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SHORT COMMUNICATION

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Why so many sperm cells? Not only a possible means of mitigating the hazards inherent to human reproduction but also an indicator of an exaptation

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ABSTRACT

Redundancy—the excess of supply over necessity—has recently been proposed for human sperm cells. However, the apparent superfluity of cell numbers may be necessary in order to circumvent the hazards, many of which can be quantified, that can occur during the transition from gametogenesis within the testes to zygosis within the female reproductive tract. Sperm cell numbers are directly related to testicular volume, and it is owing to a redundancy, and the possible exaptation, of this latter parameter that a putative excess of sperm cells is perceived.

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The question was recently posed, "Why so many sperm cells?,"[1] the context for which was with respect to human reproduction and, specifically, to the fertility of the adult male. Related to this parameter, however, is concern over the recent world-wide decline of sperm cell numbers and semen quality,[2-7] a trend which also takes into account possible increases and decreases in these parameters due to circannual and seasonal variations,[8,9] particularly in temperate zones.

The initial problem—that of the apparent redundancy of sperm numbers—reduces to the observation that the fertilization of one single egg liberated by the ovary of a female appears to require the deposition of an ejaculate from the male of many tens of millions of sperm cells. Although Reynaud et al.[1] note the evident fact that only one sperm cell effects a fertilization, this single sperm cell is one of many 'front runners' at the leading edge of a swarm of such cells. The timecourse of the arrival of other viable sperm at the location of the ovum in the female reproductive tract seems not to have been studied; nor, apparently, has effect of the volume of seminal fluid deposited been considered in the context of the rate of advancement of this sperm-bearing wave-front which eventually envelopes the ovum. Leaving aside the possibility of cell-cell cooperation during the mass migration of spermatozoa and the possible roles in this latter process of materials such as semenogelin contributed by the male,[10,11] and of female secretions within the uterine tract,[12,13] as well as chemotactic signaling between sperm and the ovum and its associated cells,[11] sperm superfluity is certainly striking when the ratio of the two gametic units (generalized as "tens of millions of sperm" to one egg) is considered purely in numerical terms.[1]

The solution to the redundancy question is, in Reynaud's view,[1] to posit the hazardous nature of the journey which spermatozoa must take within the uterine environment. Even supposing that chemotaxis and rheotaxis provide positive cues for male and female gametes to meet,[12,14] the topology of the uterine tract and its surface provides what appears to be a formidable obstacle to this meeting.[15,16] Some of the parameters, which are considered critical in this respect, have been identified,[17] and their contribution to fertilization mathematically modeled.[18]

However, excessive numbers of sperm cells can be considered in other ways if the totality of the human reproductive system is taken into account. Let us, therefore, define this supposed redundancy more closely. First, from the numerical point of view, the critical number of spermatozoa necessary, in a single ejaculate, to effect fertilization needs to be ascertained. The World Health Organization (WHO) guidelines on fertility indicate that the minimum total sperm count (TSC) required to reach a threshold probability of fertilization is between 18 and 29×10^6, the 95% CI around the 2.5th centile value of 23 $\times 10^6$.[19] The upper value for this range, 29×10^6, can be called the 'critical TSC'. Nevertheless, the TSC of normal healthy males, including those of proven fertility, varies considerably. An average ejaculate of volume 3.0–3.2 ml may contain between $46-259 \times 10^6$ sperm,[20] $38-751 \times$

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10^6,[21] or 52−837 × 10^6,[22] with an extreme limit of 1000 × 10^6.[19] Some of this numerical variation can be attributed to variation in the body mass and diet of the males studied.[21] There is also the important question of the proportion of sperm which are motile and of normal morphology as opposed to the proportion which are inert and mis-shapen. The motile fraction of the TSC ranges from to 65 to 75%.[19,20,22,23] It has been found that the mis-shapen sperm characteristic of young mice (CB57 and KE strains) are unable to negotiate the labyrinthine uterine surface,[24] and thus do not reach the oviduct. Thus, the fraction of non-motile sperm allows refinement of the question of redundancy of total sperm number per ejaculate: that is, there needs to be compensation through extra numbers for the non-fertile fraction of sperm cells if a certain rate of conception is to be maintained. Accordingly, it is the effective TSC (ETSC) which needs to be considered.

Another factor relating to superfluity of sperm cells is the probability of a conception from a single copulatory event. At the time of maximum female fertility during the menstrual cycle, and considering an unselected population sample, the probability of a conception has been estimated as 10%, whereas a value of 3% applies at apparently non-fertile times of the cycle.[25] Presumably, the ETSC has an influence on this 10% value; the conception rate could perhaps be raised if the TSC were large and composed of a high proportion of motile sperm.

The redundancy question can therefore be made more precise: if a TSC of, say, 29 × 10^6 (the critical number, at the mentioned upper boundary of the 2.5th centile in the WHO estimate) can secure a conception,[19] then what is the significance of ejaculates whose TSC values are regularly 10 times this critical number, or even greater? Two possibilities come to mind, and both would suggest that redundancy is less dramatic than it might appear. The first possibility does, indeed, relate to sperm numbers, but does so in a context where there is competition, within the vaginal and uterine tracts, between sperm of different males. The second relates only indirectly to the TSC, and draws attention to the size and structure of the pair of organs, the testes, which are its proximate source. It is in this context, as we shall see, that the possibility of a partial 'exaptation' arises, this term referring to the modification, by natural selection, of a structure which previously was dedicated to another purpose.[26]

First, regarding sperm competition: Although not much can be inferred about human sexuality in the remote past, when human communities were developing, and when, in all probability, humans and their reproductive strategies were evolving,[27] it is likely that male and female sexual behaviors, during, say, the crucial era of the Palaeolithic,[28] a period lasting about 2 × 10^6 years before present (that is, a period corresponding to approx. 80,000 human generation), were not greatly different to what they are today.[29] If anything, behaviors could have been much more free and open, unhindered by restriction imposed upon sexual play and copulation by any authoritarian body or Ecclesia. Given this more liberal—and evolutionarily formative—scenario, then a single female might regularly have participated in successive copulations with a number of males at any one time.[30] In such a polyandrous, or even promiscuous, society, competition between sperm of the different males within the uterine tract would have featured as an evolutionary factor. From the multiple ejaculates received by a female, the one that was most voluminous and with the greatest ETSC would be the one most likely to secure a conception. Moreover, if, in this polyandrous group, the male with the greatest ETSC was sufficiently judicious or intelligent to be the last to ejaculate,[31] the probability of his reproductive success would be increased,[32] particularly, as Reynaud et al. comment,[1] and others have confirmed,[33,34] if the post-ejaculatory withdrawal of the penis from the vagina also withdraws a fraction of previously deposited ejaculates. Thus, the male with the greatest ETSC—and with apparently the greatest redundancy of sperm—may actually show the best reproductive strategy, siring more offspring with similar characteristics (if they were males) than other sexually competing males with lower ETSC. Sperm superfluity could tend to become a desirable evolutionary 'goal'.

Second, regarding total sperm count and total testicular volume: The critical TSC of 29 million is achieved when a certain total testicular volume (TTV) is reached during male maturation. This is the critical TTV. Its value has been estimated by ultrasonography (which is considered to give a more accurate estimate of testicular volume than the older method of orchidometry) as between 20 and 30 ml.[23,35] A similar estimate can be reached from orchidometry,[20] using an appropriate correction factor to allow comparison with ultrasonographic data. Nevertheless, it is clear that there is much variation in the value of TTV associated with the attainment of a critical TSC of 29 × 10^6.[22,36,37]

What, therefore, is the relationship between sperm quantities in excess of the critical TSC of 29 million and the TTV? During male maturation, final testis volume is approached at the age of 18 years,[38,39] with a small increase in volume occurring for a further 10 years.[40] Thus, both the rate of sperm production and the TSC are determined in accordance with the TTV. The estimated 4-fold range of TTV (25–100 ml, estimated by orchidometry) is mirrored in a corresponding range of TSC values (50–200 × 10^6 or more).[22,37] Moreover, when both TTV and the proportion of motile sperm in the

TSC have been estimated in the same group of men, it has been found that large TTV values are associated with a large motile fraction; i.e., ETSC is higher when TTV is large, than when TTV is small.

The relationship of sperm numbers and testis volume can also be established from another, rather different type of study—that of infertile men.[41-43] In the most detailed of such studies, Sakamoto et al.[43] surveyed >500 men attending an infertility clinic and assigned their TTV values to size classes (B to I) that ranged from 10–15 ml to 45–50 ml, the larger values (in classes E-F of 30 mls upwards) being in the same range as for males in the general population.[20,23] Assessment of the whole of this infertile group, where TSC ranged from near zero to 400×10^6, TSC correlated with TTV ($r = 0.49$). Individuals with TTV <30 ml, besides being infertile, were oligospermic, and it may be supposed that development of their testes had been arrested at a juvenile stage. In cases where TTV was >30 ml, testicular growth presumably either proceeded normally and commenced earlier than usual, or continued for a longer period (see ref. 38) in order to account for TTV values in excess of the critical TTV value of 30 ml.

From the data collected from both fertile and infertile men, it can be concluded that the redundancy of sperm numbers per ejaculate is the consequence of a TTV value greater than that necessary to provide the critical TSC value of 29 million. Thus, if anything, superfluity of sperm numbers is the consequence of a redundantly large TTV. Accordingly, some explanation should be found for this feature, for it is this feature which creates the perception of sperm redundancy. Hence, the question arises of whether a TTV in excess of the critical volume commensurate with the critical TSC of 29×10^6 sperm is a partial exaptation: that is, the high testicular volume and mass have acquired a function which is beyond that of simply providing an extra—and apparently superfluous—number of sperm cells. The answer might lie in unexpected areas of human biology.

According to Short,[44] who surveyed a range of primate species for testis weight (volume) and body mass, these parameters seem to reflect the species' mating system (monogamous, promiscuous or polygamous). Short considered humans to be monogamous,[44] although his own criteria appear to place them at the interface with the promiscuous, a supposition mentioned earlier. Also noted was that the size of the human testes and their rate of sperm production were such that male germ cells would seem to be sites of high mutation rate.[44] A means of mitigating this disadvantage, is for the testes to be held in an external scrotum (as is the case in many species) where heat exchange via the Pampiniform plexus can readily take place, thereby diminishing the probability of heat-induced male germ-line mutation, an event believed to have a $Q_{10} \approx 6$,[45] and which might be linked to heat-induced oxidative stress.[46] Therefore, given a mixture of mutated, non-mobile/infertile sperm and normal fertile sperm in any given ejaculate, any increase in the number of normal sperm which compensates for those which are infertile would be desirable and would become possible if the TTV were to be increased above the critical value.

There could, however, be another, but related, reason, based on exaptive advantage, for not only the presence of testes with high TTV and additional mass but also their enclosure within an external scrotum. Assisted by an additional exaptive mass, the movement of the testes back and forth within the scrotum during copulation, as well as the raising of the testes into the inguinal canal prior to semen emission, may, respectively, accelerate the onset of emission (as a consequence of the exaptation) and maximise the TSC of the ejaculate. There also may be a visual aspect to the testicle-bearing scrotum which aids sexual selection, especially if TTV were exaptive and large, for there is an appeal to the human psyche of objects whose dimensions conform to the Golden Ratio,[47] φ, where $\varphi = b/a = 1.61$, variables a and b being lengths, and where $a > b$. Estimating a Golden Ellipsoid Ratio for testes, where a = testis length and b = testis depth, and using the data of Sakamoto[42] on human testis dimensions, we find that where the testes are small (class C), $\varphi = 1.92$, but where testes are larger, of critical TTV or above (class F), $\varphi = 1.63$ (close to the Golden Ratio); other data[22] for testicular dimensions give a similar value of $\varphi = 1.82$. Or, if for *b*, the combined testicular (~ scrotal) width is used, then for class C, $\varphi = 1.36$, whereas for class F $\varphi = 1.48$. Testes characterized by the Golden Ratio, especially if large (i.e., exaptive) and hence more eye-catching, might, together with other body parameters,[48,49] therefore be preferred by females – and, as Short put it,[44] become 'the engine if desire' – thereby rendering males with large TTV as desirable mates.

The enlargement of the testes to volumes which minimise the above-mentioned hazards could itself seem a redundancy, but which is here proposed to be a type of exaptation. This feature also appears to be an 'over-topping' phenomenon: and here reference can be made to Zimmermann's telome theory,[50] originally conceived in the context of plant morphology and phylogeny.[51] The concept of 'over-topping' (which is evidenced in the evolution of structures as diverse as redwood cedars and 4 × 4 automobiles) was originally suggested to describe the step by which a shoot system with equal dichotomous branching achieves the state where branching is unequal, with one bud and its branch outgrowing, or over-topping, a sister bud and its branch. The outcome is of both structural and reproductive advantage. In the case of

testes and sperm, the over-topping principle is, in fact, the acquisition of a new property that has become the means by which certain males develop not only a TTV greater than the TTV of congeneric males but who also gain reproductive advantage thereby.

Although not directly within the scope of the present article, it seems appropriate, in the light of the argument presented, to comment on the world-wide decline of TSC. As discussed, TSC is related to TTV, and therefore it may be asked whether the decline in the former over, say, the last 50 years, can be accounted for by a proportional reduction of testicular volume. This question seems not to have been addressed, even though the mentioned relationship between TTV and TSC points to this as a logical possibility. Nevertheless, the timecourse of the decline in sperm counts appears to coincide with an increase in testicular dysgenesis (e.g., testicular neoplasias),[6,52,53] a syndrome whose etiology may relate to exposure of affected men to toxins while they were at the foetal stage; or maybe due to some effect at a previous generation whose persistence is transmitted via epigenetic mutation.[54] It might be asked, therefore, whether the proposed exaptive increase of TTV is a relatively recent phenomenon, and has not been expressed equally throughout all populations of human males, as the diversity of TTVs might suggest,[36] and whether the observed increased incidence of testicular dysgenesis is a consequence of the increased and exaptive TTV.

Abbreviations

CI	confidence interval
ETSC	effective total sperm count
TSC	total sperm count
TTV	total testicular volume
WHO	World Health Organization

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No potential conflicts of interest were disclosed

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