

(s.d. = 11.06) $\mu\text{mol m}^{-2} \text{s}^{-1}$. Variation was due to spatial variation on shelves within and among chambers. Autotrophic biomass was estimated as in ref. 22. Bacterial densities were estimated as in ref. 23.

Statistical analysis. Significant $S/F \times \text{nutrient} \times \text{light}$ effects were determined by a full-factorial, three-way analysis of variance (ANOVA) including all interaction terms.

Received 21 May; accepted 9 September 1997.

1. Folke, C., Holling, C. S. & Perrings, C. Biological diversity, ecosystems and the human scale. *Ecol. Appl.* **6**, 1018–1024 (1996).
2. May, R. M. *Stability and Complexity in Model Ecosystems* (Princeton Univ. Press, Princeton, 1974).
3. Naem, S. Species redundancy and ecosystem reliability. *Cons. Biol.* (in the press).
4. Imhoff, M. L. Mapping human impacts on the global biosphere. *BioScience* **44**, 598 (1994).
5. Heywood, V. H. *Global Biodiversity Assessment* (UNEP and Cambridge Univ. Press, Cambridge, 1995).
6. Gitay, H., Bastow, W. & Lee, W. G. Species redundancy: a redundant concept? *J. Ecol.* **84**, 121–124 (1996).
7. Walker, B. H. Biological diversity and ecological redundancy. *Cons. Biol.* **6**, 18–23 (1992).
8. Lawton, J. H. & Brown, V. K. in *Biodiversity and Ecosystem Function* (eds Schulze, E. D. & Mooney, H. A.) 255–270 (Springer, New York, 1993).
9. Tilman, D. Biodiversity: population versus ecosystem stability. *Ecology* **77**, 350–363 (1996).
10. Cowling, R. M., Mustart, P. J., Laurie, H. & Richards, M. B. Species diversity, functional diversity and functional redundancy in fynbos communities. *S. Afr. J. Sci.* **90**, 333–337 (1994).
11. Beare, M. H., Coleman, D. C., Crossley, D. A., Hendrix, P. F. & Odum, E. P. A hierarchical approach to evaluating the significance of soil biodiversity to biogeochemical cycling. *Plant Soil* **170**, 5–122 (1995).
12. Feinsinger, P., Wolfe, J. A. & Swann, L. A. Island ecology: reduced hummingbird diversity and the pollination of plants, Trinidad and Tobago, West Indies. *Ecology* **63**, 494–506 (1982).
13. Körner, C. in *Biodiversity and Ecosystem Functioning* (eds Schulze, E.-D. & Mooney, H. A.) 117–139 (Springer, Berlin, 1993).
14. Christiansen, N. L. J. in *The Ecological Basis of Conservation* (eds Pickett, S. T. A., Ostfeld, R. S., Schachak, M. & Likens, G. E.) 167–186 (Chapman and Hall, New York, 1997).
15. Baruch, Z. et al. in *Biodiversity and Savanna Ecosystem Processes* Vol. 121 (eds Solbrig, O. T., Medina, E. & Silva, J. E.) 176–194 (Springer, Berlin, 1996).
16. Harte, J. & Kinzig, A. P. Mutualism and competition between plants and decomposers: implications for nutrient allocation in ecosystems. *Am. Nat.* **141**, 829–846 (1993).
17. Drake, J. A. Community-assembly mechanics and the structure of an experimental species ensemble. *Am. Nat.* **137**, 1–26 (1991).
18. Power, M. E. et al. Challenges in the quest for keystones. *BioScience* **46**, 609–620 (1996).
19. Daily, G. C. *Nature's Services* (Island Press, Washington DC, 1997).
20. Costanza, R. et al. The value of the world's ecosystem services and natural capital. *Nature* **387**, 253–260 (1997).
21. Lawler, S. P. & Morin, P. J. Food web architecture and population dynamics in laboratory microcosms of protists. *Am. Nat.* **141**, 675–686 (1993).
22. Wetzel, R. G. & Likens, G. E. *Limnological Analyses* (Springer, Berlin, Germany, 1991).
23. Porter, K. G. & Feig, Y. S. The use of DAPI for identifying and counting aquatic microflora. *Limnol. Oceanogr.* **25**, 943–948 (1980).

Acknowledgements. We thank J. McGrady-Steed, P. Morin, B. Sterner, D. Tilman and S. Tjossem for critical evaluations of this work, and the McKnight Land-Grant Professorship and NSF for support.

Correspondence and requests for materials should be sent to S.N. (e-mail: naem001@maroon.tcn.umn.edu).

A role for oestrogens in the male reproductive system

Rex A. Hess*, David Bunick*, Ki-Ho Lee*, Janice Bahr†, Julia A. Taylor‡, Kenneth S. Korach§ & Dennis B. Lubahn‡

* Department of Veterinary Biosciences, University of Illinois, 2001 S. Lincoln, Urbana, Illinois 61802, USA

† Department of Animal Sciences, University of Illinois, Urbana, Illinois 61801, USA

‡ Departments of Biochemistry and Child Health, University of Missouri, Columbia, Missouri 65211, USA

§ National Institute of Environmental Health Sciences, NIH, RTP, North Carolina 27709, USA

Oestrogen is considered to be the 'female' hormone, whereas testosterone is considered the 'male' hormone. However, both hormones are present in both sexes. Thus sexual distinctions are not qualitative differences, but rather result from quantitative divergence in hormone concentrations and differential expressions of steroid hormone receptors. In males, oestrogen is present in low concentrations in blood, but can be extraordinarily high in semen, and as high as 250 pg ml⁻¹ in rete testis fluids^{1,2}, which is higher than serum oestradiol in the female³. It is well known that male reproductive tissues express oestrogen receptors^{4–7}, but the role of oestrogen in male reproduction has remained unclear.

Here we provide evidence of a physiological role for oestrogen in male reproductive organs. We show that oestrogen regulates the reabsorption of luminal fluid in the head of the epididymis. Disruption of this essential function causes sperm to enter the epididymis diluted, rather than concentrated, resulting in infertility. This finding raises further concern over the potential direct effects of environmental oestrogens on male reproduction and reported declines in human sperm counts^{8,9}.

Classic cellular responses to the hormone oestrogen are mediated through nuclear oestrogen receptors (ER), which function as ligand-dependent transcription factors. Efferent ductules of the testis are known to express high amounts of ER- α ^{10,11}, higher even than uterine tissue, and both the α and β forms of ER are present in efferent ductules and the epididymis¹⁰. These ductules form a series of small tubules that transport sperm from the testis to the epididymis¹². In humans, one third of the epididymal head consists of efferent ductules¹³. In addition to ciliated cells that stir the luminal fluid, their epithelia contain non-ciliated cells that resemble proximal tubule cells in the kidney. The non-ciliated cells have a reabsorptive function that results in the uptake of water, ions and proteins from the ductal lumen^{12,14}. Ductules in the rat reabsorb nearly 90% of the rete testis fluid, coupling water and active ion transport in an electroneutral environment, in which Na⁺ and water are reabsorbed at equal rates, thereby increasing the concentration of sperm as they enter the epididymis^{15,16}. This method of concentrating sperm improves their survival and maturation during epididymal storage and ensures that a large number of sperm are released upon ejaculation, increasing the randomness of fertilization and providing genetic variation¹⁴. These data and the observation that efferent ductules contain the highest concentrations of ER in the male led us to hypothesize that oestrogen participates in the regulation of fluid reabsorption in the male reproductive tract.

To test this hypothesis, we used the ER- α gene knockout mouse (ERKO)^{17,18}. The ERKO male is infertile¹⁸, but its testes appear normal until puberty, when they begin to degenerate as early as 20–40 days of age. By 150 days, the testes are atrophic¹⁹. Sperm from the ERKO male are abnormal and sperm concentrations are significantly reduced in the epididymis¹⁹. The reproductive tract in ERKO males contains a dilated rete protruding into the testis (Fig. 1a, b). Downstream from the rete, the efferent ductules are also swollen (Fig. 1c, d), with luminal areas more than twice the size of those of wild-type males at 90 days of age. From these observations, it appears that luminal fluid is not being removed by the ductal epithelium or that there is an excess of fluid secreted by the testis, causing fluids to accumulate in seminiferous tubules, rete and efferent ductules. Epithelial cells of the wild-type (Fig. 1e) contain endocytotic vesicles and large PAS+ lysosomal granules, organelles common to cells active in the uptake of luminal fluids. However, these structures are greatly reduced or missing in the epithelium of ERKO (Fig. 1f), which is decreased in height by 45%. Based on these data, we hypothesized that an increase in testis weight would occur as testicular secretions accumulated in the lumen of the seminiferous tubule. As postulated, a transient increase in testis weight in ERKO males is seen between 32 and 81 days of age and a decrease by 185 days (Fig. 2), suggesting that long-term atrophy of testes from ERKO is caused by back-pressure of the luminal fluids^{20,21}.

We further reasoned that if the efferent ductules in ERKO mice were dysfunctional, then occlusion of the initial segment epididymis, immediately distal to the ductules, would cause fluid to accumulate more rapidly in their testes than in the wild type. Therefore, we surgically cauterized the initial segment of the epididymis, occluding the terminal end of the efferent ductules. The contralateral side served as the control. Testes were removed 48 h after surgery and the difference in weight between the occluded and sham-operated side represented the build-up of luminal fluid caused by a lack of reabsorption in the efferent ductules. After ductal occlusion, testes of ERKO weigh 30% more than testes of wild-type

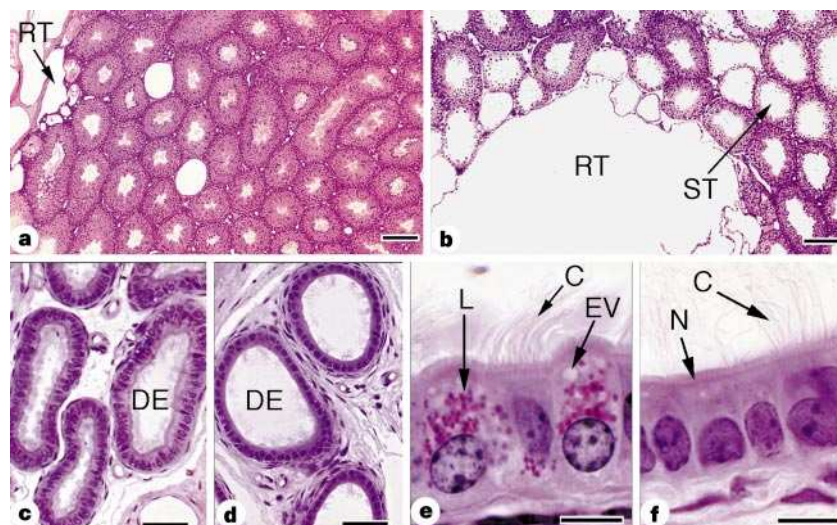


Figure 1 Seminiferous tubules, rete testis and efferent ductules in ERKO and wild-type mice. **a**, Wild-type seminiferous tubules exhibit normal spermatogenesis and a small rete testis (RT). **b**, ERKO rete testis and seminiferous tubules (ST) are dilated. Spermatogenesis appears abnormal in several tubules. **c**, Wild-type efferent ductules (DE) have narrow lumen. **d**, ERKO efferent ductules have dilated lumen. **e**, Wild-type efferent-ductule epithelium contains endocytotic vesicles (EV) and numerous PAS+ lysosomes (L). **f**, ERKO efferent-ductule epithelium is reduced in height and non-ciliated cells (N) contain fewer lysosomes and endocytotic vesicles; C, cilia. Scale bars: **a**, **b**, 100 μ m; **c**, **d**, 50 μ m; **e**, **f**, 10 μ m.

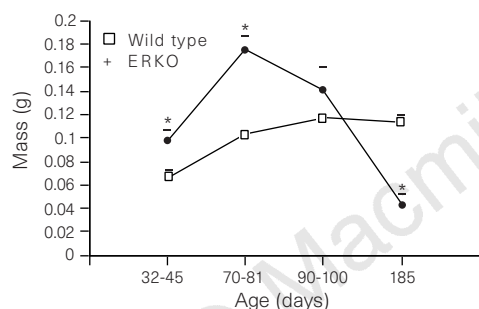


Figure 2 Testicular mass between 32 and 185 days of age (mean \pm s.e.m.). ERKO mass increases at 32–45 and 70–80 days. By 185 days, the ERKO testes are atrophic. Differences were determined by the unpaired Student's *t*-test ($P < 0.05$); $N = 5$ –8 for wild-type mice (WT) and $N = 7$ –10 for ERKO.

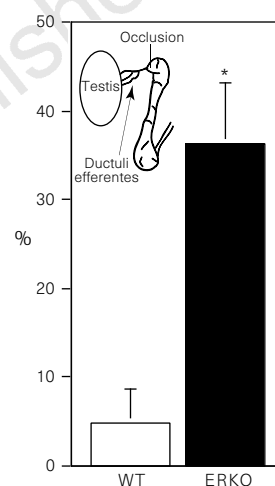


Figure 3 Change in testis mass 48 h after occlusion of the initial-segment epididymis. Values shown are mean (\pm s.e.m.) percentage difference between the occluded and sham-operated side. Differences between wild-type (WT) and ERKO means were determined by the unpaired Student's *t*-test ($P < 0.05$).

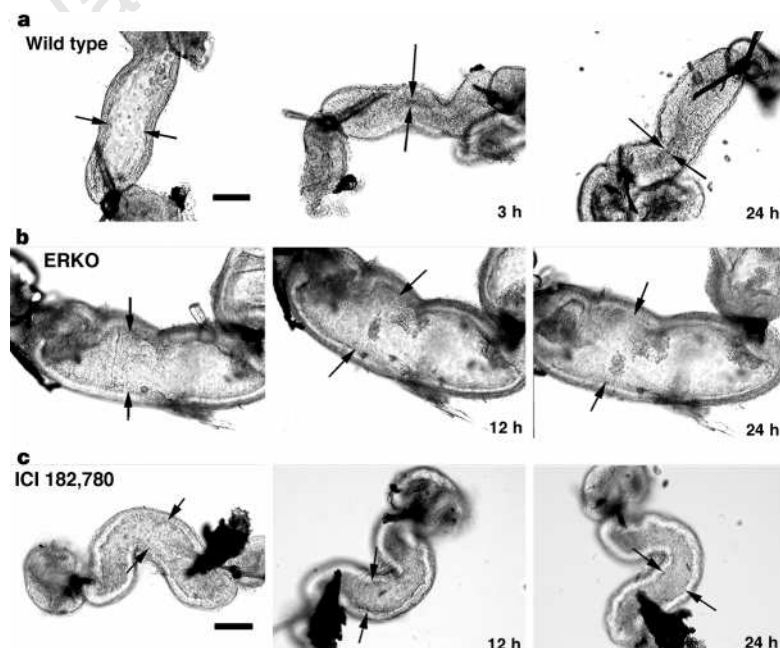


Figure 4 Ligated efferent ductules *in vitro*. **a**, Wild-type ductule lumen (between arrows) collapse by 3 h. **b**, ERKO ductule lumen (between arrows) is wider than wild type and appears to increase in diameter after incubation. **c**, Wild-type ductule treated with an anti-oestrogen (ICI 182,780) initially has a normal lumen but has a slight reduction in diameter after incubation. Scale bars, 100 μ m.

mice (Fig. 3). However, these data do not remove the possibility that the increase in weight results from an abnormal rate of fluid secretion by the seminiferous epithelium in the testis of ERKO. Therefore, we also unilaterally occluded the rete testis in a group of ERKO and wild-type males and compared differences in testicular weight changes at 24 h. Instead of showing increases in fluid secretion, the testis in ERKO secretes significantly less fluid ($P < 0.05$) in 24 h than does the wild-type: $22.4 \pm 3.0\%$ increase versus $37.9 \pm 5.3\%$, respectively. In the ERKO male, efferent ductules do not appear capable of reabsorbing luminal fluids received from the testis. Thus the ERKO mouse provides evidence that oestrogens may be responsible for the regulation of fluid transport, which increases the concentration of sperm before entering the epididymis.

To assess the function of oestrogen in adult tissues without developmental influence, we treated wild-type mice for 3 days with an anti-oestrogen compound and used *in vitro* methods of analysis to determine fluid reabsorption. ICI 182,780 (ICI Pharmaceuticals) is a pure anti-oestrogen that inhibits increases in uterine weight stimulated by 17β -oestradiol and binds both ER- α and ER- β ^{22,23}. Small segments of adult efferent ductules were isolated for organ culture and the tubular ends were ligated with fine suture, preventing the inflow of culture medium. Using this *in vitro* model, we compared the function of ductules in wild-type, ERKO and ICI-treated males over a 24-h period. In ductules from wild-type mice, the epithelium is capable of rapidly removing luminal fluid, which results in the collapse of the ductule walls (Fig. 4). After 24 h of ligation, the luminal area of ductules from wild-type decreased 82% (Fig. 5). In contrast, the luminal area of ductules from ERKO increased 46%, and ductules from wild-type mice treated with ICI showed only a slight decrease of 14%. Thus efferent ductules from ERKO are incapable of reabsorbing luminal fluid, while wild-type ductules remove most of the fluid within 3 h. Blockage of ER function, by treating ductules from wild-type with an anti-oestrogen, significantly inhibits fluid reabsorption.

Thus ER- α is important both for normal growth of the male reproductive tract and for adult function of the efferent ductules. However, because wild-type ICI-treated ductules *in vitro* did not swell like the tissues from ERKO mice, the mechanisms of oestrogen action are not fully understood. For example, it is not known whether the role of ER- β is the same as that of ER- α in efferent ductules. Recent data in HeLa cells have shown that anti-oestrogens and 17β -oestradiol produce opposite effects on ER- β , depending upon the type of response element complex formed²⁴. Thus ER- β function in ductules of ERKO males could account for the *in vitro* observations. Regardless of the precise mechanisms, developmental disruption of ER- α in mice causes a total loss of net fluid reabsorption. In the human, mutational dysfunction in ER- α and P450

aromatase (the enzyme that converts androgens to oestrogens) decreases sperm counts and results in poor sperm viability^{25–27}. Our data suggest that oestrogen deficiency or oestrogen insensitivity in man might also result in the accumulation of fluid in efferent ductules and subsequent atrophy of the testis. Tamoxifen, which is commonly known to be a mixed oestrogen agonist/antagonist in different tissues, has been used to increase sperm counts in oligospermic men²⁸. In conclusion, our data describe a physiological endpoint of oestrogen action in the male reproductive system. This finding is important given recent concerns over reported declines in human sperm counts and speculation that exposure to environmental oestrogens may be a cause of this^{8,9,29}. The extensive presence of ER (both α and β) at other sites in the male reproductive system and throughout the body^{10,11,23} makes it possible that new and unexpected functions may be found for the 'female' hormone in men. □

Methods

Histology and morphometry. Testis and mid-proximal efferent ductules were fixed and processed for light microscopy³⁰. Luminal area, ductal circumference and epithelial height were taken in 5 areas per ductule cross-section in 5 ductules per mouse.

Initial-segment epididymal occlusions and rete testis ligation. Under surgical anaesthesia, initial-segment epididymidis was occluded by cauterization or rete testis was ligated with 0000 suture. The contralateral testis was sham operated. The animals were allowed to recover and testes were taken at either 48 h (initial-segment occlusions) or 24 h (rete ligation) and weighed. For the initial segment occlusions, $N = 7$ for both wild-type and ERKO. For rete testis occlusions, $N = 14$ for wild-type mice and $N = 12$ for ERKO.

***In vitro* ligation of efferent ductules.** One group of wild-type mice was given single daily injections of ICI 182,780 (1 mg per kg) for 3 days before removal of the ductules. Efferent ductules were microdissected into 1.5-mm lengths and incubated for 24 h in M199 culture medium containing dihydrotestosterone (4×10^{-7} M), 17β -oestradiol (1×10^{-9} M), bovine lipoprotein (0.16 mg ml^{-1}) or all components plus ICI 182,780 (1×10^{-6} M) at 34°C in humidified 95% air/5% CO_2 . After 24 h, segments were ligated on both ends to prevent entry and exit of fluids. Digital images of the ductules were analysed at 0, 3 or 12 and 24 h after ligation (Figs 4, 5). Ductal segments damaged by microdissection or stretching were discarded. Only segments with rapid ciliary beat and clear lumens were ligated. $N = 3$ mice for each treatment group, and 3–12 ductal segments per animal were analysed. Differences between means were determined by a one-way analysis of variance ($P < 0.0001$) followed by Bonferroni multiple comparisons test ($P < 0.001$).

Received 29 July; accepted 17 September 1997.

- Ganjam, V. K. Amann, R. P. Steroid content of fluids and sperm entering and leaving the bovine epididymis, in epididymal tissue, and in accessory sex gland secretions. *Endocrinology* **99**, 1618–1630 (1976).
- Free, M. J. & Jaffe, R. A. Collection of rete testis fluid from rats without previous efferent duct ligation. *Biol. Reprod.* **20**, 269–278 (1979).
- Smith, M. S., Freeman, M. E. & Neill, J. D. The control of progesterone secretion during the estrous cycle and early pseudopregnancy in the rat: prolactin, gonadotropin and steroid levels associated with rescue of the corpus luteum of pseudopregnancy. *Endocrinology* **96**, 219–226 (1975).
- Cooke, P. S., Young, P., Hess, R. A. & Cunha, G. R. Estrogen receptor expression in developing epididymis, efferent ductules, and other male reproductive organs. *Endocrinology* **128**, 2874–2879 (1991).
- Greco, T., Duello, T. & Gorski, J. Estrogen receptors; estradiol; and diethylstilbestrol in early development: the mouse as a model for the study of estrogen receptors and estrogen sensitivity in embryonic development of male and female reproductive tracts. *Endocr. Rev.* **14**, 59–71 (1993).
- Schleicher, G., Drews, U., Stumpf, W. E. & Sar, M. Differential distribution of dihydrotestosterone and estradiol binding sites in the epididymis of the mouse. An autoradiographic study. *Histochemistry* **81**, 139–147 (1984).
- West, N. & Brenner, R. Estrogen receptor in the ductuli efferentes epididymis and testis of rhesus and cynomolgus macaques. *Biol. Reprod.* **42**, 533–538 (1990).
- Sharpe, R. M. & Skakkebaek, N. E. Are oestrogens involved in falling sperm counts and disorders of the male reproductive tract? *Lancet* **341**, 1392–1395 (1993).
- Auger, J., Kunstmann, J. M., Czyglik, F. & Jouannet, P. Decline in semen quality among fertile men in Paris during the past 20 years. *N. Engl. J. Med.* **332**, 281–285 (1995).
- Hess, R. A. *et al.* Estrogen receptor (α & β) expression in the excurrent ducts of the adult male rat reproductive tract. *J. Androl.* **18**, 602–611 (1997).
- Fisher, J. S. *et al.* Immunolocalisation of estrogen receptor- α within the testis and excurrent ducts of the rat and marmoset monkey from perinatal life to adulthood. *J. Endocrinol.* **153**, 485–495 (1997).
- Ilio, K. & Hess, R. Structure and function of the ductuli efferentes: A review. *Microsc. Res. Tech.* **29**, 432–467 (1994).
- Yeung, C. H., Cooper, T. G., Bergmann, M. & Schulze, H. Organization of tubules in the human caput epididymidis and the ultrastructure of their epithelia. *Am. J. Anat.* **191**, 261–279 (1991).

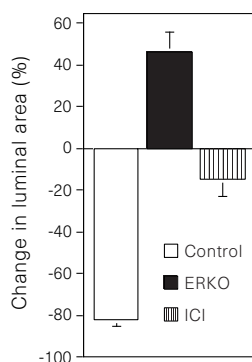


Figure 5 The effects of *in vitro* ligation on changes in luminal area of efferent ductule segments 24 h after ligation. Mean (\pm s.e.m.) percentage difference between 0 h and 24 h in luminal areas for isolated ductules from wild-type controls, ERKO and ICI-treated mice.

14. Robaire, B. & Hermo, L. in *The Physiology of Reproduction* (eds Knobil, E. & Neill, J.) 999–1080 (Raven, New York, 1988).
15. Chan, H. C., Zhou, W. L., Fu, W. O., Ko, W. H. & Wong, P. Y. Different regulatory pathways involved in ATP-stimulated chloride secretion in rat epididymal epithelium. *J. Cell. Physiol.* **164**, 271–276 (1995).
16. Clulow, J., Jones, R. & Hansen, L. Micropuncture and cannulation studies of fluid composition and transport in the ductuli efferentes testis of the rat: comparisons with the homologous metanephric proximal tubule. *Exp. Physiol.* **79**, 915–928 (1994).
17. Lubahn, D. B. et al. Alteration of reproductive function but not prenatal sexual development after insertional disruption of the mouse estrogen receptor gene. *Proc. Natl Acad. Sci. USA* **90**, 11162–11166 (1993).
18. Korach, K. S. et al. Estrogen receptor gene disruption: molecular characterization and experimental and clinical phenotypes. *Recent Prog. Horm. Res.* **51**, 159–186 (1996).
19. Eddy, E. M. et al. Targeted disruption of the estrogen receptor gene in male mice causes alteration of spermatogenesis and infertility. *Endocrinology* **137**, 4796–4805 (1996).
20. Smith, G. The effects of ligation and the vasa efferentia and vasectomy on testicular function in the adult rat. *Endocrinology* **23**, 385–399 (1962).
21. Hess, R., Moore, B., Forrer, J., Linder, R. & Abuel-Atta, A. The fungicide benomyl [methyl 1-butylcarbamoyl-2-benzimidazole carbamate] causes testicular dysfunction by inducing the sloughing of germ cells and occlusion of efferent ductules. *Fundam. Appl. Toxicol.* **17**, 733–745 (1991).
22. Wakeling, A., Dukes, M. & Bowler, J. A potent specific pure antiestrogen with clinical potential. *Cancer Res.* **51**, 3867–3873 (1991).
23. Kuiper, G. G. et al. Comparison of the ligand binding specificity and transcript tissue distribution of estrogen receptors alpha and beta. *Endocrinology* **138**, 863–870 (1997).
24. Paech, K. et al. Differential ligand activation of estrogen receptors ER α and ER β at AP1 sites. *Science* **277**, 1508–1510 (1997).
25. Carani, C. et al. Effect of testosterone and estradiol in a man with aromatase deficiency. *N. Engl. J. Med.* **337**, 91–95 (1997).
26. Morishima, A., Grumbach, M. M., Simpson, E. R., Fisher, C. & Qin, K. Aromatase deficiency in male and female siblings caused by a novel mutation and the physiological role of estrogens. *J. Clin. Endocrinol. Metab.* **80**, 3689–3698 (1995).
27. Smith, E. P. et al. Estrogen resistance caused by a mutation in the estrogen-receptor gene in a man. *N. Engl. J. Med.* **331**, 1056–1061 (1994). Erratum. *N. Engl. J. Med.* **332**, 131 (1995).
28. Krause, W., Holland-Moritz, H. & Schramm, P. Treatment of idiopathic oligozoospermia with tamoxifen—a randomized controlled study. *Int. J. Androl.* **15**, 14–18 (1992).
29. Sharpe, R. M. Declining sperm counts in men—is there an endocrine cause? *J. Endocrinol.* **136**, 357–360 (1993).
30. Hess, R. A. & Moore, B. J. in *Methods in Reproductive Toxicology* (eds Chapin, R. E. & Heindel, J. J.) 52–85 (Academic, San Diego, 1993).

Acknowledgements. We thank E. Jassim and C. Finnigan-Bunick for technical assistance, P. Cooke, V. K. Ganjam and D. J. Miller for reviews of the manuscript and A. Wakeling and Zeneca Pharmaceuticals for providing ICI 182, 780.

Correspondence and requests for materials should be addressed to R.A.H. (e-mail: r-hess@uiuc.edu).

Radial optic flow induces vergence eye movements with ultra-short latencies

C. Busettini*, G. S. Masson* & F. A. Miles

Laboratory of Sensorimotor Research, National Eye Institute, National Institutes of Health, Bethesda, Maryland 20892, USA

An observer moving forwards through the environment experiences a radial pattern of image motion on each retina. Such patterns of optic flow are a potential source of information about the observer's rate of progress¹, direction of heading² and time to reach objects that lie ahead³. As the viewing distance changes there must be changes in the vergence angle between the two eyes so that both foveas remain aligned on the object of interest in the scene ahead. Here we show that radial optic flow can elicit appropriately directed (horizontal) vergence eye movements with ultra-short latencies (roughly 80 ms) in human subjects. Centrifugal flow, signalling forwards motion, increases the vergence angle, whereas centripetal flow decreases the vergence angle. These vergence eye movements are still evident when the observer's view of the flow pattern is restricted to the temporal hemifield of one eye, indicating that these responses do not result from anisotropies in motion processing but from a mechanism that senses the radial pattern of flow. We hypothesize that flow-induced vergence is but one of a family of rapid ocular reflexes, mediated by the medial superior temporal cortex, compensating for translational disturbance of the observer.

* Present addresses: Department of Physiological Optics, University of Alabama, Birmingham, Alabama 35205, USA (C.B.); Centre de Recherche en Neurosciences Cognitives, Centre National de la Recherche Scientifique, 13402 Marseille, France (G.S.M.).

The centrifugal pattern of optic flow that we experience as we move forwards—a constant stream of images moving away from a central focus of expansion (Fig. 1a)—has been the subject of many psychophysical, physiological and computational studies (see ref. 4 for a review). Optic flow is a rich source of information about the three-dimensional layout of the environment and the observer's movements within it⁵. To maintain binocular alignment on objects of interest that lie ahead, the observer must continuously adjust the vergence angle between the eyes. The primary visual cue used to control convergence is binocular disparity⁶, though changes in object size^{7,8} as well as static perspective and overlay cues⁹ can also be used. It occurred to us that optic flow might also make a contribution as it charts the observer's rate of forward progress.

Our experimental subjects faced a vertical screen onto which large random-dot patterns were back-projected. Steps of radial flow, achieved by switching between two projected images signalling radial displacement and a size change, were applied 50 ms after the subject's eyes fixated the centre of the screen. The flow patterns elicited pure horizontal vergence (negligible vertical vergence) at latencies of roughly 80 ms in the four subjects tested. As expected from the geometry, centrifugal flow (signalling approach) resulted in increased convergence whereas centripetal flow (signalling retreat) resulted in decreased convergence. Sample vergence velocity profiles, obtained with centrifugal steps of various amplitudes (expressed in terms of the percentage change in apparent viewing distance), are shown for one subject in Fig. 1b. Initial responses were quantified by measuring the change in vergence over a 33-ms period commencing a fixed time (95 ms) after the onset of the stimulus. This meant that our measures were restricted to the initial (open-loop) vergence responses that were generated by the radial flow before it had been affected by eye-movement feedback. These measures are plotted against the percentage change in apparent viewing distance in Fig. 1c, for both centrifugal and centripetal flow. For a given step size, the increases in convergence with centrifugal flow were always larger than the decreases with centripetal flow (compare with ref. 10). Optimal steps changed the apparent viewing distance by 2–4%.

Vergence velocity profiles were always transient, rising to a peak in 30–50 ms and then declining. In our artificial viewing situation, the vergence responses to radial flow would result in binocular disparity, which would in turn tend to generate vergence in the opposing direction. However, disparity-induced vergence has been shown to have a latency approximating that of the radial-flow vergence¹¹, indicating that its earliest effects could not occur until about 80 ms after response onset. The transient nature of the radial-flow vergence cannot therefore be due to the 'closing of the disparity-vergence loop'. This conclusion is also supported by the finding that initial vergence responses were still transient with monocular viewing (discussed later).

When an observer moves forwards, retinal images not only undergo centrifugal motion but also get larger (Fig. 2a), as was the case in the above experiments. Changes in the size of a single small foveated target have been shown to elicit weak vergence eye movements in humans, but at latencies estimated to be in excess of 200 ms (refs. 7, 8). In our case, using large multi-element patterns and shorter time intervals, the size changes were irrelevant, and eliminating the size cue (as in Fig. 2b) had little effect on the vergence responses. Vergence responses to radial flow alone were almost the same as those to radial flow plus size change, and pure changes in size (as in Fig. 2c) failed to generate significant vergence (Fig. 2d).

We propose that these vergence eye movements represent a binocular response to the radial pattern of flow. However, an alternative explanation might be that tracking is essentially monocular, each eye tracking only the motion that it sees and with a strong preference for motion in the nasal hemifields. In this case, with centrifugal flow there would be a net motion vector towards