Small Supernumerary Marker Chromosomes in Human Infertility

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Abstract
Small supernumerary marker chromosomes (sSMC) are structurally abnormal chromosomes that cannot be unambiguously identified by banding cytogenetics. The objective of this study was to provide an overview of sSMC frequency and characterization in a context of infertility and to review the literature describing sSMC in relation with male and female infertility. Therefore, a systematic literature review on sSMC associated with infertility was conducted by means of a PubMed literature and a sSMC database (http://ssmc-tl.com/ssMC.html) search. A total of 234 patients with infertility were identified as carriers of sSMC. All chromosomes, except chromosomes 10, 19 and the X, were involved in sSMC, and in 72% the sSMC originated from acrocentric chromosomes. Euchromatic imbalances were caused by the presence of sSMC in 30% of the cases. Putative genes have been identified in only 1.2% of sSMC associated with infertility.

Infertility is a disease of the reproductive system defined by the failure to achieve a clinical pregnancy after 12 months or more of regular unprotected sexual intercourse [Zegers-Hochschild et al., 2014]. In about 22–28% of couples the cause of infertility remains unexplained [Kamath and Bhattacharya, 2012]. Patients with infertility are known to be a clinically heterogeneous group, as a variety of factors can influence fertility. Those can be hormonal, immunological, psychological, anatomical (internal or external genital malformation), related to age, exercise, obesity, infectious disease, resulting from surgery, or be associated with defined abnormalities in the gametes, for example aberrant semen param-
there seems to be a 7.5:0.125% [Liehr, 2011]. Distinguishing male from female, the frequency of sSMC in individuals presenting infertility is elevated to 0.288%. The frequency of sSMC in developmentally retarded patients, the sSMC rate is elevated to 0.044% of consecutively studied postnatal ones [Liehr and Weise, 2007]. The apparently reduced rate might be in part connected to the fact that 30–50% of pregnancies with a sSMC derivative are terminated [Warburton, 1991; Kumar et al., 1997; Cavani et al., 2003]. In developmentally retarded patients, the sSMC rate is elevated to 0.288%. The frequency of sSMC in individuals presenting infertility is 0.125% [Liehr, 2011]. Distinguishing male from female, there seems to be a 7.5:1 difference in the sSMC frequency for this special group [Liehr and Weise, 2007]. It is known that sSMC may lead to reduced fertility in males without additional clinical sSMC-related symptoms [Chandley et al., 1975; Manvelyan et al., 2008a]. It is also currently thought that spermatogenesis impairment due to the presence of chromosomal abnormalities including sSMC is the main cause of oligoasthenozoospermia (OAT) [Mau et al., 1997; Koç et al., 2009]. However, little is really known about the mechanism causing this kind of infertility.

By a systematic literature search on sSMC associated with infertility, we reviewed the cases of patients presenting sSMC linked with male or female reproduction difficulties and discussed the relationship between sSMC and spermatogenesis impairment, implantation difficulties, repeated abortions, and other reproductive disorders.

Materials and Methods

This review focuses on patients presenting sSMC associated with male or female reproduction difficulties. Therefore, a systematic literature search on sSMC associated with infertility was conducted by means of a PubMed literature search (using relevant terms and their combinations, e.g. sSMC, infertility, array-CGH, FISH, reproduction, abortion, miscarriage, OAT) and the sSMC database [Liehr, 2015]. The period of our literature search spanned from March 2013 to December 2014 and included peer reviewed publications and congress abstracts. Studies analyzing sSMC and discussing the relationship of sSMC and spermatogenesis impairment, implantation difficulties, repeated abortions, and other reproductive disorders were considered. All cases were characterized for their chromosomal origin and genetic content by FISH and for 21 cases by microarray analysis.

Results

The results obtained in the 234 sSMC cases with infertility are summarized in online supplementary table 1 (for all online suppl. material, see www.karger.com/doi/10.1159/000438718). All cases were characterized for their chromosomal origin and genetic content by FISH and for 21 cases by array-CGH. All human chromosomes, except chromosomes 10, 19, and X, were involved in sSMC (fig. 1). The majority (72%) of sSMC derived from an acrocentric chromosome (170 cases), and 53% of sSMC originated from chromosome 14 or 15 (125 cases). The reasons for which cyogenetic studies were performed in the 234 patients are listed by case in online supplementary table 1. They are also summarized in figure 2 where the cases are divided into 4 groups and by gender as follows: (a) unexplained infertility, comprising patients for which no etiology was found or for which details on the symptoms are unavailable; (b) OAT/others, comprising males with OAT or similar reasons of infertility associated with numerically and/or morphologically altered sperm; (c) RAB, comprising patients with repeated abortions, and (d) amenorrhea, including females suffering from primary or secondary amenorrhea or similar clinical conditions like premature ovarian failure (POF).

Overall, the most common indication was unexplained infertility, followed by RAB and amenorrhea in females and OAT/others in males. All kind of infertilities are more likely to appear when the sSMC originates from an acrocentric chromosome.

The parental origin incidence of sSMC in cases with infertility is summarized in figure 3. The relevant information was available for 41 of the 234 cases of online
Fig. 1. Chromosomal distribution of sSMC in 234 infertile patients depicted by gender, based on the data of online supplementary table 1.

Fig. 2. Distribution of causes of infertility in the 234 patients with sSMC divided by gender, based on the data of online supplementary table 1. OAT = Oligoasthenoteratozoospermia; RAB = repeated abortions.
supplementary table 1. Unexpectedly, 48.8% of the sSMC detected that are linked with fertility problems were inherited. Maternally derived sSMC occurred 2.4 times more frequently than paternally derived sSMC (fig. 3). A total of 88.2% of inherited sSMC were derived from an acrocentric chromosome (online suppl. table 1). In so-called familial cases the sSMC was proven to have been carried through more than one generation, but neither information on paternal nor maternal passage was provided.

Among the 234 cases of sSMC related to infertility, 138 were published in PubMed, and among them, 8 were precisely characterized by microarray analysis with the description of the chromosomal breakpoints and the genes included (table 1). After microarray analysis exploration in 5 cases, neither genomic imbalance nor genes were found in the studied sSMC [Baldwin et al., 2008; Sheth et al., 2011; Bertini et al., 2012; Guediche et al., 2012a; Dutta et al., 2014]. For the 3 others cases microarray analysis showed genomic imbalances and highlighted genes mapped on the sSMC [Guediche et al., 2012a, b] (table 1).

**Fig. 3.** Parental origin of sSMC in the cases listed in online supplementary table 1, provided that information was available.

**Table 1.** Overview of the 8 cases that were precisely characterized by microarray analysis

<table>
<thead>
<tr>
<th>Study</th>
<th>Karyotype</th>
<th>sSMC</th>
<th>Array analysis</th>
<th>Chromosomal regions and DNA positions</th>
<th>Number of genes</th>
<th>Fertility problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheth et al. [2011] (case P-1)</td>
<td>47,XX,+mar(100%)</td>
<td>sSMC(3)</td>
<td>no imbalance detected, 44K oligonucleotide</td>
<td>3p11.2q11.1</td>
<td>0</td>
<td>repeated abortions</td>
</tr>
<tr>
<td>Guediche et al. [2012a] (case 3)</td>
<td>47,XX,+mar(100%)</td>
<td>sSMC(15)</td>
<td>no imbalance detected, 180K oligonucleotide</td>
<td>15q11.1</td>
<td>0</td>
<td>primary infertility</td>
</tr>
<tr>
<td>Bertini et al. [2012]</td>
<td>47,XX,+mar(100%)</td>
<td>sSMC(15)</td>
<td>no imbalance detected, 44K oligonucleotide</td>
<td>15q11.1</td>
<td>0</td>
<td>POF</td>
</tr>
<tr>
<td>Guediche et al. [2012a] (cases 1 + 2)</td>
<td>47,XY,+mar(100%) and 37% in sperm</td>
<td>sSMC(15)</td>
<td>gain of 3.6 Mb, 105K oligonucleotide</td>
<td>15q11.2, 20,102,341–23,699,901</td>
<td>18</td>
<td>OAT</td>
</tr>
<tr>
<td>Baldwin et al. [2008] (case 18)</td>
<td>47,XX,+mar(80%)</td>
<td>sSMC(18)</td>
<td>no imbalance detected, 44K oligonucleotide</td>
<td>18p11.21q11.1</td>
<td>0</td>
<td>not specified</td>
</tr>
<tr>
<td>Guediche et al. [2012a] (case 4)</td>
<td>47,XX,+mar(100%)</td>
<td>sSMC(21)</td>
<td>gain of 0.266 Mb, 180K oligonucleotide</td>
<td>21p11.1, 10,866,741–11,133,106</td>
<td>6</td>
<td>POF</td>
</tr>
<tr>
<td>Guediche et al. [2012b]</td>
<td>48,XX,+mar1,+mar2 [24]/47,XX,+mar1 or 2[5]/46,XX[3]</td>
<td>sSMC(6) and sSMC(20)</td>
<td>gains of 9 Mb on sSMC(6) and 3.3 Mb on sSMC(20), 244K oligonucleotide</td>
<td>6p11.2q12, 57,354,689–66,400,962, 20p11.21q11.1, 22,833,806–26,156,226</td>
<td>42</td>
<td>repeated abortions</td>
</tr>
<tr>
<td>Dutta et al. [2014]</td>
<td>47,XY,+mar(100%)</td>
<td>sSMC(22)</td>
<td>no imbalance detected, 300K SNP array</td>
<td>22q11.1</td>
<td>0</td>
<td>repeated abortions</td>
</tr>
</tbody>
</table>

OAT = Oligoasthenoteratozoospermia; POF = premature ovarian failure.
So far, sSMC meiosis segregation in the sperm of carriers has been studied in 10 males [Martin et al., 1986; Mennicke et al., 1997; Cotter et al., 2000; Wiland et al., 2005; Paetzold et al., 2006; Oracova et al., 2009; Guediche et al., 2012a; Perrin et al., 2012]. These previous studies concerned mainly sSMC(15) and showed a frequency of sperm nuclei containing sSMC varying from 6 to 50%.

Discussion

In this review, we summarized studies concerning sSMC associated with infertility, including spermatogenesis impairment, amenorrhea, POF, implantation difficulties, and repeated abortions.

To our knowledge, more than 5,500 cases of sSMC have been previously described and analyzed by banding cytogenetic analysis and FISH [Liehr, 2015], and 234 concern sSMC associated with infertility in otherwise clinically healthy persons. Among these studies, only 8 have studied the size, chromosomal regions, and genes involved by microarray analysis [Liehr, 2015].

Frequency and Chromosomal Origin of sSMC in Infertile Patients

Studies showed that the frequency of sSMC detected in infertile patients is higher than in the general population (0.125 vs. 0.043%). This frequency is also different between male (0.165%) and female infertility (0.022%) [Liehr and Weise, 2007]. In this present review, 210 new cases have been added since the publication by Liehr and Weise [2007]. Among the 234 patients in our review, 85 are females (36%) and 149 are males (64%) (online suppl. table 1). Based on the 234 cases reported, an involvement of 21 of the 24 human chromosomes has been described in connection with infertility and sSMC formation. We found that 72% (170 cases) of sSMC detected in association with infertility derived from an acrocentric chromosome. This rate is also similar for the overall population (~70% according to Liehr [2015]). sSMC(15) has often been reported at an increased incidence in infertile males with oligo- or azoospermia, suggesting a causal effect [Cotter et al., 2000]. Consequently, it was not unexpected that sSMC(15) was the most frequently sSMC observed (fig. 1).

Parental Origin of the sSMC

In the 234 cases, 51.2% (21 cases, the relevant information was available for 41 patients) of sSMC were described as de novo (fig. 3). Among the inherited sSMC (17 cases), the maternal transmission is more frequent than the paternal one [70% (12 cases) vs. 30% (5 cases)]. The preferentially maternal transmitting mode suggests either a reduced fertility in male carriers or that the sSMC is excluded during spermatogenesis. Moreover, unpaired chromatin potentially causes a meiotic arrest during spermatogenesis that is less marked in females [Reinholdt et al., 2009].

A tendency towards gender-specific differences in the offspring has also been previously described: a maternally inherited sSMC is more likely to lead to fertility problems in sons, while a paternally inherited sSMC is more likely to lead to infertility in daughters [Manvelyan et al., 2008a]. This was confirmed by the present review as the majority of sSMC detected in females were paternally transmitted and the majority of sSMC detected in males were maternally transmitted.

sSMC and Uniparental Disomy in Infertility

A combination of sSMC and uniparental disomy (UPD) is rarely encountered, especially in a context of infertility. According to the Liehr database, only 46 sSMC cases with UPD are reported [Liehr, 2015], which are not associated with infertility. Nevertheless, UPD has to be considered especially in prenatal cases with sSMC. Every sSMC, irrespective of its chromosomal origin, may be principally connected with UPD. UPD of chromosomes 6, 7, 14, 15, 16, and 20 is most often reported. Maternal UPD is approximately 9 times more frequent than paternal UPD, and UPD in connection with a parentally inherited sSMC is, if existent, a rare event. The gender type and shape of sSMC have no effect on UPD formation [Liehr et al., 2011].

Meiosis Studies

During meiosis, a 1:1 segregation ratio for the sSMC would be predicted. Studying meiosis segregation in the sperm of sSMC carriers allows evaluating this theoretical expectation. So far, sSMC segregation in meiosis has been studied by FISH in 10 males [Martin et al., 1986; Mennicke et al., 1997; Cotter et al., 2000; Wiland et al., 2005; Paetzold et al., 2006; Oracova et al., 2009; Guediche et al., 2012a; Perrin et al., 2012]. All these studies showed a significantly increased frequency of sperm aneuploidy due to sSMC compared to control donors.

Martin et al. [1986] found in 2 fertile males that the frequency of spermatozoa with sSMC was not significantly different from 50%. Similarly, Mennicke et al. [1997] found the sSMC in approximately 50% of spermatozoa in a male carrying a sSMC(15). Four other studies
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2012. and produce severe spermatogenetic impairment, ex-
sSMC and a sexual vesicle could lead to meiosis arrest
effect during meiosis. Moreover, the association between
alteration per se causes the phenotype by a mechanical ef-
disrupted in the rearrangement, but the cytogenetic al-
the overexpression or the silencing of a gene/s which is
alteration does not cause the phenotypic effects through
sSMC cause infertility is still debated. The chromosomal
patients very difficult. The reason why heterochromatic
size of the sSMC, the variable proportion of normal/ab-
variations observed probably depend on the origin and
These data indicate an important variability in the segre-
gation of sSMC during meiosis. The inter-individual
factors to some form of selection process against the sSMC
during spermatogenesis makes adequate comparisons of
patients very difficult. The reason why heterochromatic
sSMC cause infertility is still debated. The chromosomal
alteration does not cause the phenotypic effects through
the overexpression or the silencing of a gene/s which is
interrupted in the rearrangement, but the cytogenetic al-
teration per se causes the phenotype by a mechanical ef-
effect during meiosis. Moreover, the association between
sSMC and a sexual vesicle could lead to meiosis arrest
and produce severe spermatogenetic impairment, ex-
plaining oligo- and asthenozoospermia [Perrin et al.,
2012].

Several early reports suggested the possibility of an in-
terchromosomal effect resulting in an increase in chro-
mosomal non-disjunction during meiosis associated with
sSMC [Cotter et al., 2000]. Similarly, Martin et al. [1986]
reported an increase in aneuploidy in sperm (sex chro-
mosome aneuploidy and monosomies of chromosomes
18, 21, and 22) from a sSMC carrier. However, a previous
review of the literature concluded that there was no in-
crease in trisomic conceptions or miscarriages for sSMC
 carriers [Steinbach and Djalali, 1983]. Cotter et al. [2000]
also examined the frequency of disomy 18 in the sperm of
a sSMC(15) carrier. This frequency was not significantly
higher from the control group or other published reports.
Synaptonemal complex analysis of oligozoospermic
sSMC carriers showed that the sSMC preferentially asso-
ciated with the XY bivalent at meiosis [Jaafar et al., 1994].
Similar associations of the trivalent or quadriivalent (in
Robertsonian or reciprocal translocation carriers) with
the XY bivalent were observed in patients with infertility
and spermatogenesis impairment. In fertile translocation
carriers, such associations were less likely to occur [Cotter
et al., 2000]. Even if oligozoospermia is also associated
with sperm autosomal aneuploidy, whatever is the karyo-
type, the association of autosomal chromosomal material
with the XY bivalent seems to correlate with impairment
of meiosis/spermatogenesis [Solari, 1999]. These sugges-
tions are supported by a recent study that hypothesized
that the presence of sSMC is associated with infertility by
inducing an interchromosomal effect [Guediche et al.,
2012a]. Indeed, some male carriers presented infertility
whereas others showed normal fertility with 1:1 segrega-
tion of their sSMC. Three-dimensional interphase FISH
studies in sperm of sSMC carriers might help elucidating
the influence of nuclear architecture on fertility [Manvel-
lyan et al., 2008b; Klein et al., 2012].

Mantzouratou et al. [2009] studied the meiotic and mi-
totic behavior of a ring/deleted chromosome 22 in human
embryos determined by preimplantation genetic diagno-
sis (PGD) for a maternal carrier. Twelve embryos were
analyzed, and the data showed that no embryos were
completely normal or balanced for chromosome 22 by
day 5. In this case, the ring chromosome is very stable
in the mother as she is phenotypically normal and has the
r(22) in all metaphases and interphases studied in her
lymphocytes. The couple concerned in this case presents
with a poor prognosis in terms of receiving a karyotypi-
cally normal child.

Genetic Content of sSMC in Infertile Patients

The varying degrees of phenotypic abnormalities ob-
served are most probably due to the different DNA se-
quences of the sSMC. Numerical and structural chro-
mosomal abnormalities are a common cause of human
diseases including reproductive failure. They are
traditionally identified by karyotyping, which has low
resolution and limited ability to detect gains and losses of
chromosomal material. The use of array-CGH allows the
detection of chromosome abnormalities at a higher reso-
lution [Lapierre and Tachdjian, 2005].

Only 3 cases of sSMC studied by microarray analysis
and associated with male or female infertility showed ge-
nomic imbalances and highlighted duplicated genes (ta-
ble 1). The first case presented a 3.6 Mb sSMC(15) asso-
ciated with a severe OAT [Guediche et al., 2012a]. In this
sSMC, 18 genes were mapped including the POTE gene
(POTE ankyrin domain family member B) that has been
identified to be expressed in human testis, particularly in
a specific cell type in spermatogenesis, the primary sper-
matocytes [Ise et al., 2008]. The high and specific expres-
sion of POTE in primary spermatocytes, some of which
are undergoing apoptosis, suggests a role in inducing pro-
grammed cell death, and the duplication of this gene
could explain the semen alteration of this patient. He also
has a brother that presented the same sSMC(15) with a
duplication of POTE without semen alteration. The po-
potential impact of sSMC on the predisposition to infertility depends also on others parameters, like the genetic background of the patients or if the sSMC is de novo or not.

The second case presented a POF at the age of 33 associated with a sSMC(21) [Guediche et al., 2012a]. Array-CGH data showed 6 duplicated genes including 5 genes belonging to the BAGE (B melanoma antigen) family which are expressed in some ovarian tumors [Zhang et al., 2010]. In the current study, mRNA expression showed that BAGE was not related to menopause [Zhang et al., 2010]. This patient did not present ovarian cancer, and the duplicated genes have not been described in association with POF.

The third case presented 2 sSMC associated with repeated abortions [Guediche et al., 2012b]. In the 3.3-Mb DNA fragment of sSMC(20), 35 genes were mapped. Among them, the THBD gene codes for thrombomodulin, an endothelial-associated anticoagulant protein involved in the control of hemostasis and inflammation at the vascular beds [Anastasiou et al., 2012]. This protein is also a cofactor of the protein C anticoagulant pathway which is expressed mainly on the endothelial surface of blood vessels and in placental syncytiotrophoblast cells [Stortoni et al., 2012] and therefore could be involved in the pathogenesis of pregnancy loss in this case.

Further studies by microarray analysis of the genes present in sSMC and their involvement in human infertility are needed to gain more information about their possible role in the observed symptoms.

Preimplantation Genetic Diagnosis for sSMC Associated with Infertility

The diagnosis of a sSMC, like that of any other chromosomal abnormality, has a profound impact on the whole family involved. In the case of infertility, the diagnosis of a sSMC must be evoked as one of the possible causes of the problems of the couple.

Preimplantation genetic diagnosis (PGD) is often used for selection of normal and balanced embryos for transfer during in vitro fertilization [Munne, 2002; Simopoulou et al., 2003; Munne, 2005; Otani et al., 2006]. Indeed, using appropriate specific probes, PGD can detect sSMC in pre-implantation embryos from sSMC carriers as well as aneuploidy in the embryos.

Two studies reported the use of PGD for sSMC carriers. The first paper concerns a sSMC that was identified as a familial heterochromatic dicentric derivative of chromosome 15 in a phenotypically normal male presenting primary infertility [Oracova et al., 2009]. Investigations of somatic cells combined with sperm analysis suggested genetic counseling of the couple. FISH analysis of sperm and blastomeres (PGD) was used to determine the segregation ratio of the sSMC and aneuploidy of chromosomes 13, 15, 16, 18, 21, 22, X, and Y. sSMC(15) was observed in 41% of preimplantation embryos, and the frequency of chromosomally normal embryos in PGD analysis was 40%. According to Oracova et al. [2009], it seems that the presence of sSMC(15) does not adversely affect the early development of the embryos’ morphology.

The second study concerns a supernumerary ring chromosome 22 that derived from an interstitial deletion with one of the breaks occurring at the centromere [Mantzouratou et al., 2009]. Ring/del cases can be considered to form a special subgroup among sSMC. In the case of the ring/del situation, the additional material is compensated for by the deletion, and the phenotype is normal. The couple requested PGD following the birth of a son with a mosaic karyotype. In his lymphocytes, one cell line had a copy of the ring 22 chromosome in addition to the normal 46XY complement while in other cells the ring has been lost. Twelve embryos were analyzed, and the data showed that no embryos were completely normal or balanced for chromosome 22 by day 5.

In cases of previous repeated abortions in a couple with a sSMC carrier, PGD can be considered. It can avoid the transfer of embryos carrying the sSMC, as its presence could probably be the reason of implantation failures or early embryo development perturbations. In other cases, when a member of a couple presents a sSMC associated with OAT or amenorrhea or when the infertility remains unexplained, the indication of a prenatal diagnosis in case of a pregnancy can be discussed. Considering the fact that the parent who carries the sSMC has a normal phenotype (except for infertility), the probability that the fetus presents abnormalities is low. Nevertheless, the counselor has to provide information about all known facts on sSMC and to consider the possible occurrence of additional chromosomal anomalies. Furthermore, sensitivity problems of some array platforms in the pericentromeric and boundary regions of heterochromatin can complicate analysis.

sSMC are frequently complex, and whole array-CGH characterization of the sSMC provides informed genetic counseling [Reddy et al., 2013]. For some cases, it can be speculated that the chromosomal aberration led to an even more imbalanced, and subsequently unviable, situation in the potential offspring than that present in the...
sSMC carriers themselves. The parents need to be aware that their future child could also present the same infertility problems as they are. Finally, if appropriate, the problem of uniparental disomy should be discussed [Liehr et al., 2011].

In conclusion, the implication of sSMC in infertility could be due to partial trisomy of some genes but also to mechanical effects perturbing meiosis. The genes included in these regions have to be precisely identified as their presence on the sSMC can disrupt their expression. A single microarray analysis has the capacity to generate information allowing the rapid identification of the specific gene content of sSMC at a high resolution, therefore defining the genotype-phenotype correlations associated with sSMC and infertility. Microarray analysis is also a precious tool for a precise and prudent genetic counseling as it informs on the sSMC content.

Further precise molecular and interphase-architecture studies on sSMC are needed in the future to characterize the relationship between this chromosomal anomaly and human infertility.

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References


