

# Social status predicts wound healing in wild baboons

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**Social status can have striking effects on health in humans and other animals, but the causes often are unknown. In male vertebrates, status-related differences in health may be influenced by correlates of male social status that suppress immune responses. Immunosuppressive correlates of low social status may include chronic social stress, poor physical condition, and old age; the immunosuppressive correlates of high status may include high testosterone and energetic costs of reproduction. Here we test whether these correlates could create status-related differences in immune function by measuring the incidence of illness and injury and then examining healing rates in a 27-y data set of natural injuries and illnesses in wild baboon males. We found no evidence that the high testosterone and intense reproductive effort associated with high rank suppress immune responses. Instead, high-ranking males were less likely to become ill, and they recovered more quickly than low-ranking males, even controlling for differences in age. Notably, alpha males, who experience high glucocorticoids, as well as the highest testosterone and reproductive effort, healed significantly faster than other males, even other high-ranking males. We discuss why alpha males seem to escape from the immunosuppressive costs of glucocorticoids but low-ranking males do not, including the idea that glucocorticoids' effects depend on an individual's physiological and social context.**

dominance rank | glucocorticoid hormones | *Papio cynocephalus* | Savanna baboon | ecoimmunology

During the last few decades there has been major scientific interest in how social hierarchies influence individual health (1–3). In humans, for instance, socioeconomic status predicts differences in disease risk and longevity that cannot be explained entirely by differences in education or access to resources (3, 4). Similar patterns occur in animal hierarchies (3, 5). Understanding the relationships between social status and health is important because it has implications for human well-being (3), individual disease risk (6, 7), the evolution of social behavior (8), and the spread of infectious disease (9, 10).

However, despite the importance of social status, there is currently no consensus on what factors cause status-related differences in health. One leading hypothesis proposes that differences in social status predict differences in exposure to chronic stress, which has negative impacts on health (3, 11). Specifically, members of some social ranks may be more likely to experience negative, unpredictable events or are less able to cope with these events, which in turn activate glucocorticoids, a major component of the stress response. Although the stress response has many short-term benefits, long-term exposure to glucocorticoids can compromise metabolic, cardiovascular, and immune function (3, 11). In humans, chronic stress is thought to be higher in individuals with low socioeconomic status (1, 12); in other animals the relationships between stress and social status vary across species and populations (13, 14).

In male nonhuman vertebrates, other factors besides chronic social stress may cause status-related differences in health. For instance, in societies where male reproductive success is determined by dominance rank, the energetic costs of achieving and maintaining high rank, as well as the energetic costs of reproductive effort (e.g., muscle anabolism, male–male competition, mate guarding, parental care), which are likely to be higher for high-ranking males, may limit the energy available for immune

responses (15–17). Indeed, several studies of vertebrates have documented a major life history tradeoff between male reproductive effort and health (18–20). This tradeoff is thought to be mediated by testosterone and sometimes by glucocorticoids, which help direct energetic resources toward reproduction and away from tasks associated with long-term survival, such as immune function (15, 17, 21–23). In support of this notion, experimental increases in testosterone, within normal physiological limits, suppress immune function and increase parasite loads in several species (24, 25). In addition, some studies in wild vertebrates have found that high-ranking males have high testosterone and/or glucocorticoids and poor health (18, 21, 26, 27). Hence, in addition to the social stress associated with low rank, differences in reproductive effort also may cause status-related differences in health.

However, despite experimental evidence that testosterone or glucocorticoids can suppress immune function (25, 28, 29), attempts to understand the relative roles of these hormones in natural populations are rare. Such studies are complicated by the fact that testosterone and glucocorticoids often are correlated also with differences in age and physical condition. All four of these correlates may influence status-related differences in health (5), and the causal connections between these correlates and immune responses are complex and difficult to disentangle. The complexity of these relationships may partly explain why, when researchers evaluate the effects of hormones on immune function in the wild, they often find conflicting results (15, 23, 30). For instance, in many wild vertebrates, researchers find either no relationship or a positive relationship between testosterone and immune function (22, 30–32). Relationships between stress and immune function also are complex (33, 34); short-term stress can enhance immune responses (34), and researchers do not always find evidence for the immunosuppressive effects of glucocorticoids (6, 22). These results are important because they support the idea that there may be considerable flexibility in the relationships between testosterone, glucocorticoids, and immune function, and plasticity in these connections may buffer individuals against the potentially adverse effects of glucocorticoids or testosterone (22, 23, 35).

Here we investigate several mechanisms that could explain rank-related differences in immune function. We do so using healing rates from a 27-y data set of naturally occurring injuries and illnesses in wild baboons living in the Amboseli ecosystem, Kenya. Wound healing is a common and powerful measure of immune function in captive animals, and it provides an integrative measure of immune function that combines the inflammatory and cell-mediated processes of innate immunity (28, 29, 36, 37). It can be difficult to study wound healing in natural populations, especially in wild primates where researchers are usually constrained to noninvasive methods. However, healing rates have important functional significance for wild animals; if animals fail to recover efficiently from injuries and illnesses, they are likely to experience negative consequences, such as poor

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foraging efficiency, higher predation risk, and problems acquiring mates and raising offspring (38, 39).

Male baboons are a good system for understanding the relationships between dominance rank and immune function because high male rank usually leads to high reproductive success (40, 41) and because we already know a good deal about the behavioral and physiological correlates of dominance rank in baboons (41–45). Baboons live in multimale, multifemale social groups characterized by linear dominance hierarchies. Male baboons disperse after maturity, and when they join a new group they often rise rapidly in rank. Once they obtain high rank, males experience several costs that could limit immune function. For instance, high-ranking males are more likely to engage in energetically expensive mate-guarding episodes (45, 46). These mate-guarding episodes, called “consortships,” may last from a few hours to a few days, during which time male foraging is compromised; indeed, consorting males have feeding bouts that are 10–15% shorter than those of nonconsorting males, and it is not uncommon for males to abandon consortships (46, 47). In addition, in Amboseli, high-ranking males have higher fecal testosterone levels than low-ranking males (45), both when the dominance hierarchy is unstable and when it is stable (45). Furthermore, alpha males (the highest-ranked male in each group) experience higher costs than other high-ranking (but nonalpha) males, including high testosterone, higher rates of conflict than beta males, and the most time spent in consortships (45). Finally, unlike other high-ranking males, alpha males experience high glucocorticoid levels—levels that are significantly higher than in beta males (45). Together, these correlates of high rank, especially alpha status, may suppress immune function. In support, previous research has found that high-ranking male baboons have higher parasite loads, and one highly aggressive alpha male had a low white blood cell count (48, 49).

However, although the costs of high rank may suppress immune function, there are several reasons to expect that correlates of low rank, such as old age, poor physical condition, and chronic stress, also are important in shaping male health and immune function. For instance, in baboons, dominance rank declines with age (40), and senescence alone might lead to poor immune function in low-ranking males (50). Body mass index also declines with age (43), and this effect, combined with the fact that low-ranking males are more likely than high-ranking males to be interrupted while feeding (51), might limit the energy low-ranking males can devote to immune function. Finally, glucocorticoid levels are higher in low-ranking males than in high-ranking males (other than the alpha male) (42, 45). Hence, if chronic stress has stronger negative effects on immune function than testosterone and reproductive effort, then low-ranking males should have poorer immune function than high-ranking males (with the possible exception of the alpha male). In support, prior studies found that low-ranking male baboons have a dysregulated stress response that often co-occurs with immunosuppression (42, 52), as well as suppressed insulin-like growth factor, a hormone that promotes cellular growth and wound healing (53).

Our objectives were to understand how rank and age predicted the incidence of injury and illness and to understand how rank-related differences in age and hormone levels predicted males' recovery from injuries and illnesses. Our study was conducted in the Amboseli ecosystem, Kenya, where the Amboseli Baboon Research Project (ABRP) has conducted long-term, individual-based research on wild baboons since 1971. To maintain the animals' habituation to human observers, the ABRP relies almost entirely on noninvasive observations; hence all records of injuries and illnesses were collected noninvasively by observing the animals at a distance of ~3–5 m. If low social status suppresses immune responses, we expected that low-ranking males would face a greater incidence of illness than high-ranking males. We further expected that high-ranking males would face a higher incidence of injuries than low-ranking males, as has been reported in another wild baboon population (54). After analyzing incidence, we used univariate and multivariate approaches to understand how rank, age, and several other factors predicted male recovery from

injuries and illnesses. Specifically, we tested whether high social status is associated with slower healing, as predicted by theories focused on the potentially immunosuppressive correlates of high rank, or whether high status instead is associated with more rapid healing, as predicted by theories focused on the potentially immunosuppressive correlates of low rank. Our results help clarify which mechanisms are important in creating rank-related differences in health in male nonhuman primates.

## Results

From 1982 through 2009, we observed 633 cases of naturally occurring injuries and illnesses in 166 adult male baboons living in groups with 1–17 adult males (8–47 adults of both sexes). Injuries included linear cuts or slashes, puncture wounds, contusions, scrapes, limps, and one eye injury. Illnesses were characterized by digestive problems, persistent respiratory problems, or signs of weakness, lethargy, and cachexia. Observations of injuries were much more frequent than observations of illnesses. Indeed, males were more than 12 times as likely to be injured (0.88 observations per male per year) as they were to become visibly ill (0.07 cases per male per year).

**Rank, Age, and the Incidence of Illness and Injury.** If the costs of high rank suppress immune function, high-ranking males might experience a higher incidence of illness than low-ranking males. However, we found no support for this hypothesis. Instead, both rank- and age-specific incidence of illness were highest for older, low-ranking males (Fig. S1). Specifically, the incidence of illness increased in older males and lower-ranking males, and the relationship between age and the incidence of illness was stronger than the relationship with rank (age and illness:  $r^2 = 0.64$ ,  $F = 20.59$ ,  $P = 0.0011$ ; rank and illness:  $r^2 = 0.25$ ,  $F = 5.38$ ,  $P = 0.0388$ ). Age and rank also influenced the incidence of injury. Age- and rank-specific incidences of injury were best fit by a second-order polynomial so that the highest incidence of injuries occurred in middle-aged, midranking males (Fig. S2; rank-specific incidence:  $r^2 = 0.52$ ,  $F = 8.18$ ,  $P = 0.0067$ ; age-specific incidence  $r^2 = 0.64$ ,  $F = 10.10$ ,  $P = 0.0038$ ).

**Patterns of Healing.** To inform the construction of multivariate models of healing rates, we performed a series of univariate survival analyses to understand how single variables predicted male recovery from injuries and illnesses. We assessed healing rates for 448 injuries and illnesses in 144 adult males (Table S1). Males usually required a few weeks to recover from illnesses and injuries; the median time to heal was 25 d, although the fastest-healing 25% of injuries and illnesses healed in less than 14 d, and the slowest-healing 25% of injuries and illnesses required more than 40 d to heal. These recovery rates were similar to those in a prior study on wound healing in wild baboons (55).

We tested seven univariate predictors of healing rates, including (i) illness and injury type; (ii) differences in methods of data collection before and after 1991; (iii) the male's dominance rank at the time he became injured or ill; (iv) the male's age at the time he became injured or ill; (v) the male's access to human refuse as a food source (56, 57); (vi) the size of the male's social group, as measured by the number of adult male and female members; and (vii) the season (wet or dry) at the time the male became injured or ill. The only significant univariate predictors of healing were injury and illness type [ $\chi^2 = 26.08$ , degrees of freedom (DF) = 8,  $P = 0.0010$ ], study period (median days to heal during and before 1991 = 17 d; median days to heal after 1991 = 30 d;  $\chi^2 = 26.3429$ , DF = 1,  $P < 0.0001$ ), and dominance rank ( $\chi^2 = 4.37$ ,  $P = 0.0365$ ). Fig. 1 shows a survival plot comparing healing rates of high-ranking males (ranks 1–8) and low-ranking males (ranks lower than 8). High-ranking males required a median of 25 d to heal, whereas low-ranking males required a median of 31 d to heal, ~25% longer than high-ranking males.

**Multivariate Survival Analyses of Healing Rates.** We constructed proportional hazards models to examine whether dominance



**Table 2. Proportional hazards models of healing rates for three comparisons of male rank**

Source of variation	Hazard ratio	DF	$\chi^2$	<i>P</i>
Alpha males vs. beta males ( <i>n</i> = 100; whole model $\chi^2$ = 13.74; <i>P</i> = 0.0560)				
Time period (pre- or post-1991)	1.49	1	2.65	0.1035
Injury or illness type	—	4	8.45	0.0764
Group size (number of adults)	1.46	1	0.62	0.4318
Alpha males vs. beta males	1.15	1	0.4	0.5294
Alpha males vs. other high-ranking males ( <i>n</i> = 380; whole model $\chi^2$ = 66.75; <i>P</i> < 0.0001)				
Time period (pre- or post-1991)	1.93	1	26.02	< 0.0001
Injury or illness type	—	8	29.05	0.0003
Group size (number of adults)	2.3	1	7.59	0.0059
Alpha males vs. other high-ranking males	1.55	1	6.65	0.0099
Alpha males vs. low-ranking males ( <i>n</i> = 120; whole model $\chi^2$ = 20.56; <i>P</i> = 0.0244)				
Time period (pre- or post-1991)	1.55	1	3.49	0.0617
Injury or illness type	—	7	5.09	0.6487
Group size (number of adults)	2.76	1	3.76	0.0525
Alpha males vs. low ranking males	2.49	1	11.34	0.0008

Alpha males, rank 1; beta males, rank 2; other high-ranking males, ranks 2–8; low-ranking males, ranks lower than 8.

across species, populations, and measures of immune function (15, 23, 30). One explanation for these mixed results is evolutionary flexibility in the strength of the connection between testosterone and immune function (23). Relevant to baboons, differences in life histories, especially in the pace of life, might predict variation in the tradeoff between reproductive effort, testosterone, and immune function (16, 63–65). Indeed, the strongest evidence for this tradeoff comes from short-lived, seasonally breeding species of birds, reptiles, and rodents (21, 66). Short-lived species are expected to favor reproduction over survival; hence, they might forgo immune defense in the face of increased testosterone and reproductive effort. In contrast, long-lived, nonseasonally breeding species might favor survival and immune function over reproductive effort and might not experience strong immunosuppressive effects of testosterone. However, research on the relationships between reproductive effort, testosterone, and immune responses in long-lived, year-round breeding species is rare, except in humans, for which a few studies find support for the immunosuppressive effects of testosterone (20), but others do not (67, 68). More work is needed on a range of species to understand the relationships between the pace of life histories and the immunosuppressive effects of testosterone.

Our results also differ from some prior studies on status-related patterns of parasitism in wild, nonseasonally breeding primates. For instance, early work in Amboseli found that high-ranking male baboons have higher burdens of nematode parasites than low-ranking males (48). In addition, in chimpanzees, high-ranking males have higher fecal testosterone levels than low-ranking males, and male chimpanzees with high testosterone and high glucocorticoids were infected with a richer community of intestinal parasites than were with males with low levels of both of these hormones (15, 60, 69, 70). Although these studies support the hypothesis that high testosterone and reproductive effort suppress immune function, there are at least two reasons why our results might differ from these prior studies. First, because patterns of parasite infection are influenced by both susceptibility and exposure to infectious agents, parasite burdens do not necessarily reflect differences in immune function and instead might reflect differences in parasite exposure.

Second, our results might differ from prior studies on social rank and parasitism because the tradeoffs between reproductive effort and immune function and the effects of hormones on immune responses might be complex. For instance, testosterone might suppress some types of immune response and not others, and high-ranking male baboons might be selected to prioritize wound healing over defense against gastrointestinal parasites. Wound healing involves cell-mediated innate immunity and inflammatory processes, whereas defense against intestinal parasites relies

largely on the helper T cell type 2 component of adaptive immunity; both these immune processes are energetically costly (62, 71, 72). Consequently, males might not maintain both responses at a high level. If the evolutionary costs of poor wound healing are worse for males than the costs of poor macroparasite defense, males might maintain wound healing in the face of high testosterone despite its costs. That said, research on how different arms of the immune system vary with male life histories and hormones is in its infancy (73), and more work is needed to understand the effects of testosterone on different arms of immune function.

Instead of implicating high rank as a costly social status, our results support the hypothesis that correlates of low rank lead to reduced immune function in low-ranking males (3, 11). Immunosuppressive correlates of low rank include senescence, poor physical condition, and elevated glucocorticoids (42, 43, 45). All these correlates of low rank, and interactions between them, may explain why we observed slower recovery rates in low-ranking males. Low-ranking males tend to be older (40); aging has important negative effects on both physical condition and immune function, and these effects might slow wound healing (50). Although rank was a stronger predictor of immune responses than age, males may senesce at different rates, and dominance rank may be a strong predictor of physical (as opposed to chronological) aging. Low-ranking male baboons also exhibit evidence of chronic stress, characterized by elevated glucocorticoids and dexamethasone resistance (42, 45). Such chronic stress seems to have particularly strong effects on wound healing; for instance, experimental stressors caused by negative social interactions or restraint have been shown to slow the process of wound healing in mice and humans (28, 29, 74). Finally, aging can worsen the negative effects of the stress response (75, 76); hence, old age might exacerbate the effects of stress in low-ranking male baboons.

Although our results support the hypothesis that glucocorticoids suppress immune function in low-ranking males, we also found evidence for flexibility in the relationships between glucocorticoids and immune function in baboons. In Amboseli, alpha males experience high glucocorticoid levels (45), but they recover from injuries and illnesses significantly faster than other males, even faster than other high-ranking males, who do not experience elevated glucocorticoids. These results echo studies that find that under some conditions males can escape from the adverse consequences of glucocorticoids on reproduction (35). At least three factors might contribute to the finding that glucocorticoids do not suppress wound healing in alpha males. First, alpha males' relative youth might mitigate the costs of glucocorticoids (75). Second, alpha and low-ranking males seem to experience elevated glucocorticoids as a result of different stressors and over different periods of time; such differences may alter the immunosuppressive effects

of stress. Specifically, high glucocorticoids in alpha males probably are caused primarily by energetic stress, whereas high glucocorticoids in low-ranking males probably are caused largely by social stressors (e.g., high rates of received aggression, a lack of a sense of control, and few coping mechanisms) (45). Different types of stressors can have different effects on immune response; for instance, chronic stress can suppress immune function, whereas acute stress can enhance immune responses (34). Hence, the stress response in alpha males might allow them to respond to the energetic demands of alpha status and might even promote wound healing. In addition, males might not hold alpha status long enough to experience the negative effects of chronic stress. The median number of contiguous months that males hold alpha status in Amboseli is 4 mo (range 1–56 mo), and the median total number of months at alpha status is 9 mo; this amount of time might not be long enough for males to experience chronic and dysregulated stress. Third, alpha males may experience higher levels of social support, especially grooming, than low-ranking males, and it is possible that hormonal correlates of social support (i.e., oxytocin) or the hygienic benefits of grooming may mitigate the immunosuppressive effects of glucocorticoids on wound healing (36). In support of this suggestion, alpha males spend more time than low-ranking males in consortships with females, and grooming is frequent among consort partners (45, 77). In addition, adult female baboons often form close social relationships with adult males (77, 78), and top-ranked males may experience stronger friendships than low-ranking males (79).

In addition to the effects of male rank on wound healing, we also found that low-ranking males in larger groups seemed to recover from injuries and illnesses more quickly than those in small groups. We do not yet understand why group size influences healing biology so that low-status males in larger groups heal more rapidly. These males may experience benefits relative to those in small groups that we have not yet identified, such as lower nutritional stress, but a full explanation awaits a study of multiple aspects of male life in groups of different sizes.

Finally, although our results suggest that the stress, age, and poor physical condition associated with low rank influence rank-related differences in immune function, we cannot attribute causality to these correlations. Hence, it is not clear whether (i) low dominance rank causes poor immune function because low rank leads to stress and poor physical condition or (ii) age and declining health cause both poor immune function and poor competitive ability and hence low dominance rank. Because the maintenance of high rank seems to be energetically costly and to depend on physical strength and condition, males who are not in peak physical condition are unlikely to be able to maintain high rank. In support, in our population, severe injury or illness sometimes precedes a decline in rank. That said, these two hypotheses—that health drives rank, or that rank drives health—are not mutually exclusive, and it is likely that both forces interact to shape differences in health and immune function in male baboons. In the future, longitudinal measures of health and dominance rank in males may be useful to elucidate causality by helping to reveal whether changes in physical condition or immune function precede or follow changes in rank.

## Materials and Methods

A full description of the materials and methods is given in *SI Materials and Methods*. Briefly, study subjects were wild, male baboons studied by the ABRP, Kenya. The ABRP has collected observations of the incidence and healing of naturally occurring injuries and illnesses in all study animals since 1982. Observations were not clinical diagnoses and were collected non-invasively by observing the animals at a distance of 3–5 m. Before 1991, healing was monitored every few days until the injury or illness healed. After 1991, injuries and illnesses were monitored less frequently (average time between observations = 14 d).

In addition to monitoring injuries and illnesses, observers collected a variety of life history and behavioral information that might influence healing, including (i) dominance ranks (80, 81); (ii) births, which were used to calculate age for 48% of the males in our study [for the remaining 52% of males, age was estimated to within 1 or 2 y using well-defined metrics (82)]; (iii) group membership, used to calculate group size or determine whether the male became injured or became ill in a wild-feeding group or in the group that foraged part-time at the refuse pit of a nearby tourist lodge; and (iv) the season (wet or dry) during which the male became injured.

To understand how male rank and age predicted the incidence of injury and illness, we calculated age and rank-specific incidences of injury and illness as the rate of injury or illness per male-year. To investigate predictors of healing, we first performed univariate survival analyses to test whether study period (before or after 1991), injury and illness type (Table S1), or any of the predictor variables listed above (i.e., dominance rank, age, group size, group type, and season) predicted significant differences in healing rates. We then used multivariate proportional hazards models to test whether any of our predictor variables significantly predicted healing rates, controlling for differences in study period or injury and illness type. Finally, we tested whether observer bias or differences in injury severity could explain differences in healing across males. We found no evidence that these biases could explain our results (see *SI Materials and Methods* for full details). All statistical tests were performed using JMP software (version 9.0.2). Best-fitting models were identified via likelihood ratio tests.

All protocols were noninvasive and adhered to the laws and guidelines of Kenya (Kenya Research Permit nos. NCST RRI/12/1/55011/1543 to E.A.A. and NCST 5/002/R/777 to S.C.A. and NCST 5/002/R/776 to J.A.). All protocols were approved by the Animal Care and Use Committees at the University of Notre Dame (13-030), Duke University (A0840903), and Princeton University (1689).

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