Assessment of Foetal DNA in Maternal Blood – A Useful Tool in the Hands of Prenatal Specialists

Introduction

In the last few years, first trimester screening (FTS) in 11+ to 13+ weeks of gestation has become one of the most important ultrasound examinations in pregnancy, as it allows physicians to predict several pregnancy complications including pre-eclampsia or pre-term birth. Screening for trisomies 21/18 and 13 using maternal and gestational age, foetal nuchal translucency, and maternal serum biochemistry was formerly the main reason for first trimester screening. However, today this is only one part of the overall examination. In the near future, the analysis of foetal DNA obtained from maternal blood will be used to supplement first trimester screening for aneuploidy or even replace current screening methods. In this review we show how prenatal medicine specialists can use foetal DNA analysis.

Assessment of Free Foetal DNA from Maternal Blood

The detection of foetal DNA in maternal blood or, to be more precise, in cell-free maternal plasma goes back to a study by Lo et al. published in 1997 [4]. Pregnancy-specific cell-free DNA in maternal blood or plasma constitutes around 10% of all cell-free DNA, is largely fragmented and is not

Abstract

Over the last few years, first trimester screening between 11+ and 13+ weeks of gestation has become one of the most important ultrasound examinations in pregnancy, as it allows physicians to predict several pregnancy complications including pre-eclampsia or pre-term birth. Screening for trisomies 21/18 and 13 using maternal and gestational age, foetal nuchal translucency, and maternal serum biochemistry was formerly the main reason for first trimester screening. However, today this is only one part of the overall examination. In the near future, the analysis of foetal DNA obtained from maternal blood will be used to supplement first trimester screening for aneuploidy or even replace current screening methods. In this review we show how prenatal medicine specialists can use foetal DNA analysis.

Zusammenfassung


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Bibliography

recent studies. Foetal DNA was initially used to determine an infant’s rhesus status from maternal blood in cases of potential rhesus incompatibility. This approach is now well established and has replaced the former use of amniocentesis to determine the infant’s rhesus status.

Using foetal DNA in screening for aneuploidy proved to be more difficult, as the maternal share of cell-free DNA which can be attributed to chromosome 21 predominates [5]. After initial attempts to isolate foetal DNA, scientists moved on to measure all of the cell-free DNA, i.e., both maternal and foetal DNA. Although it is difficult to distinguish between foetal euploidy and aneuploidy due to the predominance of maternal DNA, the new technology of next generation sequencing has made it possible to establish this approach. After extracting all of the cell-free DNA from maternal blood, this is then amplified using massively parallel sequencing and quantitatively attributed to the corresponding chromosomes using the human reference genome.

The precondition for this is, however, that at least 4% of the cell-free DNA is of pregnancy-specific origin. If the percentage of pregnancy-specific cell-free DNA falls below this minimum level – which becomes more likely as maternal weight increases – it is not possible to make any statement about the foetal chromosomal status [6].

To detect an abnormal karyotype, only sequencing fragments which can be unambiguously assigned to a specific position on a chromosome in the genome are used for quantification. In cases with a euploid karyotype, around 1.25% of the DNA material are from chromosome 21 depending on the chosen sequencing technology, while if trisomy 21 is present, this figure rises to approximately 1.32%. This difference is expressed as a z-score [7]. The cut-off point is set at a z-score of 3 which corresponds to three times the standard deviation for a euploid pregnancy.

Assessment of foetal DNA results in the detection of at least 95% of all foetuses with trisomy 21, with a maximum false positive rate of 0.5% (personal communication of Dr. Wera Hofmann, LifeCodexx AG, unpublished statement). In a first meta-analysis by Verweij et al., 556 euploid and 125 trisomy 21 pregnancies were investigated. The detection and false positive rates were 100% and 0.7%, respectively. However, it should be noted that these data were based on only 2 studies. A further 7 studies were excluded for reasons of quality [8]. Table 1 offers an overview of recent studies.

To date, all reference data were obtained only from high-risk collectives and included only a limited number of pregnancies with trisomy 21, with euploid karyotypes being under-represented [3]. A screening study with a similar number of cases as that used to prove the screening performance of FTS for trisomy 21 is still lacking. Nevertheless, the expectation is that the screening performance of foetal DNA in a representative group will also be very good. In a first small screening study of 2038 euploid and 8 trisomy 21 pregnancies, the screening performance of foetal DNA was compared with that of FTS for trisomy. The detection and false positive rates for foetal DNA were 100% and 0.1%, respectively, compared to 100% and 4.5% with FTS for trisomy [9].

Currently, the disadvantages of the test are its high cost (1250 € in Germany), the lengthy processing time (at least 2 weeks), and the fact that the test is limited to trisomy 21. Particularly in younger pregnant women, trisomy 21 is only present in around half of all cases with aneuploidy [10]. In the near future, tests for trisomies 18 and 13 are also expected to be available in the German-speaking countries; however, based on recent studies, the sensitivity of these tests is lower. Other numerical and structural chromosomal abnormalities cannot be detected. Moreover, problems arising from placental mosaicism also remain unresolved. As the foetal DNA found in maternal blood is mainly of placental origin and not of direct foetal origin, the test will always flag up placental mosaicism as an abnormality and will not be able to distinguish further. In any case, an invasive procedure will still be necessary to confirm an abnormal test result obtained by the assessment of foetal DNA in maternal blood.

### Assessment of Free Foetal DNA and Other Risk Stratifications Used in First Trimester Screening

With the establishment of FTS for trisomy, aneuploidy risk assessment in the first trimester has proven to be extremely valuable, particularly in view of patients’ wish to undergo screening as early as possible. Thus, foetal DNA assessment will be primarily carried out in the first trimester of pregnancy. It is safe to assume that, in the longer term, screening for aneuploidy will be managed better using foetal DNA than by using FTS for trisomy based on maternal and gestational age, foetal nuchal translucency, free beta-hCG and PAPP-A. This is predominantly due to the higher detection rates achieved by foetal DNA. In addition, the measurement of foetal nuchal translucency thickness is associated with a high inter-investigator variability. De-

### Table 1: Overview of recent studies on foetal DNA analysis in maternal blood using “massively parallel sequencing” to detect trisomy 21.

<table>
<thead>
<tr>
<th>Study</th>
<th>Euploid (n)</th>
<th>Trisomy 21 (n)</th>
<th>Detection rate (%)</th>
<th>False positive rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan et al. 2008 [28]</td>
<td>18</td>
<td>9</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Chiu et al. 2008 [6]</td>
<td>14</td>
<td>14</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Sehnert et al. 2011 [29]</td>
<td>47</td>
<td>13</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Chiu et al. 2011 [30]</td>
<td>146</td>
<td>86</td>
<td>100</td>
<td>2.1 (1)</td>
</tr>
<tr>
<td>Ehrich et al. 2011 [31]</td>
<td>449</td>
<td>39</td>
<td>100</td>
<td>0.3</td>
</tr>
<tr>
<td>Palomaki et al. 2011 [32]</td>
<td>1484</td>
<td>212</td>
<td>98.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Sparks et al. 2012 [33]</td>
<td>298</td>
<td>39</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Stumm et al. 2012 [3]</td>
<td>42</td>
<td>8</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Bianchi et al. 2012 [34]</td>
<td>532</td>
<td>89</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Sparks et al. 2012 [35]</td>
<td>167</td>
<td>35</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Nicoladis et al. 2012 [9]</td>
<td>2038</td>
<td>8</td>
<td>100</td>
<td>0.1</td>
</tr>
</tbody>
</table>

1 2-plex protocol
spite all attempts at standardisation and quality control, the measurement process remains error-prone [11, 12]. Thus, an uncomplicated blood test would be easier to carry out, while the initial counselling offered prior to any tests in accordance with the German Genetic Diagnostics Act would not differ from the counselling given prior to FTS for trisomy. Use of foetal DNA in a general population has not yet been sufficiently investigated. Most studies were limited to collectives known to be at increased risk. A larger screening study will be necessary before this test can be used more generally in low-risk collectives.

Measurement of nuchal translucency and careful assessment of foetal anatomy during the first trimester will continue to play an important role in pregnancy care, even after switching to foetal DNA, as numerous structural abnormalities and genetic syndromes are first recognised based on increased nuchal translucency or atypical sono-anatomy. Furthermore, as described above, the analysis of foetal DNA obtained from maternal blood is not always successful [6, 13, 14]. In view of the low detection rates for certain abnormalities – particularly for cardiac defects – in the 2nd trimester, the use of surrogate markers for abnormalities detectable in the 1st trimester should not become less important [15]. A study which included approximately 40000 normal pregnancies and 85 foetuses with serious cardiac defects showed that combining the assessment of nuchal translucency with that of blood flow in the ductus venosus and through the tricuspid valve in the 12+ week of gestation resulted in the detection of around 60% of all cardiac defects [16].

It has also been shown that the risk for numerous pregnancy complications can be assessed around 12+ weeks of gestation. Screening for pre-eclampsia is of particular importance, as its prevalence of between 1 and 2% justifies screening, and as the individual risk for pre-eclampsia can be reduced through the administration of aspirin to patients with an increased risk [2, 17]. The screening study of Akolekar et al., the most comprehensive study to date, investigated around 33000 normal pregnancies and 852 pregnancies with subsequent pre-eclampsia in 11+ to 13+ weeks of gestation [17, 39]. They found that a screening model that was based on the combination of previous maternal history, maternal blood pressure, resistance in the uterine arteries, and the serum markers PAPP-A and PI GF provided detection rates of more than 85% of those pregnancies that resulted in pre-eclampsia prior to 34 weeks of gestation, with a false positive rate of 10%. Today, the individual risk for developing pre-eclampsia can be calculated, just as the risk for trisomy 21.

### First Trimester Screening for Trisomy with Free Foetal DNA

Currently, many physicians consider the assessment of foetal DNA in maternal blood to be an alternative to invasive diagnostic tests. But it must be remembered that invasive diagnostic tests are currently the gold standard, with a detection rate of practically 100% for numerical and structural chromosomal abnormalities recognisable with light microscopy. Any reduction of such detection rates would be unacceptable. However, as every invasive diagnostic test is associated with a risk of miscarriage which is about 0.5% higher than the natural miscarriage rate, the assessment of foetal DNA from a maternal blood sample would be preferable as it is not associated with an additional risk of miscarriage [19, 20].

It would be easier if the assessment of foetal DNA was considered a screening test for trisomy 21. The detection and false positive rates for trisomy 21 of the PraenaTest offered by LifeCodexx are at least 95% and 0.5%, resulting in a positive and a negative likelihood ratio of 190 and 0.05, respectively. The advantage of using foetal DNA assessment becomes obvious when these figures are compared with the positive and negative likelihood ratios of 18 and 0.11 based on FTS for trisomy 21, with detection and false positive rates of 90% and 5%, respectively [21]. Even when additional ultrasound markers such as nasal bone length, tricuspid valve and ductus venosus flow are used, the figures are still 95% and 2.5% and thus lower than those for foetal DNA in maternal blood [22–24].

<table>
<thead>
<tr>
<th>Test method used</th>
<th>Detection rate</th>
<th>False positive rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis of foetal DNA obtained from maternal blood (PraenaTest®, LifeCodexx AG)*</td>
<td>at least 95%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Combined first trimester screening between 11+ and 13+ weeks of gestation [21] (age, foetal NT, free beta-hCG and PAPP-A)</td>
<td>about 90%</td>
<td>5%</td>
</tr>
<tr>
<td>Combined first trimester screening and additional ultrasound markers [22–24] (nasal bone, tricuspid valve or ductus venosus flow)</td>
<td>about 95%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Two-stage combined first trimester screening [36] (foetal NT in the 12+ week of gestation and serum biochemistry in the 9+ week of gestation)</td>
<td>about 90%</td>
<td>3%</td>
</tr>
<tr>
<td>Triple test in the 2nd trimester [37] (AFP, beta-hCG, estriol)</td>
<td>about 60%</td>
<td>5%</td>
</tr>
<tr>
<td>Quadruple test in the 2nd trimester [37] (AFP, beta-hCG, estriol und inhibin-A)</td>
<td>about 70%</td>
<td>5%</td>
</tr>
<tr>
<td>Integrated screening [37] (foetal NT and PAPP-A in the 12+ week of gestation and quadruple test in the 2nd trimester)</td>
<td>about 85%</td>
<td>5%</td>
</tr>
<tr>
<td>Sonographic soft marker screening in the 2nd trimester [27]</td>
<td>about 75%</td>
<td>13%</td>
</tr>
</tbody>
</table>

* Currently only done in collectives at increased risk.
As the analysis of foetal DNA is expressed as z-scores, it is worth considering whether it would be possible to compute a continuous likelihood ratio from the z-scores, which could be multiplied with the maternal and gestational age-related risk. Using this patient-specific risk, the patient could decide for herself, as with FTS for trisomy, whether invasive testing would be justified after having weighed the different risks. Prior to the clinical introduction of this approach, validation in the form of a prospective study done in a general population would, of course, be necessary.

Free Foetal DNA as a Secondary Test after Primary FTS for Trisomy

Until free foetal DNA assessment to ascertain the individual trisomy risk has become a standard procedure and the current problems of high costs and limited availability have been overcome, foetal DNA assessment will have to be integrated in a higher-level screening concept. The obvious thing would be to include it in a 2-stage model of FTS for trisomy. The primary test would consist of FTS risk assessment, and the analysis of foetal DNA would serve as secondary test in a subgroup of patients. The advantage of this two-stage model is the widespread availability of FTS for trisomy, the lower costs, and the opportunity to use FTS as a triage test to detect markers for chromosomal abnormalities other than trisomy 21.

The first step would consist of computing the patient-specific risk, based on maternal and gestational age-related risk, foetal nuchal translucency, and the serum markers free beta-hCG and PAPP-A. Patients would subsequently be categorised as high risk, intermediate risk or low risk. The Foetal Medicine Foundation London recommends using cut-off risks of 1 in 50 and 1 in 1000 – 65% and 1 – 1.5% and increases the detection rate to over 95%. At the same time, foetal DNA assessment will only be necessary in around 15% of cases. However, this approach also needs to be validated in clinical studies.

Foetal DNA analysis for trisomy 21 is not useful in cases with malformations such as radial aplasia due to the multiple associated chromosomal disorders. The use of foetal DNA assessment described above shows that the prior use of ultrasound screening is crucial. Prior risk assessments must be appropriate, and even atypical chromosomal abnormalities need to be recognised and taken into account. Thus, before assessing foetal DNA in maternal blood, it is first necessary to carry out detailed FTS (by an experienced investigator). It is very important to remember that only about half of all chromosomal disorders can be ascribed to trisomy 21, that foetal

As shown in Fig. 1, this 2-stage model reduces the false positive rate to approximately 1 – 1.5% and increases the detection rate to over 95%. At the same time, foetal DNA assessment will only be necessary in around 15% of cases. However, this approach also needs to be validated in clinical studies.

Foetal DNA analysis for trisomy 21 is not useful in cases with malformations such as radial aplasia due to the multiple associated chromosomal disorders. The use of foetal DNA assessment described above shows that the prior use of ultrasound screening is crucial. Prior risk assessments must be appropriate, and even atypical chromosomal abnormalities need to be recognised and taken into account. Thus, before assessing foetal DNA in maternal blood, it is first necessary to carry out detailed FTS (by an experienced investigator). It is very important to remember that only about half of all chromosomal disorders can be ascribed to trisomy 21, that foetal
chromosomal disorders only account for around 10% of all malformations, and that malformations are only responsible for around one third of perinatal mortalities. Investigations must therefore comprehensively focus on the most common pregnancy complications, as the risk of such complications can generally already be assessed with FTS. Limiting investigations exclusively to trisomy 21 would underutilize the opportunities available today and would not sufficiently weigh up the pregnancy-associated risks.

**Use of Foetal DNA Assessment in the 2nd Trimester**

Foetal DNA assessment could also be used as an alternative to amniocentesis for advanced maternal age in the 17th week of gestation. After informing patients about the test quality, use of this test in the group of patients with advanced maternal age is quite conceivable. Foetal DNA assessment would be an excellent screening test in this collective and could increase and reduce the patient-specific risk by a factor of 190 and 0.05, respectively. In practical terms, this would mean that a 40-year-old patient with an age risk of around 1 in 100 would have a risk of 1 in 2 after the test (truncated) or 1 in 2000. Such a clear reduction does not in most cases justify the use of invasive diagnostics. But as with FTS, a previous detailed ultrasound investigation which would assess the risk for other chromosomal disorders is obligatory.

It should be noted that amniocentesis based on the indication ‘maternal age’ is increasingly being replaced by FTS and thus only plays a subordinate role.

The use of foetal DNA assessment after multiple marker screening (done as part of the detailed anomaly scan) in the 21st week of gestation is also conceivable. If a constellation of markers is found which appear to be typical for trisomy 21, use of foetal DNA assessment with the likelihood ratios referred to above could provide results which would clearly show whether the risk was reduced and so prevent the patient from undergoing invasive tests [27]. But here again, it must be emphasised that risk assessment for trisomy 21 based on multiple marker screening in the 20+ weeks of gestation has become much less important since FTS has come into more general use.

**Conclusion**

In conclusion, the assessment of foetal DNA from maternal blood offers a new opportunity to simplify the risk assessment for trisomy 21 in early pregnancy in a subgroup of patients. If the detection rates should be confirmed in screening and the costs continue to drop, then in the coming years FTS for trisomy will be complemented or even replaced by foetal DNA assessment. To ensure optimal levels of patient care, it will be important to continue to carry out FTS as it offers numerous opportunities to influence the course of the pregnancy. Any development in which FTS is only used to date the pregnancy, in which an assistant takes a blood sample to determine foetal DNA, and all other potential problems are only tackled in the 20+ weeks of gestation would represent a setback of more than 20 years.

**Conflicts of Interest**

None.

**Literatur**

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