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Relations between the fertilizing ability, motility and metabolism of epididymal spermatozoa

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Summary. This paper compares the principal modifications taking place in spermatozoa during epididymal transit in several species. The relations between changes in the epididymal medium and modifications in the metabolism, motility and/or fertility of spermatozoa are reviewed with particular reference to spermatozoon forward motility. The fertilizing ability of motile testicular and epididymal spermatozoa has been described.

It is suggested that the maturation process may induce a series of spermatozoal changes in cyclic AMP content, external membrane composition and nuclear structure throughout the genital tract ; these changes would be under the control of the epididymal epithelium. The origins of these phenomena are practically unknown.

Introduction.

During their transit through the epididymis, non-motile, infertile spermatozoa, formed in the testis, progressively acquire the ability to move and fertilize an egg, thus producing a viable embryo. Although this process was discovered several decades ago, the origin of the morphological, biochemical and metabolic changes (Bedford, 1975 ; Voglmayr, 1975 ; Orgebin-Crist, Danzo and Davies, 1975) affecting these gametes is still unknown. Present research in this field is seeking to find methods of controlling the acquisition of this fertilizing ability in order to either reduce it (human contraception) or, on the contrary, increase it, as in the case of masculine sterility or during seasonal sexual quiescence in domestic animals.

Since the different changes affecting gametes have been localized in the epididymis, recent work is oriented to studies on the specific influence of well-determined regions of that organ. The relations between changes in the epididymal medium and quantifiable modifications in the metabolism, motility and/or fertility of spermatozoa are investigated in this paper.

I. — Spermatozoon changes during epididymal transit.

A. — *Localization of the development of fertilizing ability in different mammalian species.*

In spite of differences in the length and diameter of the epididymal duct, mammalian epididymides have three distinct anatomical regions in common : the anterior (caput epididymis), median (corpus epididymis) and posterior (cauda epididymis) regions (fig. 1) .

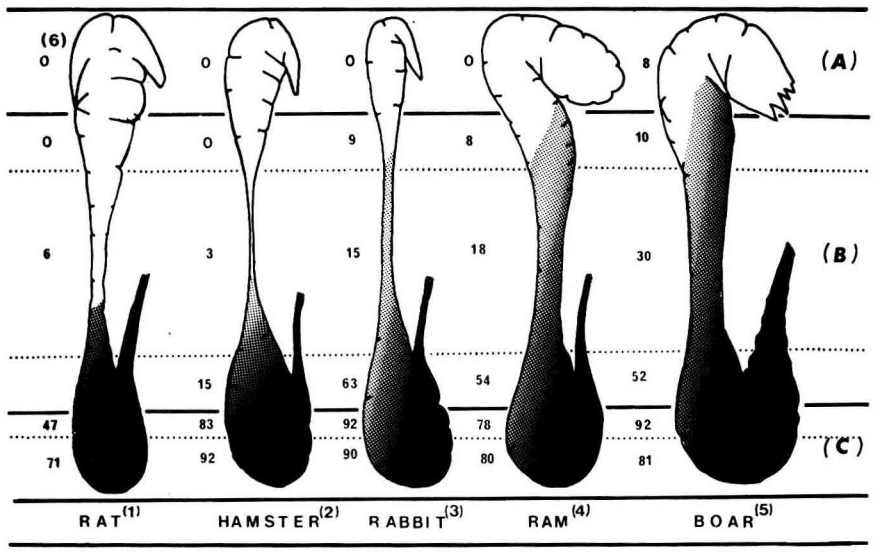

FIG. 1. — *Comparative analysis of the fertilizing ability of spermatozoa from different regions of the mammalian epididymis.* A : Caput epididymis ; B : Corpus epididymis ; C : Cauda epididymis. The gray areas indicate that fertile spermatozoa are present. Results from : 1. Dyson and Orgebin-Crist (1973) ; 2. Horan and Bedford (1972) ; 3. Bedford (1966) ; Orgebin-Crist and Jahad (1977) ; 4. Fournier-Delpech *et al.* (1979) ; 5. Holtz and Smidt (1976) ; 6. Fertility rate.

In all the species studied, spermatozoon fertilizing ability tested by intra-uterine or intra-oviductal insemination, is practically zero in the caput epididymis, develops in the corpus epididymis and is maximum in the cauda epididymis. In the rabbit (Orgebin-Crist, 1967 ; Orgebin-Crist and Jahad, 1977) and boar (Holtz and Smidt, 1976), maximum fertilizing ability (92 p. 100) is attained when the spermatozoa are sampled in the proximal cauda epididymis, while in other species, such as the rat (Blandau and Rumery, 1964 ; Dyson and Orgebin-Crist, 1973), hamster (Horan and Bedford, 1972), ram (Fournier-Delpech et *al.*, 1979) this fertilizing ability is attained only with spermatozoa from the distal cauda epididymis.

Thus, in many species, the fertilizing ability increases suddenly in the distal corpus epididymis, although in the boar there seems to be a regular augmentation between the caput and the cauda epididymis (fig. 1).

Moreover, there are frequent individual variations between animals of the same species ; 23 p. 100 of rabbits already have fertile spermatozoa in the proximal corpus epididymis and 10 p. 100 can fertilize at least 70 p. 100 of the oocytes (Orgebin-Crist and Jahad, 1977). The fertilization gradient obtained *in vitro* in the rabbit is slightly different from the former one since the fertilizing ability of spermatozoa from the caput epididymis is detected earlier (Brackett, Hall and Oh, 1978). The observation of many developmental abnormalities in eggs fertilized by spermatozoa from the proximal corpus epididymis suggests that additional nuclear changes are necessary for normal fertilization to be followed by proper egg development (Orgebin-Crist and Jahad, 1977 ; Brackett, Hall and Oh, 1978 ; Fournier-Delpech *et al.*, 1979).

B. — *Motility of epididymal spermatozoa.*

The acquisition and change in spermatozoon motility during epididymal transit have been amply described for many years (Tournade, 1913 ; Blandau and Rumery, 1964 ; Gaddum, 1968). However, these changes have been quantified and systematically localized in only a few species.

1) *In their own medium.* — Large between-species differences are apparent (table 1) ; if the spermatozoa are taken and incubated in their epididymal fluid, the number of motile gametes is zero in the boar (Dacheux and Paquignon, 1979, unpublished data) or very low at all epididymal levels in the rat or hamster (Wyker and Howards, 1977 ; Morton, Sagadraca and Fraser, 1978 ; Turner, d'Addario and Howards, 1978). However, in monkeys (Hinton *et al.*, 1979*a*), humans and rabbits (Morton *et al.*, 1978) or rams (Dacheux and Paquignon, 1979, unpublished data) motile spermatozoa appear in the corpus epididymis and their number and motility increase in the cauda epididymis.

TABLE 1

Motility of spermatozoa incubated in their own epididymal medium

Species	Sperm origin				References
	Testis	Caput ep.	Corpus ep.	Cauda ep.	
Boar	—	—	—	—	(1)
Rat	—	—	—	(+)	(2)
Mouse	—	—	—	(+)	(2)
Bull	—	—	+	++	(2)
Ram	—	—	+	+++	(1)
Rabbit	—	(+)	+	++	(2)
Monkey				+++	(3)
Man.....		+	++	+++	(2)

(1) Dacheux and Paquignon, 1979 ; (2) Morton *et al.*, 1978 ; (3) Hinton *et al.*, 1979*a*.

2) *Potential motility.* — In some species (the mouse, rat, monkey, human) immobile spermatozoa in the epididymal medium develop motility after dilution (Morton *et al.*, 1978 ; Turner, d'Addario and Howards, 1978 ; Hinton, Dott and Setchell, 1979). The number of motile gametes in these conditions increases regularly between the caput

and the caudal epididymis (table 2). The causes of this initiation of motility are not well known but the presence of calcium and the increase of intracellular cyclic AMP seem to be necessary (Morton *et al.*, 1978).

TABLE 2

Motility of epididymal spermatozoa after dilution

		RTF	Caput		Corpus			Cauda		
			Prox.	Dist.	Prox.	Med.	Dist.	Prox.	Med.	Dist.
Ram	(A)	0	0	1	5		56	66		83 (1)
Boar ...	(B)	0	0	2	10	30	46	52	75	75 (2) (3)

(1) Fournier-Delpech *et al.*, 1979 ; (2) Schellpfeffer and Hunter, 1976 ; (3) Dacheux and Paquignon, 1980.
(A) p. 100 of spermatozoa showing forward motility ; (B) p. 100 of motile spermatozoa.

The spermatozoon system of locomotion thus also begins maturation in the corpus epididymis.

C. — *Metabolism of epididymal spermatozoa.*

The metabolic changes (increase of oxidative and glycolytic metabolisms and decrease of lipid syntheses) occurring in spermatozoa entering and leaving the epididymis have been amply described (Voglmayr, 1975). The exact localization of these changes in the boar epididymis indicate that oxidative metabolism occurs mainly in the corpus epididymis (table 3). The decrease in lipid synthesis occurs principally in the cauda epididymis (Dacheux and Paquignon, 1980). These metabolic alterations are determined by the variations in the energy charge ratio or phosphate potential (Garbers *et al.*, 1973 ; Hoskins, Munsterman and Hall, 1975). It should be noted that all the data on the metabolism of epididymal spermatozoa have been obtained in condi-

TABLE 3

Epididymal boar spermatozoa metabolism

Parameters	Sperm origin					
	Caput		Corpus		Cauda	
	Post.	Ant.	Med.	Post.	Ant.	Post.
CO_2 production $\mu M/10^8$ spz/3 h..	0.55	0.73	1.17	1.35	1.48	1.40
Glucose converted to lipid $nM/10^8$ spz./3 h	2.75	2.62	2.75	2 69	1.90	1.47

(From Dacheux and Paquignon, 1980)

tions initiating potential motility (dilution in an appropriate medium). There are few data on the metabolism of spermatozoa in their own medium. It is probable that in most species, since the motility of spermatozoa is very reduced in those conditions, their metabolic activity is also low.

D. — *Relation between fertilizing ability, motility and metabolism of epididymal spermatozoa.*

The principal modifications taking place in spermatozoa during epididymal transit have been localized in the corpus epididymis (fig. 2). There is a close parallel between the acquisition of forward motility in the ram (Fournier-Delpech *et al.*, 1979) or the percentage of motile cells in the boar (Holtz and Smidt, 1976 ; Dacheux and Paquignon, 1980) and improved fertilizing ability. Metabolic increase parallels the initiation of motility. Taking spermatozoon transit time in different regions of the boar epididymis as an example (Singh, 1962), all the gamete changes terminating in « epididymal maturation » occur within 24 to 48 hrs (fig. 2). The rapidity of these processes in 24-hr culture of epididymal tubules has shown that these phenomena are under the androgenic control of 5 α-dihydrotestosterone (Orgebin-Crist and Jahad, 1978).

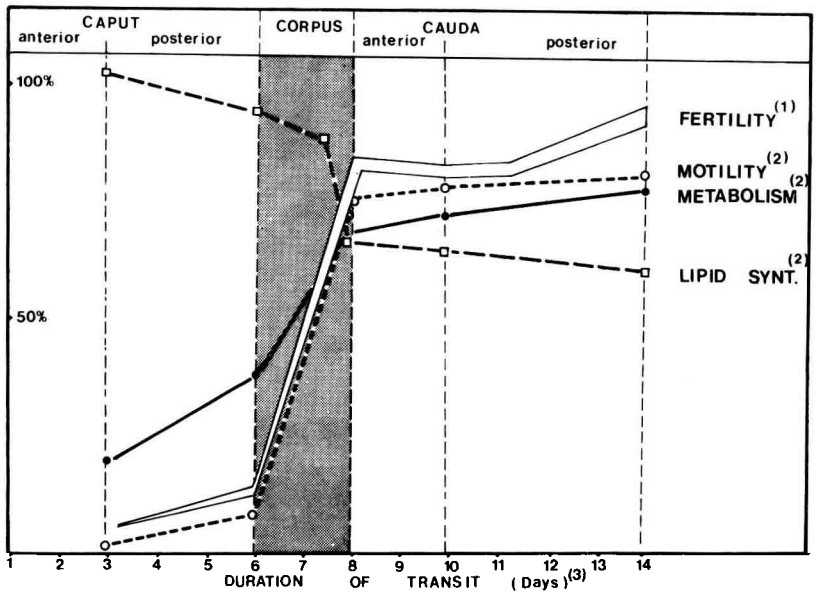

FIG. 2. — *Profile of oxidative metabolism* (●——●), *lipid synthesis* (□— — —□), *motility* (○------○) *and fertilizing ability* ([ ]) *in relation to the epididymal region and epididymal transit time of boar spermatozoa.* Results from : 1. Holtz and Smidt (1976) ; 2. Dacheux and Paquignon (1980) ; 3. Singh (1962).

II. — Epididymal effect on spermatozoon maturation.

For a long time, spermatozoon maturation was associated with aging (Glover, 1962 ; Paŭfler and Foote, 1968 ; Orgebin-Crist, 1973) in reality ,it is related to epididy-

mal activity (Orgebin-Crist *et al.*, 1975, 1978), even if the motility of ram testicular spermatozoa can be induced by a long incubation in the rete testis fluid (Voglmayr and Gandhi, 1978). However, there are few data which describe the interactions between the epididymal epithelium and the spermatozoa. It is probable that these interactions are due to the fluid bathing the spermatozoa. Micro-sampling techniques have definitely shown that the composition of the intra tubular fluid changes according to the epididymal region ; the greatest alterations are osmotic (Johnson and Howards, 1977), ionic (Levine and Marsh, 1971), organic or proteic (Fournier-Delpech, 1966, 1968 ; Peyre and Laporte, 1966*a*, *b* ; White, 1973 ; Setchell, 1974 ; Johnson and Howards, 1977). How are these observations related to the initiation of motility or fertilizing ability ? Experiments transferring the epididymal fluid or changing the composition of the incubation medium *in vitro* have established the relative importance of some epididymal characteristics.

A. — *Influence of the epididymal medium on immature spermatozoa.*

Immature testicular or epididymal spermatozoa incubated *in vitro* or *in vivo* in the fluid of the cauda epididymis (rabbit : Cooper and Orgebin-Crist, 1975 ; boar : Holtz and Smidt, 1976 ; ram : Voglmayr and Gandhi, 1978) have never been able to fertilize an oocyte or show changes in motility or metabolism that would indicate the initiation of maturation. The same is true of spermatozoa incubated in the fluid of the boar corpus epididymis (Dacheux and Paquignon, unpublished data).

The failure of these experiments seems to suggest that the maturation of immature spermatozoa is related not only to the composition of the medium in which they bathe, but probably also to the way in which the medium changes.

B. — *Effect of some components or specific changes in the epididymal fluid.*

1) *Change in the osmotic pressure.* — The osmotic variations of the medium, observed in different epididymal regions (Johnson and Howards, 1977), affect spermatozoon metabolism ; high osmotic pressures (370 mOsm/kg) especially favorise the glycolytic metabolism of spermatozoa (Dacheux, O'Shea and Paquignon, 1979) but never the development of immature spermatozoon motility.

2) *Effect of ionic composition.* — The ionic changes occurring in the fluid throughout epididymal transit are mainly a decrease of the sodium/potassium ratio (Crabo and

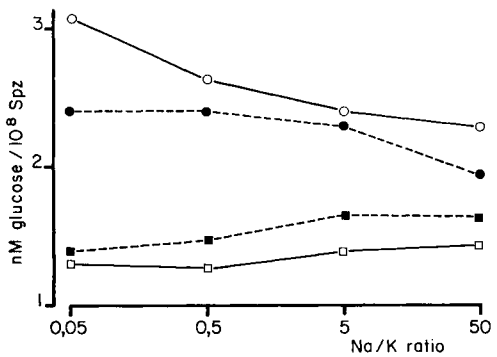

FIG. 3. — *Effect of the Na^+/K^+ ratio on glucose incorporation in lipids of testicular (o——o) and ejaculated (□——□) ram spermatozoa after 3 h of incubation, and testicular (●------●) and ejaculated (■------■) boar spermatozoa after 2 h of incubation.*

Gustafson, 1964 ; Levine and Marsh, 1971 ; Jessee and Howards, 1976). Similar variations of this *in vitro* ratio do not cause motility to develop (Pholpramool and Chaturapanich, 1979 ; Dacheux, Paquignon and Le Coz, 1980) but they modify the lipid synthesis of immature and mature spermatozoa (fig. 3) and affect the metabolism and motility of mature spermatozoa (McGrady, Nelson and Ireland, 1974 ; Dacheux, Paquignon and Le Coz, 1980).

The presence of bicarbonate stimulates spermatozoon activity *in vitro* ; the more motile the spermatozoa are, the greater is this effect (Dacheux, Paquignon and Le Coz, 1980). The presence of this ion, as that of Ca^{++} (Davis, 1978 ; Nelson, 1978 ; Morton *et al.*, 1978), seems to favorize the development of epididymal spermatozoon motility and metabolism.

3) *Effect of some organic compounds in the epididymal medium.* — The concentrations of inositol, carnitine (Brooks, Hamilton and Mallek, 1974 ; Hinton, Snoswell and Setchell, 1979), glycerylphosphorylcholine and phosphorylcholine (Dawson, Mann and White, 1957 ; Brooks *et al.*, 1974) and sialic acids (Fournier-Delpech, 1966 ; Laporte, Gillet and Peyre, 1975) are very high in the epididymal fluid.

Few direct relations have been established between the presence of inositol, sialic acids and the epididymal maturation of spermatozoa, in spite of the change in the sialic acid level of the spermatozoa during their maturation (Gupta, *et al.*, 1974 ; Laporte, 1974, 1979). The presence of a low carnitine level stimulates *in vitro* the motility of spermatozoa in the caput epididymis (Hinton and Setchell, 1980). On the contrary, high concentrations of carnitine, acetyl carnitine, GPC and PC reduce motility or metabolism (Hamilton and Olson, 1976 ; Bøhmer and Johansen, 1978 ; Turner, d'Addario and Howards, 1978). The latter effect could be the cause of the reduced motility of the spermatozoa sampled in the epididymal fluid. The presence of androgens (testosterone and DHT) in a physiological concentration does not appear to have a direct influence on the spermatozoa (Hammerstedt and Amann, 1976 ; Voglmayr, Murdoch and White, 1970 ; Voglmayr and Gandhi, 1978).

4) *Epididymal protein secretions and spermatozoon maturation.*

a) *Characteristics of epididymal fluid proteins.* — The quantity and the composition of epididymal fluid proteins change in the various epididymal regions (Koskimies and Kormano, 1975). Many testicular proteins (ABP, for example) are partially or totally reabsorbed by the epithelium of the caput epididymis (Danzo *et al.*, 1977 ; Hansson *et al.*, 1976 ; Jegou *et al.*, 1979). On the other hand, other proteins are specifically secreted in the tubule lumen (Delpech, 1974 ; Lea, Petrusz and French, 1978). Their number in various species is almost constant : 6 in the rat (Whelan and Brackett, 1979), 5 in the boar (Schellpfeffer and Hunter, 1976) and at least 4 in the rabbit (Johnson and Hunter, 1979) and the bull (Killian and Amann, 1973). These proteins develop principally between the caput and the corpus epididymis ; several are glycoproteins.

b) *Role of proteins on spermatozoa.* — Some of the proteins present in the epididymal fluid bind to the spermatozoon membrane (Delpech, 1974 ; Voglmayr *et al.*, 1979), thus altering the composition and the surface electric charge of the gametes (Olson and Hamilton, 1978 ; Moore, 1979). On the contrary, metabolism or motility is not enhanced *in vitro*, if the immature spermatozoa are incubated in the presence of corpus or

cauda epididymal proteins (Hoskins, Hall and Munsterman, 1975 ; Voglmayr and White, 1979 ; Dacheux, Paquignon and Le Coz, 1980).

The presence of epididymal proteins alone does not thus appear to be enough to trigger spermatozoon maturation. Few relations have been shown between certain characteristics of the epididymal fluid and spermatozoon modifications. The difficulty in determining these relations suggests that several specific events are probably required to trigger maturation and that those events must occur sequentially to be efficient.

III. — Intrinsic and extrinsic factors controlling spermatozoon maturation.

Garbers *et al.*, (1971) showed that the motility of mature spermatozoa was stimulated by nucleotic phosphodiesterase inhibitors. Moreover, there is a relation between the amount of cAMP present in the spermatozoa and the number of motile gametes (Tash and Mann, 1973 ; Hoskins, Stephens and Hall, 1974). The initiation of motility thus seems to be directly related to the activity of adenylcyclase or cyclic nucleotide phosphodiesterases.

A. — *Inhibitory action of phosphodiesterases on spermatozoa, depending on their maturity.*

The presence of a cyclic nucleotide phosphodiesterase inhibitor (NPI) (caffeine or theophylline) increases the *in vitro* metabolism and motility of epididymal spermatozoa. The stimulation is greater when the spermatozoa are already mature and motile (fig. 4). Maximal stimulation of caput epididymal spermatozoon metabolism and motility requires higher concentrations of NPI than does maximal cauda epididymal stimulation (Hoskins, Brandt and Acott ; 1978 ; Dacheux and Paquignon, 1980) (fig. 5),

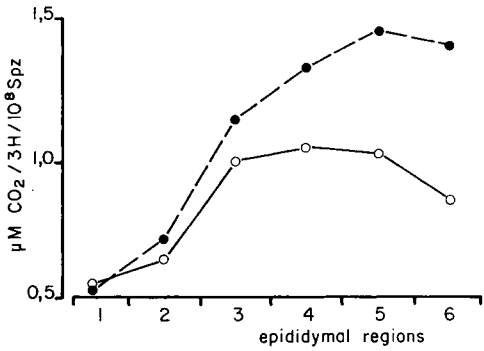

FIG. 4.

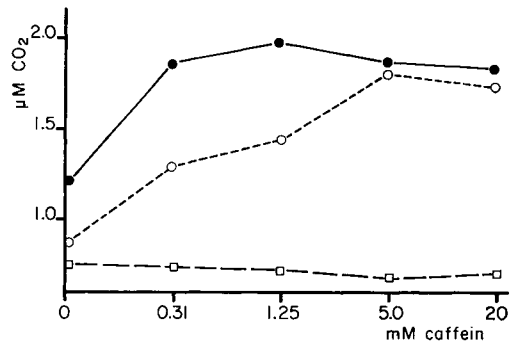

FIG. 5.

FIG. 4. — *Effect of the presence of* 0.1 *mM of caffeine on the glucose oxidative metabolism of boar spermatozoa sampled at different epididymal levels.* (From Dacheux and Paquignon, 1980) ●— — —● = 0.1 mM caffeine ; o——o = Control. 1. Post. caput ; 2. Ant. corpus ; 3. Mid corpus ; 4. Post. corpus ; 5. Ant. cauda ; 6. Post. cauda.

FIG. 5. — *Effects of increasing concentrations of caffeine on the glucose oxidative metabolism of testicular* (□— — —□), *caput* (o------o) *and cauda epididymal* (●——●) *spermatozoa incubated in tris-buffer.* (From Dacheux and Paquignon, 1980.)

but no development of forward motility is apparent. On the contrary, whatever the caffeine concentration the oxidative metabolism and the motility of testicular spermatozoa have never been shown to increase (fig. 5) (Cascieri, Amann and Hammerstedt, 1976 ; Dacheux and Paquignon, 1980), although intracellular cyclic 3′-5′ AMP concentration increases (Cascieri *et al.*, 1976).

There is thus no direct relation between intracellular cAMP content and the development of forward motility when epididymal spermatozoa are incubated *in vitro* in a synthetic medium.

B. — *Synergic action of some proteins and cyclic nucleotide phosphodiesterase inhibitors.*

1) *Epididymal proteins.* — The unique presence of either epididymal or seminal plasma proteins or of caffeine, in an incubation medium containing immature spermatozoa, cannot induce changes in motility or metabolism mimicking those observed during maturation. On the contrary, when the same proteins are present simultaneously with the cyclic nucleotide phosphodiesterase inhibitor, forward motility develops very rapidly, and metabolism is increased in a large number (40 to 50 p. 100) of the immature spermatozoa of the caput epididymis (bull : Hoskins, Hall and Munsterman, 1975). This led to the characterization of a glycoprotein, FMP (forward motility

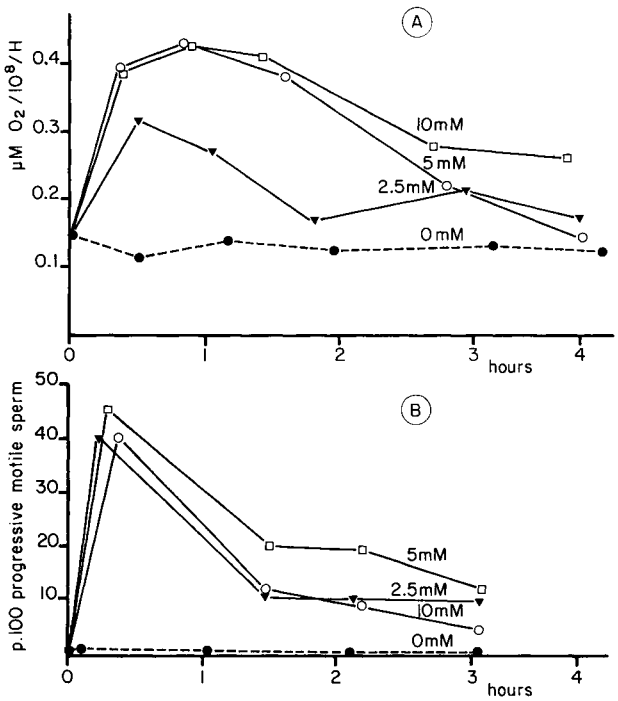

FIG. 6. — *Effect of increasing caffeine concentrations on boar testicular spermatozoa incubated in a citrate-egg yolk medium.* A : effect on oxygen uptake ; B : Effect on forward motility. (From Dacheux and Paquignon, 1980.)

protein), present in both the testicular and the epididymal fluids ; it is found in a relatively large quantity in the latter fluid, as compared to other fluids and tissues (Acott and Hoskins, 1978 ; Acott *et al.*, 1979 ; Brandt *et al.*, 1978).

It is noteworthy that the initiation of forward motility is easily obtained with the immature spermatozoa of the caput epididymis but not obtained with testicular spermatozoa (Dacheux and Paquignon, unpublished data). This lack of FMP effect on testicular spermatozoa is perhaps due to the fact that the spermatozoa have not yet undergone the change(s) necessary for maturation, changes which occur in the efferent ducts and the anterior caput epididymis.

2) *Egg yolk proteins.* — The forward motility of testicular spermatozoa can be developed by associating caffeine and lipoproteins extracted from egg yolk (Dacheux and Paquignon, 1980) : 40 to 50 p. 100 of the gametes show increased metabolism and forward motility (fig. 6).

The exact role of these different proteins on the spermatozoa is unknown ; it may be related to a change in the membrane, permitting the flagella to beat more efficiently. However, it is interesting to note that, in that case, only 30 to 60 p. 100 of the testicular spermatozoa are potentially motile.

C. — *Effect of development of forward motility on the fertilizing ability of spermatozoa.*

The increased motility and modified metabolism of the spermatozoa reflect maturation-type changes. However, the corresponding increase in fertilizing ability is not always obtained : some parallelism has been found only in the guinea-pig in which there is a correspondance between the stimulation of fertilizing ability and the motility of spermatozoa from the caput epididymis (Shilon *et al.*, 1978). *In vitro*, rabbit testicular spermatozoa when motile can penetrate the oocyte (Brackett, Hall and Oh, 1978), but no fertilization has been obtained *in vivo* with immature testicular or epididymal spermatozoa rendered motile in the boar (table 4) or the ram (Voglmayr, White and Parks, 1978). The effect of FMP on spermatozoon fertilizing ability is unknown.

TABLE 4

Effect of initiation of forward motility on the fertilizing ability of immature testicular and epididymal spermatozoa

Sperm type	Caffeine (2,5 mM)	No. of sows inseminated	Ova recovered	Ova in 2-4 cell stages	p. 100 fertilized
Testicular spermatozoa	+	6	57	0 (2)	0
Caput epididymal spermatozoa (1).	+	8	35	0 (2)	0
	—		30	0 (2)	0
Ejaculated spermatozoa	+	2	14	14	100

(1) Spermatozoa incubated in the presence of 2.5 mM of caffeine and inseminated into the right and left oviducts, respectively.

(2) No spermatozoa observed on the oocyte.

Conclusion.

The spermatozoa acquire fertilizing ability as the result of a series of changes which begin at the efferent ducts, but occur mainly in the corpus epididymis (fig. 7). The changes in motility are mostly related to a rise in the cyclic 3'-5' AMP concentration either by activation of adenylcyclase and/or cyclic nucleotide phosphodiesterase inhibition ; the reason for these modifications is unknown (Cascieri, Amann and Hammerstedt, 1976 ; Casillas, Elder and Hoskins, 1978 ; Stephens, Wang and Hoskins, 1979).

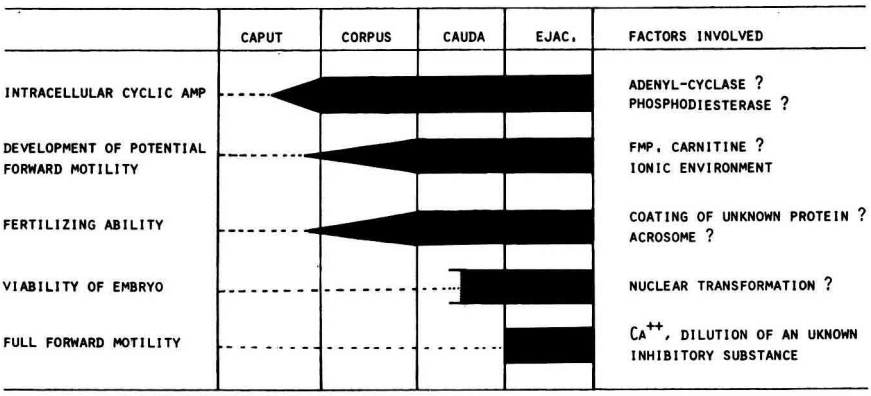

FIG. 7. — *Process of epididymal sperm maturation in mammals.*

However, for the forward motility of spermatozoa to develop, the increase of intracellular cAMP must be accompanied by a given protein environment (motility factor). The spermatozoa need more than this motility for oocyte fertilization ; changes in the membrane and the acrosome are imperative, if the oocyte is to be recognized and penetrated (fertility factors). The *in vivo* parallelism between the acquisition of motility and fertilizing ability indicates that the factors of these acquisitions probably originate in the same epididymal region. The ability to produce a viable embryo is only developed later, after additional intracellular changes. The process of spermatozoon maturation thus results from a succession of modifications accomplished under the control of the epididymal epithelium.

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Résumé. Les modifications importantes subies par les spermatozoïdes durant leur transit épididymaire, ont été comparées chez différentes espèces. Les principaux changements dans la composition ionique, organique ou protéique du fluide épididymaire ont été analysés dans le but de définir leur importance sur les modifications métaboliques et de motilité ainsi que sur l'initiation de la motilité progressive des spermatozoïdes. Le pouvoir fécondant des spermatozoïdes motiles testiculaires et épididymaires est discuté. Cette revue suggère que le processus de maturation des spermatozoïdes résulte d'une succession de modifications des gamètes (contenu en AMP cyclic, composition des membranes, et structure du noyau) tout au long du tractus génital, sous dépendance de l'épithélium épididymaire mais dont les principaux déterminismes sont pratiquement toujours inconnus.

References

ACOTT T. S , HOSKINS D. D , 1978. Bovine sperm forward motility, partial purification and characterization. J. biol. Chem., **253,** 6744-6750.

ACOTT T. S., JOHNSON D. J., BRANDT H., HOSKINS D. D., 1979. Sperm foward motility protein : Tissue distribution and species cross reactivity. *Biol. Reprod.*, **20,** 247-252.

BEDFORD J. M., 1966. Development of the fertilizing ability of spermatozoa in the epididymis of the rabbit. *J. exp. Zool.*, **163,** 319-329.

BEDFORD J. M., 1975. Maturation, transport and fate of spermatozoa in the epididymis, 303-317. In HAMILTON D. W., GREEP R. O. *Handbook of Physiology*, sect. 7 : Endocrinology, vol. **V,** *Am. Physiol. Soc., Washington D. C.*

BLANDAU R. J., RUMERY R. E., 1964. The relationship of swimming movements of epididymal spermatozoa to their fertilizing capacity. *Fertil. Steril.*, **15,** 571-579.

BØHMER T., JOHANSEN L., 1978. Inhibition of sperm maturation through intervention of the carnitine system. *Int. J. Androl.*, Suppl. **2,** 565-572.

BRANDT H., ACOTT T. S., JOHNSON D. J., HOSKINS D. D., 1978. Evidence for an epididymal origin of bovine sperm forward motility protein. *Biol. Reprod.*, **19,** 830-835.

BRACKETT B. G., HALL J. L., OH Y. K., 1978. In vitro fertilizing ability of testicular, epididymal and ejaculated rabbit spermatozoa. *Fert. Steril.*, **29,** 571-582.

BROOKS D. E., HAMILTON D. W., MALLEK A. H., 1974. Carnitine and glycerylphosphorylcholine in the reproductive tract of the male rat. *J. Reprod. Fert.*, **36,** 141-160.

CASCIERI M., AMANN R. P., HAMMERSTEDT R. H., 1976. Adenine nucleotide changes at initiation of bull sperm motility. *J. biol. Chem.*, **254,** 787-793.

CASILLAS E. R., ELDER C. M., HOSKINS D. D., 1978. Adenyl cyclase activity in maturing bovine spermatozoa : Activation by GTP and polyamines. *Fed. Proc.*, **37,** 1688.

COOPER T. G., ORGEBIN-CRIST M. C., 1975. The effect of epididymal and testicular fluids on the fertilizing capacity of testicular and epididymal spermatozoa. *Andrologia*, **7,** 85-93.

CRABO B., GUSTAFSON B., 1964. Distribution of sodium and potassium and its relation to sperm concentration in the epididymal plasma of the bull. *J. Reprod. Fert.*, **7,** 337-355.

DACHEUX J. L., O'SHEA T., PAQUIGNON M., 1979. Effects of osmolality, bicarbonate and buffer on the metabolism and motility of testicular epididymal and ejaculated spermatozoa of boars. *J. Reprod. Fert.*, **55,** 287-296.

DACHEUX J. L., PAQUIGNON M., 1980. Effects of caffeine on ram and boar spermatozoa : Influence of their stage of maturation and the medium ; initiation of progressive motility of testicular spermatozoa, 513-522. In STEINBERGER E., STEINBERGER A., *Testicular development, structure and function.* Raven Press, New York.

DACHEUX J. L., PAQUIGNON M., LE COZ A., 1980. Influence of bicarbonate, sodium, potassium and protein on metabolism and motility of immature and mature spermatozoa (in preparation).

DANZO B. J., COOPER T. G., ORGEBIN-CRIST M. C., 1977. Androgen binding protein (ABP) in fluids collected from the rete testis and cauda epididymis of sexually mature and immature rabbits and observations of morphological change in the epididymis following ligation of the ductuli efferentes. *Biol. Reprod.*, **17,** 64-77.

DAVIS B. K., 1978. Effect of calcium on motility and fertilization by rat spermatozoa *in vitro*. *Proc. Soc. exp. Biol. Med.*, **157,** 54-56.

DAWSON R. M. C., MANN T., WHITE I. G., 1957. Glycerylphosphorylcholine and phosphorylcholine in semen and their relation to choline. *Biochem. J.*, **65,** 627-633.

DELPECH S., 1974. *Contribution à l'étude du sperme épididymaire. Caractérisation d'une sialoproteine spécifique chez le rat.* Th. Doct. Etat U.E.R. Paul Sabatier nº 620, Toulouse.

DYSON A. L. M. B., ORGEBIN-CRIST M. C., 1973. Effects of hypophysectomy, castration and androgen replacement upon the fertilizing ability of rat epididymal spermatozoa. *Endocrinology*, **93,** 391-402.

FOURNIER-DELPECH S., 1966. Répartition de l'acide sialique dans le tractus génital du rat Wistar adulte normal et castré. *C. R. Soc. Biol.*, **160,** 1087-1090.

FOURNIER-DELPECH S., 1968. Electrophorèse des protéines du tractus génital du rat. Présence dans le sperme épididymaire d'une glycoprotéine migrant vers l'anode à pH 8.45. *C. R. Soc. Biol.* **162,** 558-562.

FOURNIER-DELPECH S., COLAS G., COUROT M., ORTAVANT R., BRICE G., 1979. Epididymal sperm maturation in the ram : Motility, fertilizing ability and embryonic survival after uterine artificial insemination in the ewe. *Ann. Biol. anim. Bioch. Biophys.*, **19,** 597-605.

GADDUM P., 1968. Sperm maturation in the male reproductive tract : Development of motility. *Anat. Rec.*, **161,** 471-482.

GARBERS D. L., FIRST N. L., GORMAN S. K., LARDY H. A., 1973. The effects of cyclic nucleotide phosphodiesterase inhibitors on ejaculated porcine spermatozoan metabolism. *Biol. Reprod.*, **8,** 599-606.

GARBERS D. L., LUST W. D., FISRT N. L., LARDY H. A., 1971. Effects of phosphodiesterase inhibitors and cyclic nucleotides on sperm respiration and motility. *Biochemistry*, **19,** 1825-1831.

GLOVER T. D., 1962. The response of rabbit spermatozoa to artificial cryptorchidism and ligation of the epididymis. *J. Endocr.*, **23,** 317-328.

GUPTA G., RAJALAKSHMI M., PRASAD M. R. M., MOUGDAL N. R., 1974. Alteration of epididymal function and its relation to maturation of spermatozoa. *Andrologia*, **6,** 35-44.

HAMILTON D. W., OLSON G. E., 1976. Effects of carnitine on oxygen uptake and utilization of ($U^{14}C$) palmitate by ejaculated bull spermatozoa. *J. Reprod. Fert.*, **46,** 195-202.

HAMMERSTEDT R. H., AMANN R. P., 1976. Effects of physiological levels of exogenous steroids on metabolism of testicular, cauda epididymal and ejaculated bovine sperm. *Biol. Reprod.*, **15,** 678-685.

HANSSON V., WEDDINGTON S. C., FRENCH F. S., McLEAN W., SMITH A., NAYFEH S. N., RITZEN E. M., HAGENÄS L., 1976. Secretion and role of androgen binding proteins in the testis and epididymis. *J. Reprod. Fert.*, suppl. **24,** 17-33.

HINTON B. T., DOTT H. M., SETCHELL B. P., 1979*a*. Measurement of the motility of rat spermatozoa collected by micropuncture from the testis and from different regions along the epididymis. *J. Reprod. Fert.*, **55,** 167-172.

HINTON B. T., SETCHELL B. P., 1980. Concentration and uptake of carnitine in the rat epididymis. A micropuncture study. *Proc. Meet. on Carnitine*, Dallas (in press).

HINTON B. T., SNOSWELL A. M., SETCHELL B. P., 1979*b*. The concentration of carnitine in the luminal fluid of the testis and epididymis of the rat and some other mammals. *J. Reprod. Fert.*, **56,** 105-111.

HOLTZ W., SMIDT D., 1976. The fertilizing capacity of epididymal spermatozoa in the pig. *J. Reprod. Fert.*, **46,** 227-229.

HORAN A. H., BEDFORD J. M., 1972. Development of the fertilizing ability of spermatozoa in the epididymis of the Syrian hasmter. *J. Reprod. Fert.*, **30,** 418-423.

HOSKINS D. D., BRANDT H., ACOTT T. S., 1978. Initiation of sperm motility in the mammalian epididymis. *Fed. Proc.*, **37,** 2534-2542.

HOSKINS D. D., HALL M. L., MUNSTERMAN D., 1975. Induction of motility in immature bovine spermatozoa by cyclic AMP phosphodiesterase inhibitors and seminal plasma. *Biol. Reprod.*, **13,** 168-176.

HOSKINS D. D., MUNSTERMAN D., HALL M. L., 1975. The control of bovine sperm glycolysis during epididymal transit. *Biol. Reprod.*, **12,** 566-572.

HOSKINS D. D., STEPHENS D. T., HALL M. L., 1974. Cyclic adenosine 3' : 5'-monophosphate and protein kinase levels in developing bovine spermatozoa. *J. Reprod. Fert.*, **37,** 131-134.

JEGOU B., DACHEUX J. L., TERQUI M., GARNIER D. H., COLAS G., COUROT M., 1979. Bioche-

mical and physiological studies of androgen-binding protein in the reproductive tract of the ram. *J. Reprod. Fert.*, **57**, 311-318.

JESSEE S. J., HOWARDS S. S., 1976. A survey of sperm, potassium and sodium concentrations in the tubular fluid of the hamster epididymis. *Biol. Reprod.*, **15**, 626-631.

JOHNSON A. L., HOWARDS S. S., 1977. Hyperosmolality in intraluminal fluids from hamster testis and epididymis : A micropuncture study. *Science*, **195**, 492-493.

JOHNSON W. L., HUNTER A. G., 1979. Distribution of seminal antigens and enzymes in the rabbit ductus epididymis. *J. Anim. Sci.*, **49**, 143-150.

KILLIAN G. J., AMANN R. P., 1973. Immunoelectrophoretic characterization of fluid and sperm entering and leaving the bovine epididymis. *Biol. Reprod.*, **9**, 489-499.

KOSKIMIES A. I., KORMANO M., 1975. Proteins in fluids from different segments of rat epididymis. *J. Reprod. Fert.*, **43**, 345-348.

LAPORTE P., 1974. Teneur en acides sialiques des spermatozoïdes épididymaires. Estimation indirecte, *in vivo* chez le rat. *C. R. Acad. Sci. Paris, sér. D*, **279**, 761-764.

LAPORTE P., 1979. *Evolution physiologique et facteurs de variations des acides sialiques dans l'unité testiculo-épididymaire et du fluide dans le testicule, chez le rat normal et aspermatogène.* Th. Doct. Etat, nº 290, Poitiers.

LAPORTE P., GILLET J., PEYRE A., 1975. Les sialoprotéines épididymaires. Actions de quelques facteurs exogènes et endogènes. *Ann. Biol. anim. Bioch. Biophys.*, **15**, 669-683.

LEA O. A., PETRUSZ P., FRENCH F. S., 1978. Purification and localization of acidic epididymal glycoprotein (AEG) : A sperm coating protein secreted by the rat epididymis. *Int. J. Andrology*, suppl. **2**, 592-607.

LEVINE N., MARSH D. J., 1971. Micropuncture studies of the electrochemical aspect of fluid and electrolyte transport in individual seminiferous tubules, the epididymis and the vas deferens in rats. *J. Physiol.*, **213**, 557-570.

McGRADY A. V., NELSON L., IRELAND M., 1974. Ionic effects on the motility of bull and chimpanzee spermatozoa. *J. Reprod. Fert.*, **40**, 71-76.

MOORE H. D. M., 1979. The net surface charge of mammalian spermatozoa as determined by isoelectric focusing. Changes following sperm maturation, ejaculation, incubation in the female tract, and after enzyme treatment. *Int. J. Andrology*, **2**, 449-462.

MORTON B. E., SAGADRACA R., FRASER C., 1978. Sperm motility within the mammalian epididymis : species variation and correlation with free calcium levels in epididymal plasma. *Fert. Steril.*, **29**, 695-698.

NELSON L., 1978. Chemistry and neurochemistry of sperm motility control. *Fed. Proc.*, **37**, 2543-2547.

OLSON G. E., HAMILTON D. W., 1978. Characterization of the surface glycoproteins of rat spermatozoa. *Biol. Reprod.*, **19**, 26-35.

ORGEBIN-CRIST M. C., 1967. Maturation of spermatozoa in the rabbit epididymis : Fertilizing ability and embryonic mortality in does inseminated with epididymal spermatozoa. *Ann. Biol. anim. Bioch. Biophys.*, **7**, 373-389.

ORGEBIN-CRIST M. C., 1973. Maturation of spermatozoa in the rabbit epididymis : Effect of castration and testosterone replacement. *J. exp. Zool.*, **188**, 301.

ORGEBIN-CRIST M. C., DANZO B. J., DAVIES J., 1975. Endocrine control of the development and maintenance of sperm fertilizing ability in the epididymis, 319-338. In HAMILTON D. W. et GREEP R. O., *Handbook of Physiology*, sect. 7, Vol. **V**., Am. Physiol. Soc., Washington D. C.

ORGEBIN-CRIST M. C., JAHAD N., 1977. Delayed cleavage of rabbit ova after fertilization by young epididymal spermatozoa. *Biol. Reprod.*, **16**, 358-362.

ORGEBIN-CHRIST M. C., JAHAD N., 1978. The maturation of rabbit epididymal spermatozoa in organ culture : Inhibition by antiandrogens and inhibitors of ribonucleic acid and protein synthesis. *Endocrinology*, **103**, 46-53.

PAŬFLER S. K., FOOTE R. H., 1968. Morphology, motility and fertility of spermatozoa recovered from different areas of ligated rabbit epididymides. *J. Reprod. Fert.*, **17**, 125-137.

PEYRE A., LAPORTE P., 1966*a*. Action de la testostérone et de l'œstradiol sur les sialo-protéines de la queue de l'épididyme de rat impubère castré. *C. R. Soc. Biol.*, **196**, 2178-2180.

PEYRE A., LAPORTE P., 1966*b*. Evolution des acides sialiques épididymaires chez le rat impubère et adulte. *C. R. Acad. Sci. Paris, Sér. D*, **263**, 1872-1875.

PHOLPRAMOOL C., CHATURAPANICH G., 1979. Effect of sodium and potassium concentrations and pH on the maintenance of motility of rabbit and rat epididymal spermatozoa. *J. Reprod. Fert.*, **57**, 245-251.

SCHELLPFEFFER D. A., HUNTER A. G., 1976. Specific proteins of the male reproductive tract, 115-128. In SPILMAN C. M. *et al.* « *Regulatory mechanisms of male reproductive physiology* ». Excerpta med., Amsterdam.

SETCHELL, 1974. Secretions of the testis and epididymis. *J. Reprod. Fert.*, **37**, 165-177.

SHILON M., PAZ (FRENKEL) G., HOMONNAI Z. T., SCHOENBAUM M., 1978. The effect of caffeine on guinea pig epididymal spermatozoa : Motility and fertilizing capacity. *Int. J. Androl.*, **1**, 416-423.

SINGH G., 1962. Durée de passage dans l'épididyme des spermatozoïdes de verrat marqués au ^{32}P. *Ann. Biol. anim. Bioch. Biophys.*, **2**, 43-46.

STEPHENS D. T., WANG J. L., HOSKINS D. D., 1979. The cyclic AMP phosphodiesterase of bovine spermatozoa : Multiple forms, kinetic properties and changes during development. *Biol. Reprod.*, **20**, 483-491.

TASH J. S., MANN T., 1973. Adenosine 3' : 5'-cyclic monophosphate in relation to motility and senescence of spermatozoa. *Proc. roy. Soc., London, Ser. B*, **184**, 109-113.

TOURNADE A., 1913. Différences de motilité des spermatozoïdes prélevés dans les divers segments de l'épididyme *C. R. Soc. Biol.*, **74**, 738.

TURNER T. T., D'ADDARIO D., HOWARDS S. S., 1978. Further observations on the initiation of sperm motility. *Biol. Reprod.*, **19**, 1095-1101.

VOGLMAYR J. K., 1975. Metabolic changes in spermatozoa during epididymal transit, 437-451. In HAMILTON D. W., GREEP R. D., *Handbook of Physiology* Sect. 7, Endocrinology, Vol. **V**, Am. Physiol. Soc., Washington D. C.

VOGLMAYR J. K., FAIRBANKS G., JACKOWITZ M. A., COLELLA J. R., 1979. Maturation changes in surface proteins of ram spermatozoa. *Biol. Reprod.*, **10**, suppl. 1, 81A.

VOGLMAYR J. K., GANDHI J., 1978. Survival of ram testicular spermatozoa *in vitro* : Effects of glucose, glucose metabolites, rete testis fluid proteins, selected androgens and phospholipids. *Theriogenology*, **9**, 463-478.

VOGLMAYR J. K., MURDOCH R. N., WHITE I. G., 1970. Metabolism of ram testicular spermatozoa in the presence of testosterone and related steroids. *Acta endocr.*, **65**, 565-576.

VOGLMAYR J. K., WHITE I. G., 1979. Effects of rete testis and epididymal fluid on the metabolism and motility of testicular and post-testicular spermatozoa of the ram. *Biol. Reprod.*, **20**, 288-293.

VOGLMAYR J. K., WHITE I. G., PARKS R. P., 1978. The fertilizing capacity of ram testicular spermatozoa freshly collected and after storage in cauda epididymal fluid. *Theriogenology*, **10**, 313-321.

WHELAN H. A., BRACKETT B. G., 1979. Epididymal luminal fluid proteins. *Biol. Reprod.*, **20**, suppl. 1, 21A.

WHITE I. G., 1973. Biochemical aspects of spermatozoa and their environment in the male reproductive tract. *J. Reprod. Fert.*, suppl. **18**, 225-235.

WYKER R., HOWARDS S. S., 1977. Micropuncture studies of the motility of rete testis and epididymal spermatozoa. *Fertil. Steril.*, **28**, 108-112.