Novel phenotype of mouse spermatozoa following deletion of nine -defensin genes

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Epididymis VI

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**INVITED REVIEW**

**Novel phenotype of mouse spermatozoa following deletion of nine β-defensin genes**

Julia R Dorin

β-defensin peptides are a large family of antimicrobial peptides. Although they kill microbes *in vitro* and interact with immune cells, the precise role of these genes *in vivo* remains uncertain. Despite their inducible presence at mucosal surfaces, their main site of expression is the epididymis. Recent evidence suggests that a major function of these peptides is in sperm maturation. In addition to previous work suggesting this, at the MRC Human Genetics Unit, Edinburgh, has shown that homozygous deletion of a cluster of nine β-defensin genes in the mouse results in profound male sterility. The spermatozoa derived from the mutants had reduced motility and increased fragility. Epididymal spermatozoa isolated from the cauda region of the homozygous mutants demonstrated precocious capacitation and increased spontaneous acrosome reactions compared with those from wild-types. Despite this, these mutant spermatozoa had reduced ability to bind to the zona pellucida of oocytes. Ultrastructural examination revealed a disintegration of the microtubule structure of mutant-derived spermatozoa isolated from the epididymal cauda region, but not from the caput. Consistent with premature acrosome reaction and hyperactivation, spermatozoa from mutant animals had significantly increased intracellular calcium content. This work demonstrates that *in vivo* β-defensins are essential for successful sperm maturation, and that their disruption alters intracellular calcium levels, which most likely leads to premature activation and spontaneous acrosome reactions that result in hyperactivation and loss of microtubule structure of the axoneme. Determining which of the nine genes are responsible for the phenotype and the relevance to human sperm function is important for future work on male infertility.


**Keywords:** acrosome reaction; antimicrobial; capacitation; epididymis; sperm; β-defensins

**BACKGROUND TO β-DEFENSINS**

β-defensins are cationic peptides with a canonical six cysteines in their mature secreted form, which were first isolated as antimicrobials, and their presumed function is in host defense. The β-defensin gene family consists of 40 family members at five gene loci in humans and more than 50 genes over four loci in the mouse. The main cluster is on chromosome 8 in both humans and mice with 10 and 31 β-defensin genes, respectively. In humans, seven of the chromosome 8 genes lie at two distinct loci approximately 5 Mb apart as highly copy number variable(CNV) clusters, which vary between 2 and 7 copies per genome.

It is, therefore, possible that phenotypic change may be present owing to reduced or increased copy number. Increased copy number above the mean diploid number of 4 has been associated with an increased risk of psoriasis. It is evident that the evolutionary history of this gene family is complex with evidence for both rapid positive as well as negative selection. Despite recent evidence of an increasing functional repertoire of β-defensin peptides, which includes involvement in pigmentation, immune cell attraction and immunomodulation, the physiological function of mammalian β-defensins *in vivo* remains uncertain.

**Previous work on the importance of β-defensins in sperm function**

Interestingly, β-defensins are highly expressed under normal conditions in different segments of the epididymal epithelium and are likely to be secreted into the lumen, and some have been shown to be present on the plasma membrane of sperm cells. It seems likely therefore that they are involved in reproductive function, and a few studies over the last decade have suggested that β-defensins influence sperm maturation.

The rat β-defensin Bin1b (SPAG11 or EP2) has been shown to induce immature and immotile spermatozoa to become progressively motile *in vitro*. In addition, the β-defensin DEFB126 on chromosome 20 has recently been linked to the ability of human spermatozoa to penetrate hyaluronic acid gel (which mimics the consistency of female cervical secretions). Men homozygous for a frameshift mutation in *DEFB126* are not infertile but have reduced the chance of paternity in the first year. DEFB126 is quite different from other β-defensins, as it has an extensive C-terminal tail containing O-linked glycosylation sites that are not seen in other defensins. It is presumed that this glycosylation is important for its function. Additionally, in the rat incomplete knockdown of Defb15 suggests that this peptide influences sperm motility, but apparently not the capacitation process or the acrosome reaction (AR).

Most recently low levels of human β-defensin 1 (hBD1) have been found in spermatozoa from infertile men with low sperm motility. This work also shows that the affected spermatozoa have a defect in bacteriocidal activity, and this can be corrected by addition of exogenous peptide.

**GENERATION OF A β-DEFENSIN GENE KNOCKOUT IN THE MOUSE**

The mouse is a good model of certain aspects of innate immunity although...
many of the multigene families have species- or environment-specific clades, and the β-defensin family is no exception. Some of the human defensin genes have single-gene orthologues in the mouse whereas some have several paralogues. Single-gene deletion can result in an obscure phenotype, as functional redundancy in gene families can play a significant role in obscuring functional roles. Some years ago my laboratory, and others created mice that were deleted for Defb1 (the mouse orthologue of the gene for hBD1) and the homozygous animals had a subtle gross phenotype: a defect in bacterial clearance from the airway and an increased number of inflammatory cytokines in sera, and the mutant animals all had a normal obvious phenotype, although PCR analyses on genomic DNA or RT-PCR on cDNA synthesized from RNA from epididymides demonstrated evidence of comparable numbers of spermatozoa in the lumen. However, the homozygous mice produced from the ES cell lines (official allele name Del(chr8Defb1-Defb13)JrDo but abbreviated here to DefbΔ9), had no obvious phenotype, although PCR analyses on genomic DNA or RT-PCR on cDNA synthesized from RNA from epididymides demonstrated the presence and expression of the nine deleted defensin genes in both heterozygous and wild-type mice, but their absence from homozygous mutant animals. Importantly, genes that are expressed in the epididymis and adjacent to, but outside the deletion (including Bin1b and Defb33), were not altered in their expression level. We did not find any increase in inflammatory cytokines in sera, and the mutant animals all had a normal body weight. Genotypic classes from heterozygous crosses were all in the expected 1:2:1 Mendelian ratio.

The homozygous deletion mice did, however, have an increased level of bacteria in urine extracted from the bladder. This supported the work that we had published previously on the Defb1 KO mice; Defb1 being one of the genes deleted in the defensin cluster KO mice. β-defensins are classically known as antimicrobial peptides, so we tested the mature peptides in vitro against a Gram-negative bacterium (Pseudomonas aeruginosa, PA01); all the peptides except Defb15 were strong antimicrobials in either oxidized or reduced form. The active antimicrobials include Defb50, which does not have the canonical six cysteines (the second cysteine of the motif is missing)(see Table 1). Defb50 has poor antimicrobial activity in its oxidized form, but even this improves under reduced conditions. These results support recent work by Schroeder et al. which suggests that some β-defensins display improved activity following reduction. Despite deletion of the expression of these antimicrobials from the homozygous mice, there was no indication that the mutant mice had increased inflammatory profile under normal specific pathogen-free animal housing conditions.

### INFERTILITY PHENOTYPE OF MUTANT DEFBΔ9/DEFBΔ9 MICE

The mice that were initially produced as heterozygotes from chimeric animals derived from blastocysts injected with the ES cell gene-targeted lines and mated to C57Bl/6 females and were then inter-crossed to generate homozygous deletion mice. These mutant animals contained a high contribution of genetic background from the 129/Ola E14 ES cells, and the homozygous males at this point were fertile but showed a reduced ability to impregnate wild-type CD1 females. The male deletion mice sired equivalent numbers of litters but a low number of pups per litter. When the mice were inbred to four backcross generations onto C57Bl/6, the male homozygotes generated were completely infertile although homozygous females had normal fertility.

**DefbΔ9/DefbΔ9 spermatozoa are fragile**

In an effort to ascertain if the defect in fertility was due to sperm production, sperm numbers released from excised cauda region of the epididymis were assessed, but they were not significantly different between mutants males and wild-type C57Bl/6 male mice. In addition, tissue sections along the length of the epididymis were histologically normal, with evidence of comparable numbers of spermatozoa in the lumen. However, we did observe that isolated spermatozoa dropped onto a microscope slide were more fragile, as the number of headless tails counted was significantly higher in the mutants than in the wild-type animals.

**DefbΔ9/DefbΔ9 spermatozoa have reduced motility and spontaneous acrosome reactions**

In collaboration with Prof. Chris Barratt (University of Dundee), we used computer-assisted sperm analysis to determine the total and progressive motility of the spermatozoa from mutant and wild-type littermates. The sperm cells were very gently isolated from the cauda region of excised tissue to reduce any trauma to them, but nevertheless those from the mutants had a very obvious and significantly lower percentage of progressive motility both before capacitation, at zero time, and after capacitation.

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**Table 1: Amino acid sequence in single letter format, of the β-defensin peptides encoded by the genes deleted in the DefbΔ9/DefbΔ9 mice.**

<table>
<thead>
<tr>
<th>Peptide</th>
<th>Signal sequence</th>
<th>Mature peptide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defb 1</td>
<td>MKTHFYFLVMIGFLFSQMEPG</td>
<td>--VGLTSLGRRTDQYKCLQHGFCLRSCPSNTKLGQKTCKPDKNCCSK</td>
</tr>
<tr>
<td>Defb 2</td>
<td>MKLTCFLTLTSLLYLMVKGWGS</td>
<td>--HPGTFWMRKCPMPKMTAFGDCNSYSSMGLCNRNTKCSVCCMPVRFMDNI</td>
</tr>
<tr>
<td>Defb 3</td>
<td>MRTLCSLLICLFLSSYTTYTP</td>
<td>--AVGSLKIGYEAEAHLHHTNGRYQRACPPSARRPOSPEKPKNCCKYMK</td>
</tr>
<tr>
<td>Defb 9</td>
<td>MRTLCSLLICLFLSSYTTYPPANS</td>
<td>--IVGYSEMERHKKKGGYCYYFSSSHKKGDFPEWPRCKNICK</td>
</tr>
<tr>
<td>Defb 10</td>
<td>MRTLCSLLICLFLSSYTTYP</td>
<td>--AVGDLKHLIKAQTRCYYKFGGFHYNIQPQNSRFMSHCPNENLRCCKNQKF</td>
</tr>
<tr>
<td>Defb 11</td>
<td>MRTLCSLLICLFLSSYTTYPPAVG</td>
<td>--DLKHLIKALQRCDYKFGGGFYNMSCPPKTFCNQPDHHLHCINNKMKLEGST</td>
</tr>
<tr>
<td>Defb 35</td>
<td>MPQRTVFVFCLFVFQQLFPTG</td>
<td>--------EIAWETCLRLGKGR-RACCDEEEGKVGKLNKNNCCERR</td>
</tr>
<tr>
<td>Defb 15</td>
<td>MRTLFLELFVLFDEPAKN</td>
<td>--FDLDSRSRNGR-TTSLNKNEELAV-COQNKLCCVTVQFGGKSKSNQSDGSGHMGTWG</td>
</tr>
<tr>
<td>Defb 13</td>
<td>MRRISLIVAGLVLQGLYPAG</td>
<td>--TLYRRFLKKMNGGC-EAECFTFEQKICUTQANFLCLCRKREEH</td>
</tr>
</tbody>
</table>

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**β-defensins and sperm function**

J.R. Dorin
induction, at 90 min. Further work demonstrated that the deletion mouse-derived spermatozoa had a higher percentage of spontaneous acrosome reactions (ARs) at time 0 and also at 90 min. The presence of an intact acrosome was measured by several different techniques. The first was the ability of spermatozoa to bind a fluorescently-labelled Pisum sativum (PSA) lectin that interacts with to the glycoalcalyx carbohydrate molecules of the acrosome. Secondly, an antibody to zonadhesin was used to demonstrate if binding was increased owing to loss of the acrosome revealing the zonadhesin epitope that binds the antibody. Finally, acrosomal integrity following Coomassie Blue G250 staining of fixed sperm cells was determined since acrosome-reacted spermatozoa lack G250 staining. By all these criteria, the spermatozoa from the mutant males had significantly increased level of spontaneous ARs. The level present upon isolation was maximal, as it appeared to be equivalent to the level evident in wild-type mouse sperm incubated for 90 min in capacitation medium.

Capacitation is the process by which spermatozoa in close proximity to the egg in the female reproductive tract will undergo physiological and membrane changes that enable fertilization of the oocyte. No direct procedure is available to determine capacitation status, but AR induction provides information on the rate of capacitation. Therefore, the extent of sperm capacitation can be evaluated indirectly by measuring the number of cells without an acrosome (using PSA binding to indicate acrosomal presence) following induction of the AR, as only capacitated cells can undergo this process. Capacitation of spermatozoa isolated from the cauda epididymidis was induced by the calcium ionophore A23187. The DefbΔ9/DefbΔ9-derived spermatozoa displayed the maximal percentage of capacitation immediately after exposure to the drug. This level did not increase after 90 min, whereas the status of sperm capacitation for wild-type spermatozoa increased from 6% to 23% over this same period.

DefbΔ9/DefbΔ9 sperm cannot bind to unfertilized eggs

As the mutant-derived spermatozoa were both acrosome reacted and capacitated, we tested if they were able to fertilize eggs by using a sperm-egg binding assay with wild-type eggs. The number of wild-type spermatozoa that could bind to the cumulus-free eggs from superovulated CD1 females was around 20 per egg after 45 min, but only negligible numbers of mutant spermatozoa were bound. Recent studies in the mouse have shown that spermatozoa that have undergone the AR can penetrate the zona pellucida (ZP), although this is not an efficient process,

DefbΔ9/DefbΔ9-derived spermatozoa have disordered microtubular structures

When ultrastructural analyses were made with transmission electron microscopy on spermatozoa released from the cauda epididymidis, an abnormally high number of cells with disruption of the classic 9 + 2 microtubule arrangement in the axoneme of spermatozoa from the mutants was observed compared with spermatozoa from wild-type littermates (41% for −/− vs 4% for +/+). (see Figure 1). We also analyzed tissue samples from the caput and cauda regions and examined the structure of the sperm tails still within these organs so as to avoid artefacts producing damage due to processing. These analyses also revealed that spermatozoa present in the cauda (but not the caput or testes) of DefbΔ9/DefbΔ9 mutants showed an increase in the disruption of the microtubule structure, where the 9 + 2 arrangement was disintegrated. It may be of note that a very similar microtubular disruption phenotype is also seen in spermatozoa of mice with deletion of the group III secreted phospholipase A1 (sPLA1,-III), and as in the DefbΔ9 mutants, this is only present in sperm cells isolated from the cauda.

Interestingly, secreted phospholipase A2 enzymes have a cysteine-rich structure and, like defensins, exhibit antimicrobial activity.

When we measured the level of intracellular calcium in the mutant spermatozoa isolated from the cauda of the homozygous DefbΔ9/DefbΔ9 males, we found that it was significantly higher than that of wild-type spermatozoa under the same conditions. Thus, in the absence of the deleted β-defensins, there is a significant increase in intracellular calcium, and the likely consequence of this is an increase in spontaneous AR and microtubule disruption (possibly caused by hyperactivation). Normal spermatozoa may be able to withstand premature activation,

UNANSWERED QUESTIONS REMAIN

These data show a clear function of one or more of the β-defensins in the deleted cluster being essential for sperm function, but it is not known if the sterility of the male reproductive tract is compromised. Is loss of genes with in vitro antimicrobial function important in vivo for infection defense? What of the immunomodulatory activity of defensins: is this of relevance in the epididymis? At the moment, we do not know which of the nine defensins genes are responsible for the unique fertility phenotype.

It is suggested that epididymal maturation of sperm cells more likely occurs in the caput or corpus of the epididymis rather than the cauda. The defensins present in the deletion have been shown to be present in distinct regions of the epididymis. Defb15, 35 and 13 are expressed in the upper region (segments 1, 5 and 6, respectively), whereas Defb2, 9, 10, 11 and 50 expression is focused in segment 8 of the cauda region, while Defb1 is expressed in the penultimate segment of the epididymis.
Using mass spectrometry, we have only been able so far to detect Defb2, Defb11, and Defb15 on isolated wild-type cauda spermatozoa. Rat Defb15 has been reported to bind to the acrosomal region of caput sperm cells, and incomplete knockdown results in rats with reduced sperm motility, but no defect in capacitation or AR.13 Interestingly, Defb15 has an extended carboxyl tail containing an extra cysteine and six potential serine or threonine residues that would support O-linked glycosylation. O-linked glycosylation is considered a key feature of the function of DEFB126 in human spermatozoa, and it also seems to affect the ability of spermatozoa to move in a viscous hyaluronic acid used as a cervical mucus substitute. There is a parologue of Defb15 not within the deleted region, and this gene (Defb34) is only three amino acids different from Defb15 in the mature segment of the peptide, which may make Defb15 a less likely candidate to affect spermatozoa.

It may be that deletion of a single-gene might not demonstrate a strong enough phenotype for it to be easily recognized. The three human orthologues to Defb15, Defb35 and Defb13 (DEFB106, DEFB105 and DEFB107, respectively) are on the chromosome 8p23.1 highly copy number-variable block. In primates, protection against loss of fertility from mutation might be a selective advantage that allows the increase in number-variable block. In primates, protection against loss of fertility from mutation might be a selective advantage that allows the increase in number-variable block.

CONCLUDING REMARKS

For the first time, we show here that β-defensin antimicrobial peptide genes have a profound effect on sperm function in vivo, and this is manifest in the Defb105/Defb106 mice by increased intracellular calcium, precocious capacitation, increased spontaneous ARs, and microtubule destabilization, which results in lack of motility and profound infertility. This provides evidence for β-defensins being essential for appropriate control of intracellular calcium and regulation of the AR. It is most likely that their loss results in destabilization of the sperm membrane that allows calcium influx and microtubule disruption. This improved understanding of the function of these antimicrobial peptides in mice leads the way to investigating the role of the human orthologues in sperm function and fertility, and opens the possibility of the development of novel contraceptive agents with antimicrobial action for local use in the female reproductive tract.

COMPETING FINANCIAL INTERESTS

The author declares no competing interest.

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