnostic sensitivity towards CIN2+. Therefore, diagnostic sensitivity must be measured towards the real disease which is invasive cervical cancer. It is the sensitivity towards invasive cervical cancer which is the basis for estimating the effect of applying different diagnostic technologies in the cervical cancer prevention programs. We
are aware that most professionals measure diagnostic sensitivity towards the pseudo endpoint of histologically confirmed CIN2+. For diagnostic tests with a sensitivity of 90-95% towards CIN2+ (e.g. HPV-DNA testing technologies) this distinction is less important than for diagnostic tests having less sensitivity towards CIN2+. Since most scientists have investigated the properties of HPV-DNA testing technologies having high sensitivity towards CIN2+, the distinction between sensitivity towards CIN2+ and cervical cancer has so far been ignored, also in the United States. We believe it is now utterly important to measure true diagnostic sensitivity in the correct way by investigating the sensitivity of different technologies towards invasive cervical cancer.

**Sensitivity of cytology**

Several reports estimating the sensitivity of cytology towards invasive cervical cancer have been published during the last decades. Most of them focus on the sensitivity towards CIN2+ indicating a sensitivity of about 50% (see section ‘Positive predictive value towards CIN2+’). Several authors presume that existing screening programs using cytology have reduced the incidence of invasive cervical cancer by about 70%. This presumption is the same for both United States and for Norway, but has inherent uncertainties since the situation today is compared to the situation 30-50 years ago not taking into the account the dramatic change in lifestyle during this period. It is also impossible to study the rate of invasive cervical cancer and corresponding deaths in today’s society without preventive measures such as cytology.

The high-quality databases of the Norwegian Cancer Registry support the theory that cytology has a rather low sensitivity towards invasive cervical cancer. It is documented that 40-50% of women developing invasive cervical cancer (within the screening program) have a satisfactory screening history. About 80% of the women developing invasive cervical cancer have one or more Pap smears during the preceding 24 months. For these women cytology did not prevent cervical cancer. These facts support the assumption that the sensitivity of cytology is between 20 and 50%.

**Sensitivity of HPV-DNA testing technologies**

There are many studies using HPV-DNA testing technologies on invasive cervical cancer cases. Based on meta-analysis published by IARC the overall sensitivity is about 85%. However, recent studies comparing HPV-DNA testing technologies with E6/E7 mRNA technology indicate an overall sensitivity of about 90%. As mentioned above, many opinion leaders advocate the use of cytology to limit the number of HPV-positive women referred to colposcopy and for collection of biopsies. This implies that the estimated sensitivity of HPV-DNA testing technologies will be counteracted by the subsequent cytology analysis. In any real-world application of HPV-DNA testing technologies triage with cytology is thus being used reducing the effective sensitivity to the sensitivity of cytology, which is estimated at about 50% (Figure 4).

**Sensitivity of E6/E7 mRNA technology**

Studies are available comparing the sensitivity of E6/E7 mRNA technology with HPV-DNA testing technologies on invasive cervical cancer. They show the diagnostic sensitivity of E6/E7 mRNA technology to be comparable to the HPV-DNA technologies tested. The sensitivity of E6/E7 mRNA technology towards invasive cervical cancer is about 90%, which is illustrated in Figure 5. This implies that a E6 mRNA negative test result will have the same negative predictive value compared to HPV-DNA testing technologies when looking at invasive cervical cancer cases.

Compared to HPV-DNA testing technologies, E6/E7 mRNA technology is the only technology available which has documented a lower sensitivity towards CIN2+. With an optimal sensitivity towards invasive cervical cancer and at
the same time a lower sensitivity towards CIN2+, E6/E7 mRNA technology is the only technology available to give both high assurance against the development of cervical cancer and at the same time reflect the “real world” knowledge of significant regression of CIN2+. This is strongly reflected in Figure 1, presenting the stage where women must be treated.24,27,34,78

Specificity in a screening population

Specificity is a way to measure false positives, *i.e.* patients without a disease positive by a diagnostic test. All patients enrolled in some sort of follow-up routine should be included when specificity is calculated.

Invasive cervical cancer and pre-cancerous lesions are rare conditions. Only about 11,270 (National Cancer Institute about cervical cancer, www.cancer.gov/cancertopics/types/cervical) women in the United States develop invasive cervical cancer annually (0.3 ‰ of the women tested annually). In addition, we expect that only about 1% or less are treated by conization annually. In a diagnostic setting, this implies that specificity is approximately 100% minus the positivity (abnormal) rate of the diagnostic test. If the positivity rates of different diagnostic tests are known (as exact numbers or as fixed ratios between the different tests), it is easy to calculate the expected diagnostic specificity (or relative specificity) in a screening population for these tests.

**Specificity of cytology**

The rate of abnormal cytology is estimated at about 6% in the United States. This implies a screening specificity of about 94%. In the literature, the specificity of cytology varies quite a bit depending on the study population at hand. A lower rate of abnormal cytology implies an increase in specificity. Some studies have also calculated specificity based on other cut-offs such as LSIL or HSIL resulting in very high specificities. This, however, does not reflect the basic requirement to include all patients enrolled in some sort of follow-up routine when calculating specificity.

**Specificity of HPV-DNA testing technologies**

As previously mentioned, the positivity rate of HPV-DNA testing technologies is estimated at about 3 times the rate of abnormal cytologies, *i.e.* 18%. This implies a screening specificity of about 82%. This specificity will be the same regardless of whether or not cytology is included to triage HPV-DNA positive cases. HPV-DNA testing technologies have a high number of false positives which will result in a multitude of women referred to follow-up routines.

**Specificity of PreTect HPV-Proofer**

As previously mentioned, we expect the positivity rate of E6/E7 mRNA technology to be about 25% less than the abnormal rate of cytology, *i.e.* 4.5%. This implies an expected screening specificity of about 95.5%.

Using the E6/E7 mRNA technology will avoid about 80% of the false positives detected by HPV-DNA testing technologies, decreasing the economic costs and psychological burdens of unnecessary follow-up.

**Conclusions**

In this paragraph we discussed the key properties of cytology, HPV-DNA testing technologies and E6/E7 mRNA technology. The key properties, *i.e.* PPV, sensitivity towards cervical cancer and specificity in a screening population including all referred clinical studies, are summarized in Table 2.

In addition, the follow-up rate is estimated as the positivity (abnormal) rate minus the number of identified CIN2+. With a rough per annum regression rate of 50% of test positives the accumulated follow-up rate is also indicated for the second year. The use of cytology has reduced the invasive cervical cancer incidence and mortality significantly during the last decades, but only in women older than 40 years of age.
age. Recently however, this rate of decline in cervical cancer mortality has leveled off and it may even be increasing slightly in young women. The reason is likely to be the limited sensitivity of on-time cytology, less coverage rate in the young female population or it may be general increased unprotected sexual activity. To be able to achieve further reduction in ICC incidence and mortality new technologies have to be implemented. The use of HPV-DNA testing technologies will most likely not increase the sensitivity towards ICC compared to the use of cytology due to the fact that cytology is included as a triage step for HPV-DNA testing technologies. In addition, screening specificity is dramatically reduced compared to the use of cytology only.

The E6 mRNA technology is likely to perform better than both cytology and HPV-DNA testing technologies (with cytology triage) in a screening setting (Figure 6). The number of E6 mRNA technology positives are comparable to the number of women referred to colposcopy in today’s cytology-based screening. All E6/E7 mRNA technology positive women may then be referred directly to colposcopy and biopsies or direct treatment. The E6/E7 mRNA technology will result in superior PPV and sensitivity. In addition, the specificity will be comparable to the specificity of cytology.

Incident follow-up rate and the total number of women in a follow-up routine will be comparable when using E6/E7 mRNA technology or cytology. Using HPV-DNA testing technologies, about 16% of women screened will be directly referred to a follow-up routine. The size of the accumulated follow-up group is likely to exceed 20% when using HPV-DNA testing technologies resulting in unnecessary psychological strain and huge costs.

Based on all the discussions within this review, it is clear that the main driving engine and the cause of cervical pre-cancer and the main cause of invasive cervical cancer is the expression of E6 and E7 from HPV 16, 18, 31, 33 and 45. In some areas the HPV 35, 52 and 58 may be included, but it has been proved that the prevalence of these HPV types decline from cytological normal to confirmed invasive cervical cancer. There is a reason to believe that these HPV types may only be transient when discovered in cancer. However, it is very clear that it is only HPV 16, 18, 45 and maybe 33 that increase its prevalence from within cytological normal cases to histological confirmed invasive cervical cancer. The need for the detection and informing women about other HPV types is not clear. It is very clear that in a typical screening population including a high number of cytological normal cases the HPV DNA testing may miss from 14 to 40% of the women.

Table 2. Summary of the estimated key properties.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Cytology, %</th>
<th>DNA with cytology triage, %</th>
<th>PreTect HPV-Proofer, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positivity (abnormal rate)</td>
<td>6</td>
<td>18</td>
<td>4.5</td>
</tr>
<tr>
<td>Positive predictive value (PPV)</td>
<td>17</td>
<td>5</td>
<td>31</td>
</tr>
<tr>
<td>Sensitivity towards ICC</td>
<td>50</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Specificity</td>
<td>94</td>
<td>82</td>
<td>95</td>
</tr>
<tr>
<td>Follow-up</td>
<td>5</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Accumulated follow-up year 2</td>
<td>7.5</td>
<td>24</td>
<td>4.5</td>
</tr>
</tbody>
</table>

![E6 mRNA technology](image)

Figure 6. E6/E7 mRNA technology used in primary screening.
References


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