Antler Growth: Nutritional and Endocrine Factors

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Abstract

Antlers may be thought of as growing in 4 phases. First the pedicle grows under the control of testosterone when the stag reaches a threshold body weight. When the pedicle has reached about 6 cm the velvet antler develops; this is accompanied by lowered testosterone secretion and increased levels of insulin-like growth factor. In the third stage the antler is cleaned of velvet while testosterone levels are high. After testosterone levels have fallen the antler is cast, although suppression of testosterone may not be solely responsible for this. During the growth of all subsequent antlers, plasma levels of testosterone are very low even after gonadotrophin releasing hormone challenge. At the tissue level testosterone may be metabolised via the aromatase pathway to oestradiol which is involved in the mineralisation of the antler, or via the 5α reductase pathway to 5α dihydrotestosterone which is involved in antler cleaning. There are evidently major gaps in our knowledge of this unique tissue.

Keywords: androgens, Cervus elaphus, *luteinising hormone, testosterone, antler casting, pedicle, antler*

Introduction

Important differences in antler growth exist between the various genera and species of deer, as for example between the genus *Rangifer* and the genus *Cervus*. This paper is concerned principally with antler growth in the latter genus and particularly in the red deer, *Cervus elaphus*, although data derived from other species are used where relevant. The paper concentrates on aspects of endocrinology and nutrition which we consider relevant to improving our understanding of the regulation of antler growth and to identifying potentially fruitful areas for further research. Therefore where appropriate some hypotheses are developed. For more extensive reviews of antler growth the reader is referred to the monographs by Chapman (1975) and Goss (1983) and the Proceedings of the Caesar Kleberg Symposium on antlers (Brown 1983).

The influence of nutrition on antler growth is the subject of much apocryphal literature. However, controlled studies are rare and those involving adequate numbers of animals extremely so. As Chapman (1975) noted, "the importance of food has been appreciated for several centuries, for as Twici, who was huntsman to King Edward II, remarked 'The head grows according to the pasture, good or otherwise' (Dryden 1908)". Despite such observations, in any study of the influence of nutrition a distinction must be made between effects on the growth of the young deer and initiation of the pedicle, effects on the ultimate body size of the stag, and effects prior to and during the period of active antler growth.

The study of the endocrine regulation of antler growth also has a long history, for in 55 B.C. Aristotle made some interesting observations on the relationship between the testis and antlers: "If stags are castrated before they are old enough to have horns, these never appear; but if castrated after they have horns their size never varies, nor are they subject to annual change" (after Cresswell 1862 cited by Chapman 1975). However, it is only in the last $30 - 40$ years that the scientific study of the endocrinology of antler growth has advanced significantly over that of Aristotle. During this time a number of candidates for the role of the putative *antler stimulating hormone* have been proposed. The list includes growth hormone (Bubenik *et al* 1975), prolactin (Wislocki *et al* 1947, Mirarchi *et al* 1978), and testosterone (Bubenik 1983), but there is little direct convincing evidence for a role for any of these hormones in actually stimulating the growth of the antler.

For the purposes of discussion the antler growth cycle is best considered in 4 sections:

(i) Pedicle

(ii) First antler

(iii) Antler casting

(iv) Growth of later antlers

The antler growth cycle in red deer is illustrated in Fig. 1.

The Pedicle

The normal development of the antler depends on the presence of the pedicle which arises from the

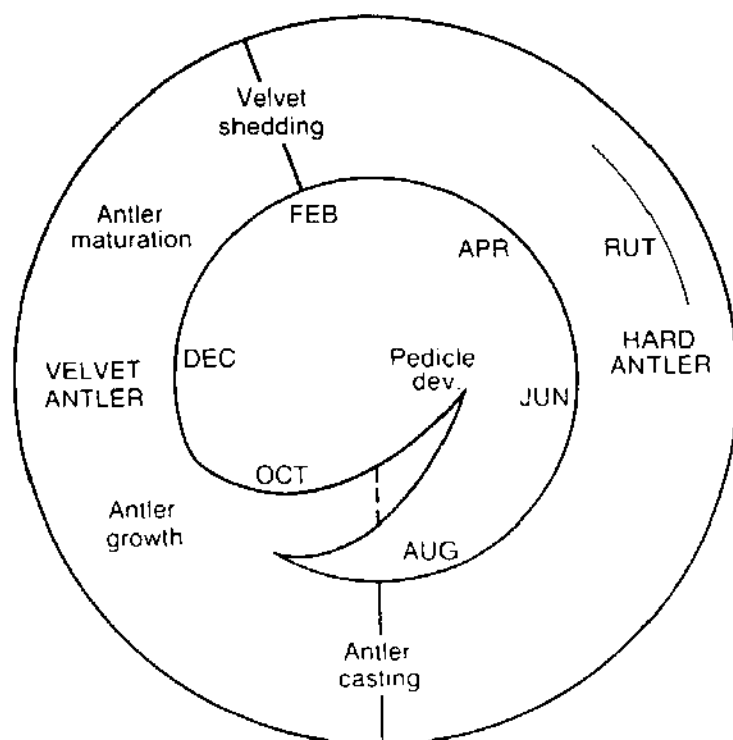**CYCLE OF ANTLER GROWTH IN RED DEER STAG**

Fig. 1: Outline of the antler growth cycle in the red deer stag.

frontal bone of the skull. The timing of initiation of the pedicle in relation to photoperiod and nutrition in *Cervus* spp. has been the subject of several studies. For example, Goss (1969, 1980) found that sika deer grew their pedicle when they were less than 1 year of age regardless of the light cycle under which they were raised, and regardless of whether day length was increasing or decreasing. In red deer, recent studies have shown conclusively that the pedicle is a secondary sexual character whose development is associated with the onset of puberty as postulated by Lincoln (1971). This is apparent from both castration and endocrine studies and is supported by the fact that the timing of pedicle initiation is highly correlated with body weight, which is of course dependent on the level of nutrition. The results of 3 such studies are shown in Table 1. Pedicle initiation tended to occur at a threshold body weight irrespective of age or season of the year; consequently stags fed on a higher plane of nutrition grew their pedicles earlier than their more poorly fed peers. The mean liveweight at pedicle initiation varied between studies from 41 to 56 kg; this may represent a difference in the genetic potential for growth among the stags involved.

The influence of prepubertal castration on pedicle initiation has already been mentioned. More recently it has been shown that testosterone administration promotes pedicle development in both prepubertally castrated males and in intact

females (Wislocki *et al* 1947; Jaczewski 1976 Fletcher 1978). Treatment with prolactin did not produce such an effect (Jaczewski and Krzywinska 1974).

Although the effects of castration and testosterone replacement on the pedicle are well reported, much less is known of the actual endocrine events about the time of pedicle initiation. For this reason Suttie *et al* (1984) performed GnRH (gonadotrophin releasing hormone) challenge tests on young stags; this technique provides information on the endocrine status of the pituitary through the effect of GnRH on luteinising hormone (LH) release and indirectly on the status of the testis through the effect of LH on testosterone release (plasma levels of the hormones were monitored at intervals over a 3-hour period following the administration of GnRH). The data are summarised in Table 2.

Before pedicle initiation basal levels of LH were high and testosterone concentrations virtually zero. However, in response to GnRH administration (20 ng/kg) there was a very large release of LH from the pituitary and a very small release of testosterone into the plasma from the testis. Therefore at this time it is concluded that the pituitary is very responsive to GnRH but that the testis is relatively unresponsive to LH. However, as pedicle growth was initiated the situation changed with declines in both the basal LH level and the LH response to GnRH. In contrast, while the basal level of testosterone was still undetectable, the testosterone response (via LH) to GnRH increased as the pedicle developed.

Table 1: Age and weight of red deer calves at pedicle initiation in 3 experiments

	Age (weeks)	Weight (kg)
Expt 1[1]		
Fed to appetite ($n = 6$)	19	41
Restricted (6)	31	44
s.e.m.	3.0**	1.9[ns]
Expt 2[2]		
Pelleted feed (5)	32.6	50
Meadow hay (5)	38.8	47
s.e.m.	1.5**	2.1[ns]
Expt 3[2]		
Pelleted feed (6)	36.6	55
Meadow hay (6)	39.4	51
s.e.m.	1.2*	1.7*

[1] Suttie and Kay (1983); the group fed *ad libitum* initiated pedicles on decreasing days in autumn, whereas the diet-restricted deer initiated on increasing days in spring
[2] Fennessy unpubl.; diets fed *ad libitum* from 28 to 38 weeks of age, thereafter all deer fed the pelleted feed (barley-lucerne-linseed) *ad libitum*

Table 2: Plasma LH and testosterone (T) levels at various stages of pedicle development and growth of the first antler and their response to GnRH challenge

| | Mean basal concentration[1] (ng/ml plasma) | | GnRH response[2] (peak height; ng/ml plasma) | |
	LH	T	LH	T
Pedicle				
Pre	5.7	0	29.4	1.1
Early	4.7	0	20.6	1.2
Late	3.5	0	24.5	1.9
Antler				
Early velvet	2.5	0	14.4	2.1
Mid – late velvet	4.6	0	20.5	1.2
Full velvet	2.8	0	10.5	0.8
Cleaning	3.5	1.8	12.7	7.3
Hard (rut)	4.6	1 4	12.9	13.3

[1] Single blood sample taken at c. 0930 hours from 6 stags
[2] GnRH (20 ng/kg liveweight intravenously) response in 6 stags. The response is the maximum level recorded in blood samples taken frequently over a 3-hour period. Stags were not anaesthetised and were manually restrained for sampling (Suttie *et al* 1984)

Consideration of the data on prolactin levels around the time of pedicle initiation suggests that it is most unlikely that prolactin is directly involved in the process of pedicle initiation. The mean prolactin profile for 6 stags from birth to 27 months of age is shown in Fig. 2. The prolactin levels largely reflect changes in day length, and in this group pedicle initiation occurred over a wide timespan during which time plasma prolactin levels varied widely (values for individual stags at initiation ranged from 4.2 to 33.3 ng prolactin/ml with a mean of 14.6 ± 2.8) (Suttie 1981; Suttie and Kay 1985).

Our hypothesis concerning pedicle initiation is outlined in Fig. 3. As threshold body size is attained, both the amplitude and the spike frequency of LH release from the pituitary increases (Suttie and Fennessy unpubl.) presumably in response to an increased frequency of luteinising hormone releasing hormone (LHRH) release from the hypothalamus (Clarke and Cummins 1982; Levine *et al* 1982). In turn there is an increase in testosterone release from the testis (Suttie and Fennessy unpubl.). The testosterone acts on the putative androgen receptors in the periosteum of the frontal bone promoting growth of the bony pedicle, an effect which cannot be brought about by oestrogen or weaker androgens
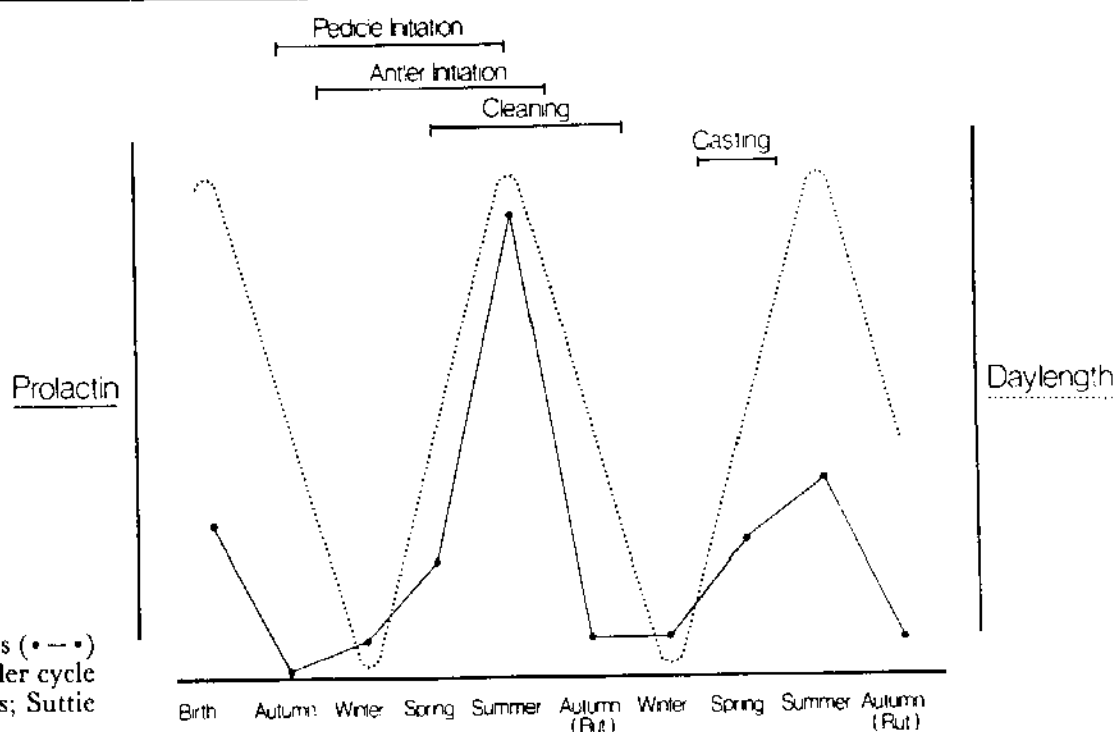

Fig. 2: Prolactin concentrations (•–•) in plasma in relation to the antler cycle and day length (mean of 6 stags; Suttie *et al* 1984).

PEDICLE INITIATION

THRESHOLD BODY
SIZE ATTAINED

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Hypothalamus

LHRH
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Pituitary
LH  — spike frequency
    — spike height
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NEITHER OESTROGEN
(NOR WEAKER ANDRO-
GENS?) CAN DUPLICATE
THIS EFFECT

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Testis
Testosterone — frequency
            — height
```

−ve

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Target Organ
Receptors on frontal
bones
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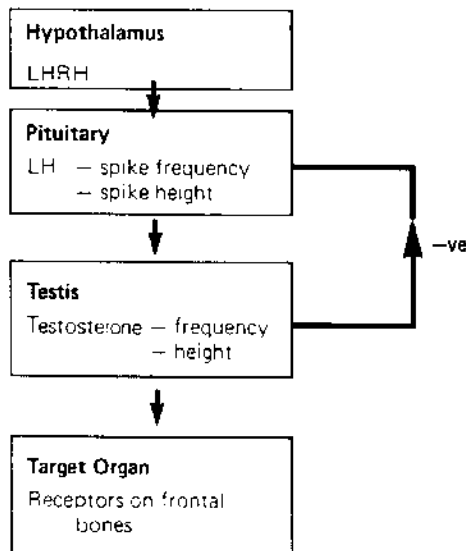
Fig. 3: Our hypothesis relating to pedicle initiation.

Fig. 4: Pattern of growth of the pedicle and first antler of the red deer stag (mean of 10 stags; bars indicate s.d.).

(Goss *et al* 1964). It is hypothesised that during pedicle initiation, the androgen gradually sets up a negative feedback at the hypothalamic and/or pituitary level such that the LH pulse frequency is reduced. In both sheep and cattle there is evidence that the negative feedback operates at both levels (D'Occhio *et al* 1982; Gettys *et al* 1984).

First Antler

The first antler commences growth after the permanent bony pedicle has reached a length of 5 − 6 cm. At antler initiation the deciduous cartilaginous antler (i.e. the velvet antler) begins growing from the tip of the pedicle. Therefore it is apparent that the growth of the first antler depends on the growth of the pedicle, and if pedicle initiation is delayed, then antler initiation will be delayed also. However, the pedicle/antler interrelationship notwithstanding, there is evidence that a low plane of nutrition retards and restricts the development of the first antler. In this respect Suttie and Hamilton (1983) fed 2 groups of stags on either a high or low plane of nutrition during winter followed by a summer on a very poor-quality hill pasture in Scotland (Table 3). A low plane of nutrition before and during antler
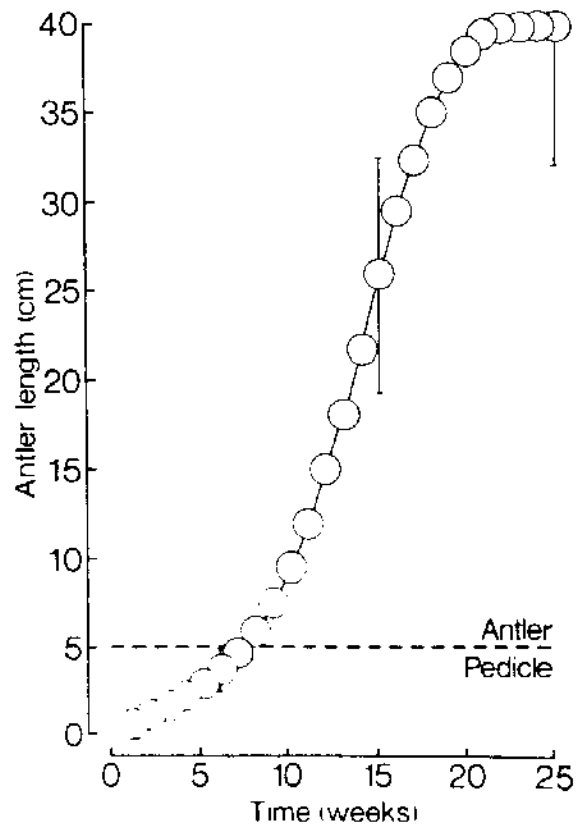
development resulted in lighter, shorter antlers. Although red deer normally grow only single spikes for their first antlers, it appears that a high plane of nutrition may facilitate branching. In this experiment, pedicle initiation was 15 weeks later in the low plane group, antler initiation was 12 weeks later, and antler cleaning 8 weeks later.

The typical pattern of growth of the pedicle and the first antler is shown in Fig. 4. These data are derived from a group of 10 stags with a 90-day range in the date of pedicle initiation (Fennessy unpubl.). There was no relationship between either antler length or the time taken to grow the first antler and the date of pedicle initiation or any parameter of body weight. The mean antler length was 40 ± 2.5 (s.e.m.) cm and the growth period was 11.8 ± 0.5 weeks.

The pattern of LH and testosterone response to a GnRH challenge changes from pedicle

Table 3: Influence of nutrition on antler development

Nutrition	Pedicle initiation	Liveweight (kg) at Antler initiation	Antler cleaning	Weight (g)	Antlers Length (cm)	Points
High plane	48	58	64	48	22	1.22
Low plane	47	57	62	18	10	1.00
s.e.m.	1.7^{ns}	2.1^{ns}	1.6^{ns}	8.1^{**}	2.2^{**}	0.1^{*}

development through the period of antler growth to the time of antler cleaning (i.e. stripping of the velvet) (Table 2). During the time of early antler growth, the peak LH level in response to GnRH was markedly reduced compared with that during pedicle development, although it then increased again reaching relatively high levels at the time of rapid antler growth, before falling again. However, testosterone responses which reached a peak in late pedicle – early antler then started a decline which continued through antler development. At the time of antler cleaning and during the rut testosterone responses were very high; in fact basal levels (i.e. in the absence of GnRH stimulation) of testosterone were detectable only during these latter stages.

As stated previously pedicle initiation occurred over a wide range of plasma prolactin levels (Suttie *et al* 1984). However, when individual stags are considered prolactin levels were elevated during velvet antler growth compared with those recorded during pedicle development, although it must be remembered that most of the velvet antler growth occurred during the period of increasing day length, so it is possible that the prolactin levels simply reflect the influence of day length. The plasma prolactin profile for a typical stag in this study is presented in Fig. 5. The influence of day length notwithstanding, a role for prolactin in the regulation of the antler cycle is a possibility. In this respect prolactin is known to block LHRH receptors in the pituitary (Bartke 1980) and also to block LH receptors on the Leydig cells of the testis (Ravault *et al* 1982). Therefore it is considered possible that the fall in the peak testosterone response to GnRH observed during antler development and accompanied by a fall in basal LH levels may be a consequence of elevated prolactin. Nonetheless, it is pertinent that the testosterone response to GnRH during the first antler cycle was always detectable, in marked contrast to that in later cycles of antler growth.

Recent work with young red deer stags growing their first antlers (Suttie *et al* 1985) has pointed to the possibility that the somatomedin, insulin-like growth factor 1 (IGF-1) may be involved in the growth of the velvet antler. In this experiment with 6 stags, the plasma level of IGF-1 was low during pedicle growth and was markedly higher during the
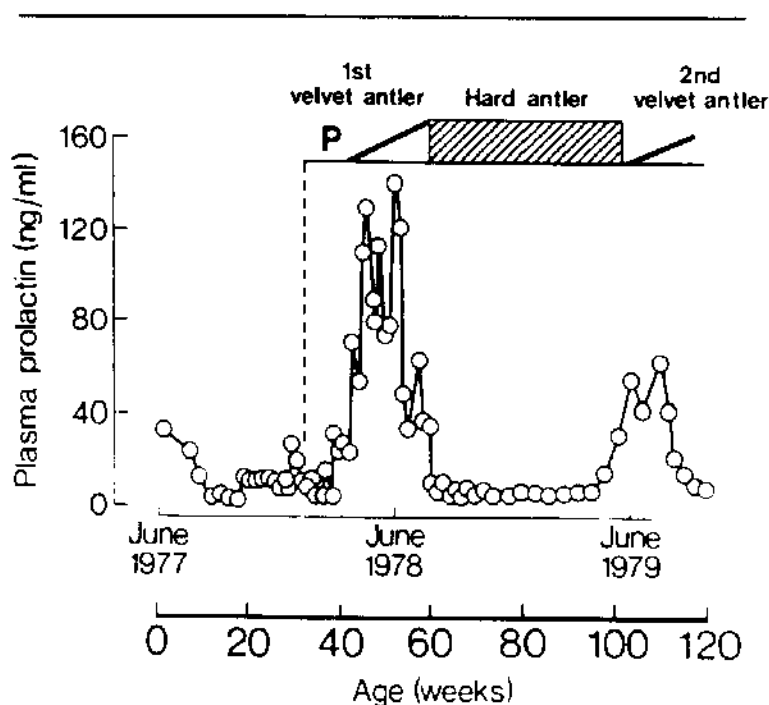

Fig. 5: Prolactin concentration in plasma for 1 stag in relation to the antler cycle (the pattern is typical of those in a group of 12; P = pedicle; Northern Hemisphere data; Suttie *et al* 1984).

antler growth phase (Table 4). Since IGF-1 is involved in cartilage growth, restoring the growth of cartilage in hypophysectomised rats (Schoenle *et al* 1982), it seems possible that IGF-1 stimulates antler cartilage growth and is therefore an antler stimulating hormone. However, a considerable amount of further work is necessary before any firm conclusions can be drawn either way.

Having considered the hormonal pattern observed during the growth of the first antler, we can advance a tentative hypothesis concerning its regulation. However, a brief description of the cell types present in the growing antler is first necessary (Fig. 6). The growing tip of the antler is composed of mesenchymal cells, pre-chondroblasts, and chondroblasts and is covered by a layer of epidermis and dermis. The lower regions of the growing antler reflect the nature of the tissue — chondroblasts and oesteoblasts, etc. In Fig. 7 our hypothesis for the endocrine regulation of the growth of the first antler is presented.

The first important feature of the hypothesis is that velvet antler growth is associated with a

Table 4: IGF-1 (ng/ml) levels at 4 stages of pedicle and antler development (mean ± s.e.m., *n* = 6)

Pedicle growth	Velvet antler growth	Antler growth complete	Antler clean of velvet
83.3 ± 7.05[1]	150.7 ± 20.00	102.5 ± 8.00	79.5 ± 6.56

[1] Newman-Keuls test, df 4,20; IGF-1 during velvet growth higher (P < 0.05) than during other stages

THE GROWING ANTLER

Epidermal cells
Mesenchymal cells

Chondroblasts/Clasts

COLLAGEN

CALCIFIED
CARTILAGE

OSTEOBLASTS/CLASTS

Osteoclastic
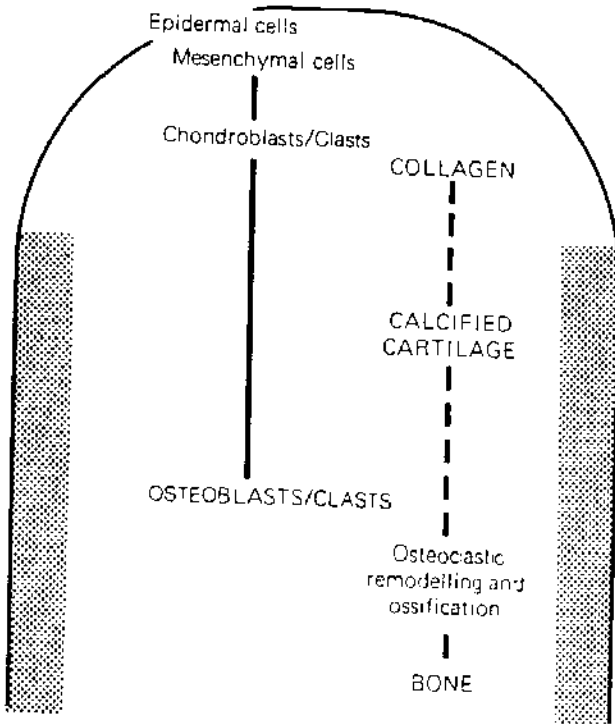remodelling and
ossification

BONE

Fig. 6: Pattern of cell types and differentiation of the growing antler (adapted from Banks 1974 *in* Banks and Newbrey 1983).

ceased the testosterone levels increase resulting in osteoclastic remodelling of the bone and finally cleaning. Nonetheless there is evidence (Suttie and Fennessy unpubl.) that in comparison with the second antler, the first antler is more calcified at the same stage of growth and grows at a much slower rate. The higher level of testosterone during the period of velvet antler growth may be partly responsible for the greater degree of calcification while these 2 factors may explain the relatively slow rate of growth and the lack of branching of the first antler in the red deer stag.

Antler Casting

The clean hard antler is essentially a dead bone attached to living bone (the pedicle) and as such it is almost axiomatic that it will be cast eventually. Castration while in hard antler results in antler casting, and since testosterone implants maintain the dead-live antler-pedicle junction thus preventing casting (Wislocki *et al* 1947), it is clear that testosterone plays a major role in maintaining the hard antler. Indeed plasma testosterone concentrations (both basal and in response to GnRH administration) at the time of casting are very low. Compared with other times of the antler cycle, LH concentrations are also low at the time of natural antler casting, probably indicating a cause-effect relationship with testosterone. However, casting may still occur when LH levels are very high after castration or very low after treatment with medroxyprogesterone acetate (Fig. 8). Therefore the important factor is clearly the low testosterone. It may be that the elevated levels of prolactin found at casting (Suttie *et al* 1984) act as an antigonadotrophin and are responsible for

reduction in the responsiveness of the pituitary to LHRH, with consequent reductions in LH release and hence testosterone release. In addition the testis becomes partly refractory to LH stimulation. Prolactin may have a role in the regulation of these events. The second important feature is that the reduced level of testosterone coupled with the elevated levels of IGF-1 therefore result in the growth of the velvet antler. After antler growth has

FIRST ANTLER

Hypothalamus
LHRH

Pituitary
LH

Early-mid velvet

Late velvet

TESTIS BECOMES
PARTLY "REFRACTORY"
TO LH. IGF 1
MUST BE PRESENT

Testis
Low
Testosterone

Target Organ
1. Chondroblasts
2. Osteoblasts

TESTIS RECOVERS AND SHOWS
INCREASED RESPONSIVENESS
TO LH.

Testis
High
Testosterone

Target Organ
1. Osteoclasts
   (remodelling)
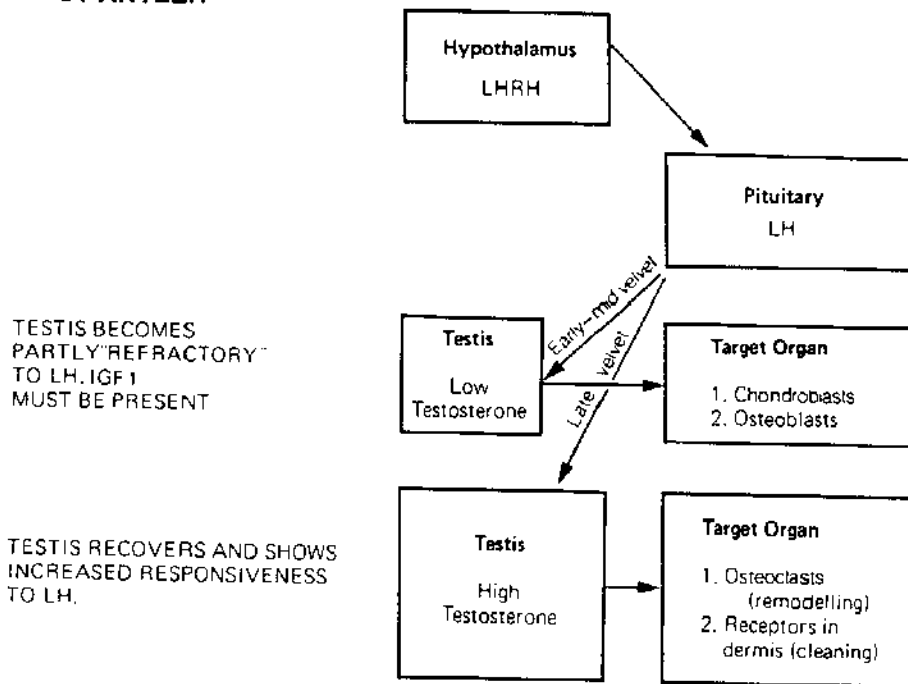2. Receptors in
   dermis (cleaning)

Fig. 7: Our hypothesis on endocrine regulation of the growth of the first antler.
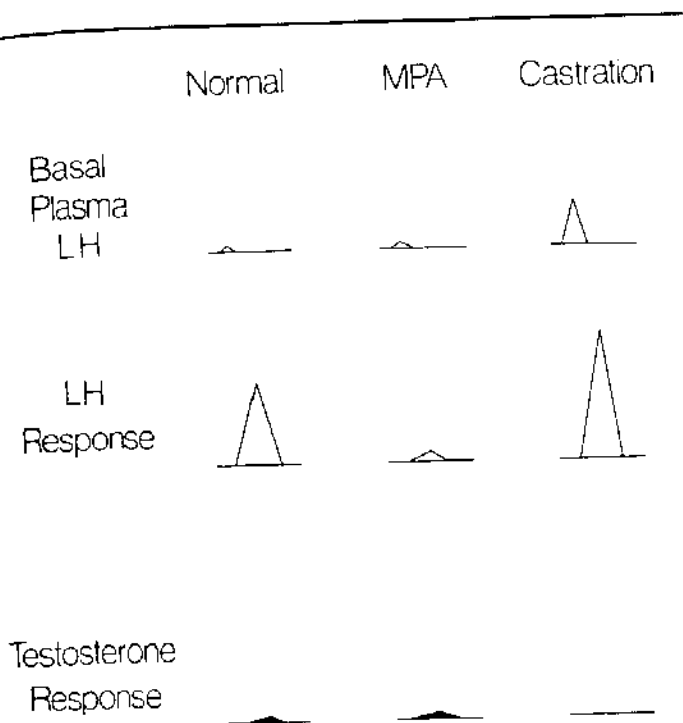
Fig. 8: Stylised diagram showing plasma LH and testosterone (T) responses to GnRH administration in stags at the time of normal casting and casting induced by castration or by treatment with medroxyprogesterone acetate (MPA; 150 mg intramuscular).

in the maintenance of the hard antler in the stag, more detailed biochemical evidence indicates that testosterone is apparently incapable of reducing or preventing localised bone resorption *in vitro* (Caputo *et al* 1976). If the basic assumption is made that antler casting is little other than localised bone resorption (Goss 1983), then it is apparent that some other mediator(s) in addition to testosterone must also be involved *in vivo*. Such possibilities include prostaglandin E_2 (Klein and Raisz 1970) and osteoblast activating factor (Raisz *et al* 1975).

Our hypothesis relating to antler casting is outlined in Fig. 9. It seems likely that the photoperiodic and nutritional effects are mediated at the hypothalamic and/or pituitary level which results via LH in a reduction in circulating testosterone. In the presence of very low levels of testosterone casting follows. It is proposed that cells in the tip of the pedicle are released from steroid (testosterone) inhibition, permitting an inflammatory-like process to take place which results in selective bone resorption. However, as testosterone itself is incapable of preventing bone resorption, the actual process must be mediated by other factors.

the reduced level of LH recorded in intact stags at this time. Cyclic changes in day length influence the timing of antler casting and it may be that this effect is brought about through changes in the plasma prolactin level. While changes in day length affect the time of casting more than does the level of nutrition, nutrition can have some effect as shown in Table 5. On 3 of the 4 properties in this study, stags fed hay supplemented with concentrates from late June — early July until casting, cast their old antlers significantly earlier than the controls fed hay only. It seems likely that this effect is mediated via prolactin or other hormones which result in a depression in the level of circulating testosterone.

Despite the evidence for the role of testosterone

Growth of Later Antlers

It is well known that there is a general relationship between antler size and body size in that larger deer have larger antlers (Huxley 1926, 1931). Such a relationship for 16 red deer stags (aged 3 years) fed high-quality diets to appetite indoors is shown in Fig. 10.

To ascertain the influence of some specific nutritional manipulations on antler size, 3 studies were carried out with pen-fed stags at Invermay (Fennessy and Corson unpubl.). Two studies were concerned with the protein content of the diet fed during winter in the 3 − 4 months prior to antler casting. The results of the first experiment with 2-year-old stags are shown in Table 6. Using either 2-year-old liveweight or hard antler weight in the following year (as 3-year-olds) as covariates, the stags fed the high-protein diet had significantly heavier antlers than the controls fed the low-protein diet. However, when the study was repeated with 3-year-old stags there was no response to the level of dietary protein. Any reason for the difference between years must be highly speculative, but it is possible that the response to the extra protein was mediated by endocrine events. Such effects could also be a function of the age and the relative maturity of the stags concerned. In the third experiment, feed intake was restricted during the first 65 days of antler growth (Table 7). There was a small but non-significant reduction in antler size. While the rate of antler growth is affected by nutrition (presumably through the amount of

Table 5: Casting date of antlers as affected by nutrition during winter in groups of stags on 4 farms[1]

Diet	A	B	C	D
Hay only	8/10	29/9	17/9	20/9
Hay + ½ supplement	29/9[ns]	21/9[ns]	9/9*	21/9[ns]
Hay + supplement[2]	25/9*	16/9*	9/9*	15/9[ns]

[1] Experiments conducted by P F Fennessy, K R Drew, and G H Moore (Invermay) and P D Muir and A R Sykes (Lincoln College), unpubl. data
[2] Full supplement 2.1 − 2.9 kg/head/day of a barley-lucerne-linseed pelleted diet; 11 − 18 stags/group; *P<0.05 for comparison with groups fed hay only

CASTING

Photoperiod ————————— Entrains

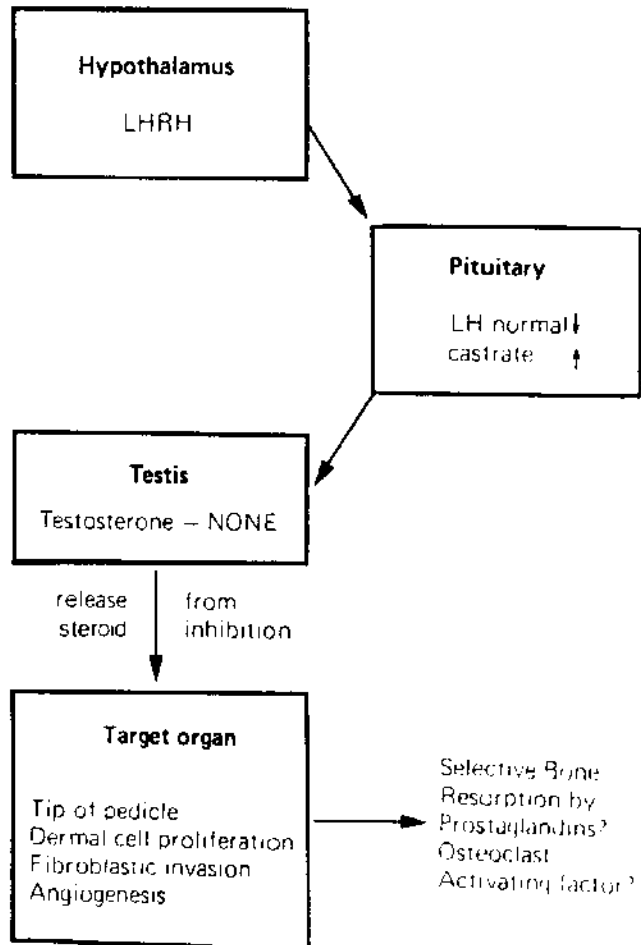High plane of Nutrition —— Advances

Low plane of Nutrition —— Retards

Fig. 9: Our hypothesis relating to casting of the hard antler.

substrate diverted towards antler growth) the actual causative mechanism is not known. However, it seems likely that the nutritional effects are mediated via endocrine events. The role proposed for IGF-1 offers one such mechanism awaiting further investigation.

The importance of the hypothalamic-pituitary-testis axis in the overall regulation of the antler cycle has already been discussed specifically in relation to the growth of the pedicle and first antler. In contrast to the situation with the later antlers, the first antler grows after a period of intense androgenic activity associated with pedicle growth. The later antler, however, regenerates from a healing wound following casting of the old antler at a time of extremely low testosterone levels. Therefore various studies have been carried out in attempts to further define the endocrine events occurring at various times of the cycle.

Since both LH and testosterone are released into the circulating blood in a pulsatile or spike fashion in the male red deer (Lincoln and Kay 1979), there

Table 6: Effect of protein content of winter diet on hard antler weight in 2-year-old stags indoors (8 per group)

Diet	Covariate:[1]	Hard antler weight (1 antler, kg)	
		Liveweight	3-year-old antler
Low protein[2]		0.488	0.514
High protein		0.668	0.643
RSD		0.126*	0.075**

[1] Data presented are adjusted means calculated from the regression of hard antler weight on either peak 2-year-old liveweight or on 3-year-old antler weight

[2] Low protein c. 14% crude protein in dry matter; high protein 23%
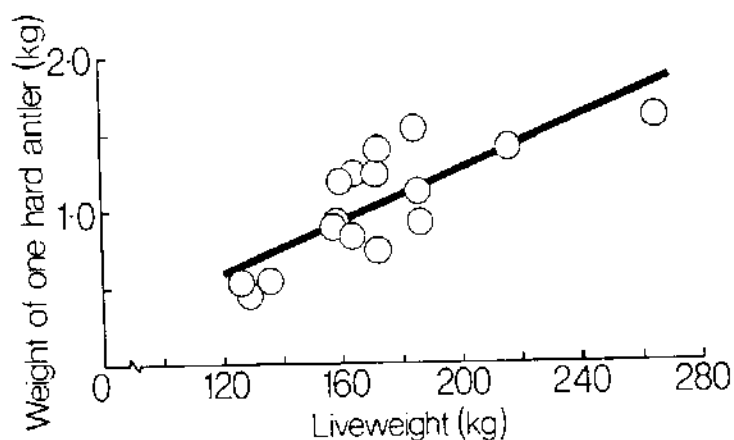
RSD, residual standard deviation

Table 7: Effect of level of feed intake during first 65 days of antler growth on weight of antler in 4-year-old stags indoors (5 per group)

Feed intake	Antler weight (kg)[1]
Ad libitum	1.100
Restricted (c. 80% of *ad lib.*)	0.936
RSD	0.115(*)

1 Adjusted mean value for weight of 1 antler at 65 days from analysis of covariance using 3-year-old hard antler weight as covariate; (*) P < 0.10
RSD, residual standard deviation

Fig. 10: The relationship between the weight of 1 hard antler and liveweight for a group of 16 red deer stags (3 years old) fed indoors on a high-quality pelleted diet *ad libitum*.

are potential problems in interpreting data from single blood samples. However, the mean basal levels of LH and testosterone from a number of stags can be expected to provide some indication of the pulse frequency of hormone release provided that there are not compensating changes in amplitude. Similarly the proportion of samples showing evidence of a *spike* (i.e. an elevated level) of these hormones would also provide such an indication. Based on these suppositions, the seasonal LH and testosterone values show distinct patterns with the peak LH occurring during velvet antler growth and the testosterone peak occurring during the hard antler phase particularly about the time of the rut. As the mean testosterone concentration increased, the LH concentration declined, further evidence for a negative feedback of testosterone on LH in the red deer stag. The data, together with that for the GnRH responses, are presented in Table 8.

The essential features of the data for the GnRH-induced responses in LH and testosterone are:

- the very low testosterone response at casting;
- the low testosterone during the period of velvet antler growth in contrast to that observed during the growth of the first antler;
- the increases in testosterone response after the summer solstice, during which time antler cleaning occurs; and
- the very high testosterone response during the rut and its subsequent decline.

In contrast to these very marked changes in the testosterone response to GnRH (through LH), the changes in the LH responses through the antler cycle were small. However, some pattern in the pituitary LH response to GnRH was evident with the lowest respones at casting and during growth of the antler. Responses were apparently higher at the time when antler growth was complete. The lower response during the rut could be expected,

Table 8: Plasma LH and testosterone (T) at various stages of the antler cycle

Antler state	n	Evidence of pulse (n stags)[1] LH	T	Mean basal concentration (ng/ml) LH	T	GnRH response[2] (change: ng/ml plasma) LH	T
Hard (Jul)	8	0	1	0.3	0.8	18.5	7.9
Casting (Oct)	8	1	0	0.4	0.1	9.5	0.6
Mid velvet (Nov)	8	7	0	7.1	0.3	9.7	0.6
Full velvet (Jan)	8	8	4	7.5	1.1	18.9	1.9
Cleaning (Feb)	8	5	7	2.5	3.9	18.8	6.4
Hard (Apr rut)	12	0	12	0.4	12.6	10.3	61.1
Hard (Jun)	10	0	7	0.4	3.2	13.9	18.8
Hard (Jul)	8	0	4	0.4	3.7	—	—
Casting (Aug – Sep)	14	3	0	0.6	0.1	—	—

1 Single blood sample taken at c. 0900 hours: any value of LH or T > 1 ng/ml was taken as evidence of a pulse
2 GnRH response: 8 stags were allocated to each of 4 levels of GnRH (1, 3, 10, 95 µg intravenously i.e. 2 stags per level on each occasion); the response is defined as the change from the basal (time zero) sample to the peak recorded following GnRH administration. To facilitate sampling the stags were anaesthetised with approximately 0.5 – 1.0 mg/kg Xylazine (Rompun Bayer Ltd), administered using a blowpipe system (Corson et al 1984).

coincident with a high testosterone level and the negative feedback of testosterone on LH.

Although it appears that the plasma testosterone concentration, the pulse frequency of testosterone release, and the response of the testis to LH are at their lowest during the period of velvet antler growth, there is evidence that some androgen is necessary for normal antler growth and differentiation in red deer. For example:

• if a castrated stag has the velvet antler removed at intervals, each successive antler has a lower rate of growth and fewer points (Suttie *et al* unpubl.);
• the presence of the epididymis results in a more normally shaped antler in the castrate (Lincoln 1975);
• extracts of unossified velvet antler administered to rats have androgenic properties (Y. C. Kong *pers. comm.*), yet the circulating level of testosterone at the time the antler is grown is very low; similarly the concentration of testosterone *per se* in the antler at this time is very low.

However, the source of this androgenic steroid is not known and clearly requires considerably more intensive study. In this respect it seems possible that the precursor cells of the antler tip must be primed by testosterone. Since the antler tip cells are at least partly derived from the dermal and periosteal cells of the pedicle, then this requirement would be satisfied by priming of the pedicle cells by testosterone during the hard antler phase. This could explain the observation that each successive antler grown by a castrate stag is smaller than its predecessor.

Although the role of the testis in the mineralisation and cleaning of the antler has been known since the time of Aristotle, there has been very little specific work designed to unravel the actual underlying processes. Briefly, testosterone treatment of castrates results in the mineralisation and cleaning of the castrate velvet antler (Wislocki *et al* 1947; Goss 1963; Suttie *et al* unpubl.); oestrogens are also effective (Goss 1968; Fletcher and Short 1974; Bubenik and Bubenik 1978). However, the situation is not clear and there is evidence that the metabolites of testosterone may have vital roles. In this respect testosterone may be metabolised via the following pathways:

testosterone → 19-OHT $\xrightarrow{aromatase}$ oestradiol

$\downarrow$ *5αreductase*

5αDHT
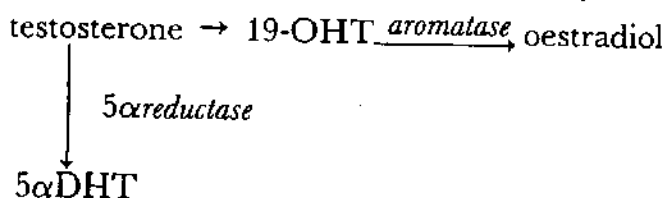
The possible importance of testosterone metabolites is indicated by the work of Morris and Bubenik (1983) who treated castrate white-tailed deer with various androgens and found that while 5αdihydrotestosterone (5αDHT) resulted in drying of the velvet, the degree of mineralisation was much less than that caused by administration of 19-hydroxytestosterone (19-OHT). However, the latter androgen had no effect on the velvet skin of the antler. When 19-OHT was administered together with an aromatase blocker, the androgen was without effect, suggesting that it is oestradiol which is mainly responsible for mineralisation of the antler. Based on the above observations and the fact that mineralisation occurs prior to cleaning of the velvet the following hypothesis is proposed.

The 2 essential features of the hypothesis are first that the dermal cells of the antler are the target tissues for 5αDHT, whereas it is the osteoclastic cells of the antler proper which are the target cells for the oestradiol, and secondly that at low levels of testosterone the principal metabolite is oestradiol but as testosterone concentration increases 5αDHT becomes relatively more important, as of course does testosterone itself. Consequently the metabolism of testosterone is of considerable importance. Therefore a 2-phase model of testosterone metabolism is proposed (Fig. 11) such that at low levels of testosterone the synthesis of oestradiol is already maximal.

The observation that oestrogens have also been shown to be effective in causing cleaning of the antler poses a problem to this hypothesis. However, the levels of oestradiol in the castrates implanted with oestrogens (Fletcher and Short 1974) were
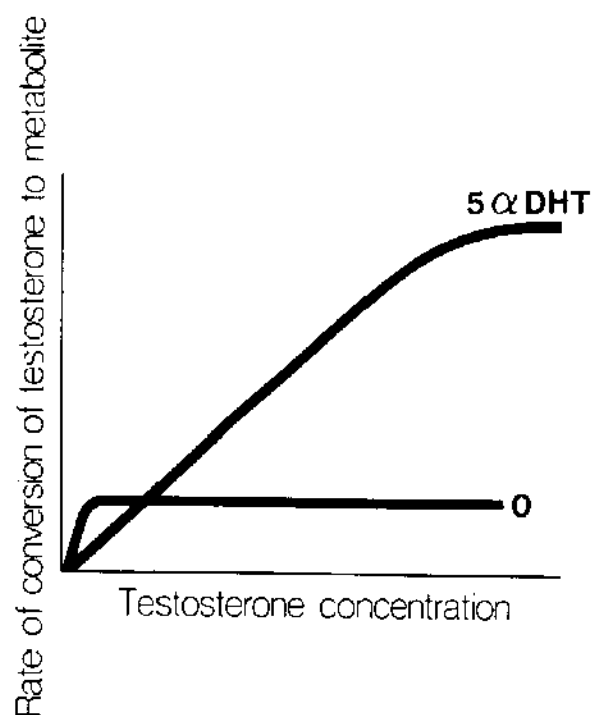

Fig. 11: The 2-phase model of testosterone metabolism (5αDHT, 5αdihydrotestosterone; O, oestradiol).

much higher than the normal baseline physiological levels recorded in deer (Bubenik *et al* 1979; Suttie 1981) raising the possibility that the reported effects of oestrogens were actually pharmacological rather than physiological.

The 2-phase testosterone model is also potentially useful in explaining initiation of growth of the first antler in that as the testosterone concentration (i.e. pulse height and pulse frequency) declines after pedicle formation, the cells of the pedicle tip are released from testosterone and 5αDHT inhibition thus allowing antler growth to proceed. In addition it is known that testosterone concentration is still moderately high in the stag growing the first antler compared with that recorded for the adult stag. Therefore it is proposed that oestradiol concentration would also be higher causing a relatively greater mineralisation of the antler, thus having an inhibitory effect on the rate of antler growth. This would account for the observation that the spike antler is relatively more mineralised than the adult antler of a stag at the same proportional stage of growth.

Although our understanding of the nutritional and endocrine factors influencing the antler cycle has developed greatly in recent times, there are still very many unknowns. The important areas where much more work is required include the actual mechanism of antler casting, the endocrine regulation of growth, differentiation in the antler tip particularly at the level of the cell and the gene, and factors regulating the growth rate of the antler and ultimate size.

References

Banks W J and J W Newbrey 1983 Antler development as a unique modification of mammalian endochondral ossification. *In: Antler Developement in Cervidae.* R D Brown editor, Caesar Kleberg Wildl. Res. Inst., Kingsville, Texas. pp. 279 – 306.

Bartke A 1980 Role of prolactin in reproduction in male animals *Fed. Proc. 39:* 2577 – 2581.

Brown R D (Editor) 1983 *Antler Development in Cervidae.* Caesar Kleberg Wildl. Res. Inst., Kingsville, Texas.

Bubenik G A 1983 The endocrine regulation of the antler cycle. *In: Antler Development in Cervidae.* R D Brown editor, Caesar Kleberg Wildl. Res. Inst., Kingsville, Texas. pp. 73 – 107.

Bubenik G A and A B Bubenik 1978 The role of sex hormones in the growth of antler bone tissue. The effect of antioestrogen therapy. *Saugetierk. Mitt. 26:* 284 – 291.

Bubenik G A, A B Bubenik, G M Brown, A Trenkle and D A Wilson 1975 Growth hormone and cortisol levels in the annual cycle of white-tailed deer *(Odocoileus virginianus). Can. J. Physiol. Pharmacol. 53:* 787 – 792.

Bubenik G A, A B Bubenik and J Zamecnik 1979 The development of circannial rhythm of oestradiol in plasma of white-tailed deer *(Odocoileus virginianus). Comp. Biochem. Physiol. 62A:* 869 – 872.

Caputo C B, D Meadows and L G Raisz 1976 Failure of estrogens and androgens to inhibit bone resorption in tissue culture. *Endocrinol. 98:* 1065 – 1068.

Chapman D I 1975 Antlers—bones of contention. *Mammal Review 5:* 121 – 172.

Clarke I J and J T Cummins 1982 The temporal relationship between GnRH and LH secretion in ovariectomised ewes. *Endocrinol. 111:* 1737 – 1739.

Corson I D, P F Fennessy and J M Suttie 1984 An improved design for a home-made projectile syringe *N.Z. Vet. J. 32:* 74 – 75.

D'Occhio M J, B D Schanbacher and J E Kinder 1982

Relationship between serum testosterone concentration and patterns of luteinising hormone secretion in male sheep. *Endocrinol. 110:* 1547 – 1554.

Fletcher T J 1978 The induction of male sexual behaviour in red deer *(Cervus elaphus)* by the administration of testosterone to hinds and estradiol-17β to stags. *Horm. Behav. 11:* 74 – 88.

Fletcher T J and R V Short 1974 Restoration of libido in castrated red deer stag *(Cervus elaphus)* with oestradiol 17-β. *Nature 248:* 616 – 618.

Gettys T W, M J D'Occhio, D M Henricks and B D Schanbacher 1984 Suppression of LH by oestradiol, dihydrotestosterone and trenbolone acetate in the acutely castrated bull. *J. Endocrinol. 100:* 107 – 112.

Goss R J 1963 The deciduous nature of deer antlers. *In: Mechanisms of Hard Tissue Destruction.* AAAS Publ. 25, Washington. pp. 339 – 369.

Goss R J 1968 Inhibition of growth and shedding of antlers by sex hormones. *Nature 220:* 83 – 85.

Goss R J 1969 Photoperiodic control of antler cycles in deer II. Alterations in amplitude. *J. Exp. Zool. 171:* 223 – 234.

Goss R J 1980 Photoperiodic control of antler cycles in deer V. Reversed seasons. *J. Exp. Zool. 221:* 101 – 105.

Goss R J 1983 *Deer Antlers: Regeneration, Function and Evolution.* Academic Press, New York.

Goss R J, C W Severinghaus and S Free 1964 Tissue relationship in the development of pedicles and antlers in the Virginia deer. *J. Mamm. 45:* 61 – 68.

Huxley J S 1926 The annual increments of the antlers of the red deer *(Cervus elaphus). Proc. Zool. Soc. London 1926:* 1021 – 1035.

Huxley J S 1931 The relative size of antlers in deer. *Proc. Zool. Soc. London 1931:* 819 – 864.

Jaczewski Z 1976 The induction of antler growth in female red deer. *Bull. Acad. Polon. Sci. 24:* 61 – 65.

Jaczewski Z and Krzywinska K 1974 The induction of antler growth in a red deer male castrated before puberty by traumatisation of the pedicle *Bull. Acad. Polon. Sci. Ser. V. 32:* 67 – 72.

Klein D C and Raisz L G 1970 Prostaglandins: Stimulation of bone resorption in tissue culture. *Endocrinol. 86:* 1436.

Levine J E, K-Y Pav, V D Ramirez and G L Jackson 1982 Simultaneous measurement of LHRH and LH release in unanaesthetised and ovariectomised sheep. *Endocrinol. 111:* 1449 – 1455.

Lincoln G A 1971 Puberty in a seasonally breeding male, the red deer stag *(Cervus elaphus). J. Reprod. Fert. 25:* 41 – 54.

Lincoln G A 1975 An effect of the epididymis on the growth of antlers of castrated red deer. *J. Reprod. Fert. 42:* 159 – 162.

Lincoln G A and R N B Kay 1979 Effect of season on the secretion of LH and testosterone in intact and castrated red deer stags *(Cervus elaphus) J. Reprod. Fert. 55:* 75 – 80.

Mirarchi B E, B E Howland, R E Scanlon, R L Kirkpatrick and L M Sanford 1978 Seasonal variations in plasma LH, FSH, prolactin and testosterone concentrations in adult male white-tailed deer. *Can. J. Zool. 56:* 121 – 127.

Morris J M and G A Bubenik 1983 The effects of androgens on the development of the antler bone. *In: Antler Development in Cervidae.* R D Brown editor, Caesar Kleberg Wildl. Res. Inst., Kingsville, Texas. pp. 123 – 141.

Raisz L G, R A Luken, G R Mundy, J W Dietrich, J E Horton and C L Trummel 1975 Effect of OAF from human leucocytes on bone metabolism *J. Clin. Invest. 56:* 408 – 413.

Ravault J P, B Barenton, M Blanc, A Daveau, D H Garnier, R Ortavant, J Pelletier, M de Reviers and M Terqui 1982 Influence of 2 Br-α-ergocryptine (CB154) on the secretion of prolactin, LH, FSH and testosterone and on testicular growth in rams subjected to different photoperiods. *Reprod. Nutr. Develop. 22:* 989 – 998.

Schoenle E, J Zapf, R E Humbel and R E Froesch 1982 Insulin-like growth factor 1 stimulates growth in hypophysectomised rats. *Nature 296:* 252 – 253.

Suttie J M 1981 The influence of nutrition and photoperiod on the growth and development and endocrine status of captive red deer and Soay rams. *Ph.D. thesis,* Univ. Aberdeen, Aberdeen.

Suttie J M, P D Gluckman, J M Butler, P F Fennessy, I D Corson and F J Laas 1985 Insulin like growth factor 1 antler stimulating hormone? *Endocrinol 116:* 846 – 848.

Suttie J M and W J Hamilton 1983 The effect of winter nutrition on growth of young Scottish red deer. *J. Zool. 201* 153 – 161.

Suttie J M and R N B Kay 1983 The influence of nutrition and photoperiod on the growth of antlers of young red deer. *In: Antler Development in Cervidae.* R D Brown editor, Caesar Kleberg Wildl. Res. Inst., Kingsville, Texas. pp. 61 – 71.

Suttie J M and R N B Kay 1985 The influence of plane of winter nutrition on plasma concentrations of prolactin and testosterone and their association with voluntary food intake in red deer stags *(Cervus elaphus). Anim. Reprod. Sci. 8:* 247 – 258.

Suttie J M, G A Lincoln and R N B Kay 1984 Endocrine control of antler growth in red deer stags. *J. Reprod. Fert. 71:* 7 – 15.

Wislocki G B, J C Aub and C M Waldo 1947 The effects of gonadectomy and the administration of testosterone propionate on the growth of antlers in male and female deer. *Endocrinol. 40:* 220 – 224.