Potential application of fetal epigenetic markers on the non-invasive prenatal detection of chromosomal abnormality

Identification of fetal chromosomal aneuploidy is a predominant reason for pregnant women to undergo prenatal testing, most of which are invasive and carry a risk for fetal loss. The presence of fetal DNA in maternal circulation has offered an opportunity for non-invasive prenatal detection [1]. However, this fetal DNA exists only as a minor fraction among the co-existing background of maternal DNA [2, 3]. Hence, the use of fetal DNA in maternal plasma to detect fetal aneuploidy is technically challenging. With the advent of massively parallel genomic sequencing (MPGS) to shotgun (non-specifically) sequence all the fetal and maternal DNA molecules, non-invasive prenatal detection of fetal trisomy 21 could now be achieved at high sensitivity and specificity [4–6].

However, using MPGS for non-invasive prenatal detection of fetal aneuploidy requires a turn-around-time of 7–10 days [7], the use of expensive equipment and reagents and the use of relatively complex bioinformatics methods. Thus, investigators have been seeking alternatives for the non-invasive prenatal detection of aneuploidy. Most of these alternatives rely on the fetal-specific nucleic acid species or polymorphisms for analyzing the fetal DNA in maternal plasma. For instance, the existence of epigenetic (DNA methylation) signatures that are specific to the fetus, but not its mother, has facilitated the development of fetal epigenetic markers in maternal plasma for the non-invasive analysis of the fetal chromosome of interest. In this issue of Clinical Chemistry and Laboratory Medicine, Lim and colleagues have demonstrated that a fetal-specific DNA methylation pattern (fetal epigenetic marker) on chromosome 21 could now be achieved at high sensitivity and specificity [8].

The use of epigenetic marker to specifically identify the fetal DNA in maternal plasma was first demonstrated in 1999 [9]. However, that fetal epigenetic marker was polymorphism-dependent and could only be applied in certain fetal-maternal pairs. The first polymorphism-independent fetal epigenetic marker was the unmethylated form of the serpin peptidase inhibitor, clade B (ovalbumin), member 5 (also known as maspin) gene (U-SERPINB5 or U-maspin), as discovered by a candidate gene approach [10]. Since U-SERPINB5 is located on chromosome 18, it has been further demonstrated for the first time that non-invasive detection of fetal trisomy 18 could be achieved using fetal epigenetic marker [11].

Seeing this promising demonstration, various investigators have launched screening efforts at high resolution and wide genome coverage to systematically identify more fetal epigenetic markers [12–17]. CpG islands (CGIs), which harbor a high density of CpG sites, often undergo DNA methylation. The first study to systematically investigate CGIs on chromosome 21 for fetal epigenetic markers at single-nucleotide resolution has covered 114 (76% of all the 149 CGIs defined by bioinformatics criteria) and involved the use of the Epityper platform, cloning and conventional Sanger sequencing techniques [12]. This study has provided the first empirical evidence that the fetal (placental) and the maternal (blood cell) genomes harbor a lot of DNA methylation differences. Since the placenta and maternal blood cells are the respective sources of fetal and maternal DNA in maternal plasma, these DNA methylation differences could be developed into fetal epigenetic markers. In that study, a panel of 22 (19% of 114 analyzed CGIs) fetal epigenetic markers have been identified, including the unmethylated form of the phosphodiesterase 9A gene (U-PDE9A), which has been developed by Lim and colleagues as a potential non-invasive prenatal test for trisomy 21 in 2011 [18].

Later, using more sophisticated screening techniques, namely combined bisulfite and restriction analysis (COBRA), investigators have screened beyond the CpG islands for fetal epigenetic markers on 51 regions on gene promoters located on chromosome 21 [14]. This study has discovered the methylated form of the holocarboxylase synthetase gene (M-HLCS) as a fetal epigenetic marker. To compare the relative chromosome dosage, the concentrations of this fetal epigenetic marker M-HLCS were normalized against those of a fetal genetic marker on chromosome Y, zinc finger protein, Y-linked (ZFY). Hence,
this chromosome dosage approach was dubbed as the epigenetic-genetic (EGG) approach, and has been demonstrated to be useful for the non-invasive prenatal detection of trisomy 21 (Tables 1 and 2) [14].

In the current study by Lim and colleagues, the use of the fetal epigenetic markers for chromosome 21, M-HLCS, has already minimized the interference of the co-existing maternal chromosome 21 DNA sequences [8]. To compare the relative chromosome dosage, the authors normalized the concentrations of the fetal epigenetic marker M-HLCS by another fetal epigenetic marker on chromosome 3, namely the methylated form of the Ras association (RalGDS/AF-6) domain family member 1 gene (M-RASSF1A). Using conventional quantitative polymerase chain reaction (qPCR) to measure M-HLCS and M-RASSF1A, the authors have already achieved a sensitivity of 90% and a specificity of 92.5% in the non-invasive prenatal detection of fetal trisomy 21. Despite this, there is room for improvement for Lim’s approach.

To explore ways to improve the performance of using fetal epigenetic markers for non-invasive prenatal detection of trisomy 21, we have tabulated the salient features of other studies similar to this current one in Table 1. While each study has its own unique features and could not be directly compared with each other, it is noted that study using digital PCR seems to give better sensitivity and specificity, compared with the conventional quantitative polymerase chain reaction (qPCR). To perform a digital PCR experiment, one will dilute the template DNA from each sample to average concentrations below 1 molecule per well and analyze by PCR in literally hundreds or thousands of replicate PCR wells [19]. For each sample, some PCR wells will be positive, while others will be negative for the targeted marker. Since most positive wells contain just one template molecule, counting the positive wells will enable the absolute quantification of the original template DNA. Translating the exponential but analog nature of qPCR into a ’1’ or ‘0’ signal in digital PCR [20], digital counting platforms should facilitate more precise and accurate quantification [21].

Besides the use of a digital PCR platform, we also note that those similar studies involved the use of fetal genetic markers, rather than fetal epigenetic markers, to quantify a reference chromosome for relative chromosome dosage analysis [14, 16, 22]. Normalizing against a fetal epigenetic marker, namely M-RASSF1A located on chromosome 3, Tong and colleagues have found that the relative dosage of chromosome 21 of more than half of the trisomy 21 placentas overlapped with the euploid (normal) reference interval, which was defined as the mean ratio of M-HLCS to M-RASSF1A±1.96 standard deviation (SD) of the euploid placentas as 0.86–1.63 (Table 2). In contrast, normalizing against a fetal genetic marker, namely ZFY located on chromosome Y, they have found that the relative dosage

### Table 1: Studies on non-invasive prenatal detection of trisomy 21 using fetal epigenetic markers.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Pre-treatment</th>
<th>Quantification method</th>
<th>Fetal chr21 marker</th>
<th>Fetal reference chromosome marker (nature of marker)</th>
<th>No. of trisomy 21 fetuses tested positive/No. of trisomy 21 fetuses</th>
<th>No. of euploid fetuses tested negative/No. of euploid fetuses</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tong et al. [14]</td>
<td>MSRE</td>
<td>Digital PCR</td>
<td>M-HLCS</td>
<td>ZFY (genetic)</td>
<td>5/5</td>
<td>23/24</td>
<td>100.0%</td>
<td>95.8%</td>
</tr>
<tr>
<td>Lim et al. [8]</td>
<td>MBD</td>
<td>qPCR</td>
<td>M-HLCS</td>
<td>M-RASSF1A (epigenetic)</td>
<td>9/10</td>
<td>37/40</td>
<td>90.0%</td>
<td>92.5%</td>
</tr>
<tr>
<td>Lim et al. [18]</td>
<td>MBD</td>
<td>qPCR</td>
<td>U-PDE9A</td>
<td>M-PDE9A+U-PDE9A (epigenetic)</td>
<td>15/18</td>
<td>85/90</td>
<td>83.3%</td>
<td>94.4%</td>
</tr>
</tbody>
</table>

chr21, chromosome 21; MBD, methyl-CpG binding domain-based enrichment; MSRE, methylation-sensitive restriction enzyme digestion; qPCR, quantitative polymerase chain reaction.

### Table 2: Data from Tong et al. [14] on the prenatal detection of trisomy 21 using fetal epigenetic or genetic markers as reference.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pre-treatment</th>
<th>Quantification method</th>
<th>Fetal chr21 marker</th>
<th>Fetal reference chromosome marker (nature of marker)</th>
<th>No. of trisomy 21 fetuses tested positive/No. of trisomy 21 fetuses</th>
<th>No. of euploid fetuses tested negative/No. of euploid fetuses</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Placenta</td>
<td>MSRE</td>
<td>Digital PCR</td>
<td>M-HLCS</td>
<td>M-RASSF1A (epigenetic)</td>
<td>3/12</td>
<td>10/10</td>
<td>25.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Placenta</td>
<td>MSRE</td>
<td>Digital PCR</td>
<td>M-HLCS</td>
<td>ZFY (genetic)</td>
<td>12/12</td>
<td>10/10</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Maternal plasma</td>
<td>MSRE</td>
<td>Digital PCR</td>
<td>M-HLCS</td>
<td>ZFY (genetic)</td>
<td>5/5</td>
<td>23/24</td>
<td>100.0%</td>
<td>95.8%</td>
</tr>
</tbody>
</table>

chr21, chromosome 21; MSRE, methylation-sensitive restriction enzyme digestion; qPCR, quantitative polymerase chain reaction.
of chromosome 21 of all trisomy 21 placentas were greater than the upper limit of the reference interval, which was calculated from the euploid placentas as 1.08–1.62 (Table 2). Therefore, by normalizing against a fetal genetic marker instead of fetal epigenetic marker, Tong and colleagues were able to improve the performance of the test. They reasoned that the M-HLCS/ZFY ratio has a smaller inter-individual variation that the M-HLCS/M-RASSF1A ratio because the genetic ZFY marker has less heterogeneity compared with the epigenetic M-RASSF1A marker.

The limitation of normalizing against a fetal genetic marker is that not all pregnancies could be covered. For instance, the M-HLCS/ZFY ratio is inapplicable to pregnancies with female fetuses, which contain no chromosome Y and hence no ZFY. To overcome this, one may increase the coverage by using a panel of paternally-inherited polymorphism markers located on autosomes as demonstrated in another publication [22]. Since these so-called autosomal genetic reference markers are commonplace in the genome, population coverage could be achieved readily.

In the current study, Lim and colleagues have demonstrated the potential use of fetal epigenetic marker for the non-invasive prenatal detection of trisomy 21 [8]. The use of digital PCR platform and normalization with a fetal genetic marker will further improve the performance of the test. Taken together with the panels of forthcoming fetal epigenetic markers systematically discovered from the increasingly comprehensive screening efforts [12–17], there is a good chance that they may serve as a supplement or an alternative to MPGS-based non-invasive prenatal detection of fetal chromosomal aneuploidy in the future.

Conflict of interest statement

Author’s conflict of interest disclosure: The author has held and filed patent applications on aspects of the use of nucleic acids in maternal blood for noninvasive prenatal testing, a proportion of which has been licensed to Sequenom, Inc.

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References


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