Evaluation of Reproduction and Raising Offspring in a Nursery-Reared SPF Baboon (*Papio hamadryas anubis*) Colony

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Abstract

Baboons (*Papio hamadryas anubis*) of a conventional breeding colony were nursery-reared to create a specific pathogen-free (SPF) baboon breeding program. Because the founding generations were nursery-reared until two years of age, it was suspected that the SPF baboons would exhibit increased reproductive challenges as adults. Mothering behavior was of interest, because SPF females were not exposed to parental role models during the nursery-rearing process. We compared reproductive data from the SPF baboon breeding program during its first 10 years with data from age-matched baboons during the same period from an established, genetically-similar conventional breeding colony. We also evaluated records documenting mother-infant behaviors within the SPF colony. The average age of menarche in SPF females was 3.3 years. The overall live birth rate of both SPF and conventional females was approximately 90%, with no difference in pregnancy outcome between the two colonies. The average age at first conception for SPF females was earlier (4.2 years) than that of the conventional females (4.7 years). In both colonies, primiparous females were more likely to abort than multiparous females. Similarly, primiparous females were more likely to lose their infants to death or human intervention. A mothering score system was developed in the SPF colony to facilitate intervention of poor mother-infant relationships. Records revealed 70% of SPF mothers were able to raise one or more of their infants successfully to at least 180 days of age, which did not differ from conventional mothers. SPF females returned to postpartum estrus 27 days sooner on average than the conventional females, independent of dam age. The nursery-rearing process used for recruitment into the SPF colony therefore did not have an adverse effect on reproduction or rearing offspring.

Keywords

Baboon; Nursery-rearing; Reproduction; Mothering Score; Abortion; Live Birth Rate

Introduction

Long-term effects of maternal separation and subsequent nursery rearing of infant nonhuman primates (NHPs) have been studied for decades [Harlow et al. 1966; Ruppenthal et al. 1976; Sackett et al. 2002; Seay et al. 1964; Tsuchida et al. 2008; Worlein and Sackett 1997]. The ability of nursery-reared monkeys to develop appropriate behaviors related to reproduction, offspring care, and intraspecific social interactions have been of long-standing

concern for NHPs reared in captivity [Harlow et al. 1966; Ruppenthal et al. 1976; Sackett et al. 2002; Seay et al. 1964; Tsuchida et al. 2008; Wolf et al. 2010; Worlein and Sackett 1997; Young and Bramblett 1977]. It is often hypothesized that nursery-reared NHPs are inferior to their mother-reared counterparts in numerous physiologic and psychological ways [Sackett et al. 2002]. This is likely due, in part, to early studies of socially isolated rhesus macaques (*Macaca mulatta*), which demonstrated that the nursery-reared animals lacked the social competence to reproduce or raise offspring normally [Harlow et al. 1966; Seay et al. 1964]. However, subsequent research on *Macaca* spp. suggested that infants and juveniles with at least some opportunity for intraspecies social interaction developed into reproductively successful adults that could be housed in typical social groups and rear their young without incident [Ruppenthal et al. 1976; Sackett et al. 2002; Shapiro et al. 1995; Tsuchida et al. 2008]. However, the extent to which such results from studies on macaques apply to baboons is not known.

Baboons (*Papio* spp.) have long been studied in both captive and wild settings [Altmann 2001; Nitsch et al. 2011; Zinner et al. 2006], and reproductive characteristics of many species have been well-documented. Typically, female baboons reach menarche at 3–4 years of age and become reproductively active shortly thereafter, although the timing and frequency a female baboon will become pregnant has been strongly associated with social rank and hierarchy in captive colonies [Garcia et al. 2009]. Post-partum amenorrhea (PPA) and interbirth intervals (IBI) have been used to successfully evaluate reproductive fitness in olive baboons [Garcia et al. 2009]. A survey of an olive baboon breeding colony in France exhibited an average PPA of 145 days, and an average IBI of 450 days [Garcia et al. 2006]. The baboon menstrual cycle lasts approximately 33 days, and in addition to being reproductively active year-round, (non-seasonal breeders), they exhibit an overt menstruation which aids veterinary and research staff in monitoring baboon reproduction and health in captivity [Tardif et al. 2012]. Average gestation length is 185 days, and similar to that of humans, baboons have a single discoid placenta [Tardif et al. 2012]. Furthermore, variation in stress-related behaviors and infant abuse in captive olive baboons (*Papio hamadryas anubis*) during pre- and postpartum periods has been documented to exhibit parallels with human postpartum psychiatric disorders and infant abuse [Brent et al. 2002]. These features make female baboons an attractive animal model for studying human reproductive and postpartum disorders.

At the Baboon Research Resource (BRR) of the University of Oklahoma Health Sciences Center (OUHSC), maternal-rearing of infant olive baboons was considered the standard arrangement within the conventional breeding colony. However, circumstances occasionally deemed it necessary to nursery-rear infants, such as investigations of infant behavioral and physiological development, and cases in which infants suffered abuse or neglect when left with their mothers. With the development of an SPF colony, veterinary and research personnel of the BRR decided to introduce baboons free of targeted viruses through a recruitment nursery which reared baboons from birth to two years of age [Wolf et al. 2010].

OUHSC Baboon SPF program

At the time of this study, the OUHSC BRR maintained two baboon breeding colonies: a long-standing conventional baboon colony that involved routine monitoring for endemic viruses, and a newer "super clean" specific pathogen-free (SPF) baboon colony. The SPF baboon colony was initiated in 2002 to breed baboons free of 13 viruses that adversely affect baboon health, confound biomedical research, or threaten occupational health. To create and expand the SPF colony, it was necessary to remove neonates from the conventional colony within 12–48 hours after birth, to be nursery-reared in a dedicated SPF recruitment facility [Payton et al. 2004]. The nursery rearing strategy was specifically designed to encourage

normal social behavior, particularly breeding and parenting behavior. The goal was to avoid any potentially detrimental behaviors that might result from a socially restricted rearing environment (i.e., the absence normal mother rearing) by providing numerous opportunities for healthy social interactions. Once juvenile baboons met the SPF exclusion requirements for the super-clean viral status at 18–24 months of age, they were relocated to the SPF baboon colony facility.

A retrospective analysis of colony reproduction records was conducted on nursery-reared SPF adult female baboons and their offspring to evaluate the success of reproduction and infant rearing practices. Similar reproductive data on age-matched females from the conventional colony during the same time period were obtained to compare the SPF colony with a genetically related, predominately mother-reared population. Maternal behavioral records were also used to evaluate the abilities of nursery-reared females in the SPF colony to raise their own offspring. It was hypothesized that the SPF nursery-rearing process did not adversely affect the breeding success of the SPF colony when compared with that of the OUHSC conventional colony. Statistically speaking, the intent was to demonstrate that there was no significant difference between SPF colony mothers and conventional colony mothers, in terms of offspring production, by rejecting the null hypothesis that SPF females would have worse mothering skills than conventional colony females.

Methods

Animal Care

All housing and procedures performed at the OUHSC BRR were in compliance with the *Guide for the Care and Use of Laboratory Animals* [ILAR 2011]. All protocols for maintaining conventional and SPF baboon colonies were approved by the OUHSC Institutional Animal Care and Use Committee. This research adhered to the American Society of Primatologists principles for the ethical treatment of primates. The comparative medicine program at OUHSC was fully accredited by AAALAC-International.

Pathogens excluded in the SPF colony

The super clean SPF baboon colony targeted 13 viruses for exclusion: Baboon Cytomegalovirus (BaCMV), Baboon Rhabdinovirus (BaRV), Herpesvirus Papio 1 (HVP1), Herpesvirus Papio 2 (HVP2), Human Herpesvirus 6 (HHV6), Simian Varicella virus (SVV), Simian Foamy virus (SFV), Simian T-lymphotropic Virus (STLV), Simian Immunodeficiency virus (SIV), Simian Retrovirus Type D (SRV), Simian virus 40 (SV40), Measles virus, and Monkeypox virus. All viruses have been identified within the conventional baboon colony except SIV, SRV SVV, Measles, and Monkeypox. [Blewett et al. 2000; d'Offay et al. 2007; Payton et al. 2004]. In addition, both the conventional and SPF baboon colonies were monitored regularly for the parasites *Trichuris trichuria*, *Strongyloides stercoralis*, and *Strongyloides fulleborni*. Disease surveillance was performed regularly to ensure that baboons recruited into the SPF colony were free of targeted pathogens [Wolf et al. 2010]. Any infants in the SPF recruitment nursery that demonstrated positive results were immediately culled from the program, returned to the conventional colony, and their remaining cage mates in the recruitment nursery were tested biweekly for two months until verified as virus-free.

Rearing procedures

The nursery-rearing procedures for baboons entering the SPF colony have been described elsewhere [Wolf et al. 2010] and will be summarized here. Four to eight pregnant females in the conventional baboon facility were chosen at a time based on similar conception and expected delivery dates. The morning after parturition, veterinary staff removed newborns

from the mothers and transported the infants to be nursery-reared at the SPF recruitment nursery. To minimize transmission of pathogens from the conventional baboon colony, the recruitment nursery utilized dedicated staff and equipment.

Infant baboons were initially housed singly in stainless steel cages (61×61×41 cm) equipped with a hanging cloth surrogate and bottle holder, and fed infant formula until weaned onto commercial chow at three months of age. Beginning at two weeks of age, infants spent increasing periods of time in a larger cage (183×122×196 cm) with two to four age-matched infants during weekdays. Once weaned, infants were placed into groups of three to five and housed together full-time.

Infants born to SPF females in the SPF colony were allowed to remain with their mother in her natal social group. Occasionally, a mother exhibited behaviors that jeopardized the health or safety of her infant. In these cases, the infant was removed from the mother and nursery-reared in a dedicated SPF nursery until 180 days of age. Nursery procedures for SPF-born infants were similar to procedures used in the recruitment nursery; however, a separate facility was used to nursery-rear SPF-born infants in order to minimize the risk of viral contamination. Therefore, all animals in the SPF colony, including SPF-born infants reared in a nursery, were never in contact with animals in the SPF recruitment nursery.

Juvenile and Adult housing

At 18–24 months of age, baboons reared in the SPF recruitment nursery that conformed to the required viral status entered one of the SPF breeding groups. During the formative years of the SPF program (from 2002–2010), breeding groups were composed of harems of 10–15 animals in gang cages. In 2011, these six harem groups were combined based on social and genetic compatibility and moved to four large indoor corrals, each composed of 15–45 animals. The SPF colony had a limited number of breeding males, and therefore sexually mature males were rotated among other social groups to obtain optimal genetic diversity. Each breeding male was assigned a primary group where he spent about nine months of each year, and the remaining three months was integrated with another group composed of females with infants and juveniles. One or two social groups that lacked a permanent breeding male had three to six months per year with a visiting male. During the study period, four SPF males were confirmed by DNA testing [Kanthaswamy et al. 2010] to have sired the first generation of SPF-born progeny evaluated in this study. Conversely, the conventional colony at OUHSC was composed of four large indoor-outdoor corrals, with at least three breeding males permanently established in each social group during the study period. Detailed results of the genetic management program, including male reproductive parameters and the limited impact on inbreeding, will be presented in a separate publication.

Reproduction Records

A visual recording system was used to monitor the progression of each female's cycle at least three times weekly in both colonies by veterinary staff [Cary et al. 2002]. The beginning of a female's menstrual cycle was defined as the first observable sign of menstruation, followed by the progression of anogenital turgescence. Pregnancy was diagnosed based on an absence of anogenital turgescence at the expected time of a female's cycle. Conception was estimated as the date of last maximal sex skin turgescence in the presence of an adult male, followed by an absence of cyclicity [Cary et al. 2003]. Any observed abortions, stillbirths, or live infants were recorded the day they were observed. Abortion was defined as a loss of pregnancy that occurred prior to gestation day 160. Stillbirth was defined as a term-aged (160 day gestation or older) infant found dead but with no signs of abuse (i.e., gravel marks, bruising, cuts or trauma) [Cary et al. 2002]. To help

distinguish a true stillborn fetus from a peri- or postnatal death, a necropsy including a lung flotation test was performed on all recovered carcasses.

Data collection

Reproductive data were collected on all females in the SPF baboon colony over 10 years, from 1 January 2002 to 31 December 2011. During this period, 34 nursery-reared females were recruited into the SPF baboon colony and reached sexual maturity. Collected data included age at menarche, age at first conception, abortions and stillbirths, number of days post-partum to resumed cycling (referred to as post-partum amenorrhea, PPA), and infant outcomes. Possible infant outcomes included successful mother rearing, nursery-rearing as a result of poor maternal care, or death. Successfully mother-reared infants were defined as infants reared by their mothers and lived to at least 180 days of age. This was the approximate age when most infants became partially weaned from their mothers, and began to consume most of their daily caloric input from solid foods (unpublished observations). These data were used to determine reproductive and mothering trends, live birth rates, and interbirth intervals (IBI).

For comparison, 49 adult females from the conventional baboon colony, with birth dates that overlapped those of the SPF females (3 February 2003 to 4 May 2007), were evaluated. Of these, 42 had reproductive records through 31 December 2011. Reproductive and mothering data similar to that of the SPF females and their infants were collected. However, neither age at menarche nor behavioral data on mothering skills were available from most conventional colony females and were thus not included for comparison.

Mothering Score System

Because all adult females in the SPF colony were nursery-reared and lacked exposure to typical mothering behavior in their early developmental period, it was important for SPF staff to critically evaluate how SPF females responded to their infants. Behavioral staff in the SPF baboon colony observed mother-infant interactions closely beginning on the day of the infant's birth. Basic evaluation criteria were used to score mothering behavior on a 5-point scale: 'excellent,' 'fair,' 'poor,' 'bad,' or 'absent' (Table 1). Scores were recorded in the mother's health records during the first 72 hours after parturition. Repeated observations of 'excellent' to 'fair' behaviors suggested a high likelihood that the infant would thrive if left to be reared by its mother. Alternately, observations of 'poor' to 'bad' behaviors multiple times within the first 72 hours after birth typically resulted in the decision to nursery-rear the infant. Similarly, an infant was removed from a mother and nursery-reared if a complete absence of contact between the mother and the infant were observed.

Statistical Analysis

Reproductive and rearing data were compiled from health records and used to compare the conventional and SPF colonies. The analysis of variance (ANOVA) was used for continuous data, with statistical testing conducted using the omnibus F-test [Snedecor and Cochran 1967]. Contingency table modeling was used for count data, with statistical testing conducted with the likelihood ratio G^2 statistic [Agresti 2002]. All statistical tests were conducted using the nominal level of $P = 0.05$ (2-tailed tests throughout) for statistical significance. All statistical analyses were performed using SYSTAT version 11.0 (Systat, Inc., Richmond, CA).

Results

Descriptive Statistics of the SPF Colony

Thirty-four nursery-reared females were successfully recruited into the SPF baboon colony and reached sexual maturity (Table 2). The average age at menarche was $3.27 \pm$ SE 0.10 years. Eleven adult females were removed from the SPF colony after reaching menarche but prior to any documented conceptions. Such removals occurred due to breaks in SPF status, severe health problems, or for research purposes. Twenty-two females conceived at least once and 20 gave birth to at least 1 live infant. A total of 62 conceptions resulted in an overall live birth rate of 90.2% (Table 2). One SPF female successfully conceived her third infant in the SPF colony but was moved to the conventional colony prior to parturition due to a break in viral status. This infant was included in the total conceptions within the SPF colony, but was not included in live birth rate or other outcome data. The mean age at first conception was $4.22 \pm$ SE 0.14 years.

The number of live births of each SPF female ranged from 1–5, with an average of $2.5 \pm$ SE 0.5 infants. Pregnancy outcomes were listed in Table 3. Nine infants born into the SPF colony died within 180 days of birth (16.4%), and 8 died before 10 days of age (14.5%). Five abortions occurred (8.1%); four in nulliparous females and one in a multiparous female after three successful term pregnancies. Two of the nulliparous females that aborted subsequently became pregnant and delivered live infants. One stillbirth occurred at 178 days gestation in a female who delivered a live infant the previous year, and subsequently delivered four live infants at 180 days gestation or longer (range 180–191 days).

PPA occurred on average $178 \pm$ SE 9.9 days after delivery, in cases where the mother successfully reared the infant until 180 days of age or older. In multiparous females (N = 16), the average IBI was $413 \pm$ SE 18 days. Of the total number of live infants born into the SPF colony (N = 55), 70.9% were successfully reared by their mothers.

Descriptive Statistics of the Conventional Colony

Data from 49 age-matched, predominately mother-reared females from the conventional colony were evaluated for comparison of reproductive fitness. Age at menarche was not available. Forty-two of the conventional colony females became pregnant by the end of 2011, resulting in 113 conceptions and a 90.3% live birth rate during this period. The average age of these females at first conception was $4.69 \pm$ SE 0.09 years, or about five months (157 days) later than the SPF females.

As in the SPF colony, the number of live births born to each mother ranged from 1–5. Mean PPA occurred at $205 \pm$ SE 8.8 days, when females successfully reared their infants to at least 180 days of age. In multiparous females (N = 30), the average IBI was $385 \pm$ SE 14 days. Of the total number of live infants left with their mothers to be reared in the conventional colony (N = 72), 79.2% were successfully mother-reared (Table 3).

Overall, there were no differences in pregnancy outcome (abortion/stillbirth, live birth, neonatal death) by colony type (conventional versus SPF) ($G^2 = 0.920$, df = 2, P = 0.631). This suggested that mothers of SPF offspring did not have defective maternal care that resulted in worse pregnancy outcomes. However, when the same reproductive outcomes were analyzed according to maternal parity, there was a very strong association ($G^2 = 15.911$, df = 2, P < 0.0001). Specifically, primiparous mothers were 15.3 times more likely to have an abortion or stillbirth rather than a live-birth, were 1.8 times more likely to have an abortion or stillbirth rather than a neonatal death, and were 3.7 times more likely to experience a neonatal death compared to females of parity 2 or higher.

There was a significant difference in maternal age at first conception between colony types (F = 8.336, df = 1,61, P = 0.005). Specifically, SPF females first conceived at an average age of 4.22 years (± SE 0.14) compared to 4.69 years (± SE 0.09) of age. Regarding PPA, neither dam age at conception (F =0.441, df = 1,76, P = 0.509) nor infant sex (F = 0.090, df = 1,78, P = 0.765) had any effect. However, there was a significant effect of colony type (F = 4.649, df = 1,78, P = 0.034) and maternal parity (F = 16.485, df = 1,78, P < 0.0001). The effect of parity was not an artifact of small sample sizes, because collapsing the higher parity categories (parity 4 or higher) revealed the same inverse linear effect of increased parity on decreased PPA (F = 4.154, df = 1,91, P = 0.034). The difference between colonies was noticeable. Specifically, SPF colony mothers had an average PPA of 178 ± SE 9.9 days, compared to 205 ± SE 8.8 days for conventional colony dams. This represented an average difference between colonies of nearly a month (26 days). The effect of parity on PPA was weaker in the conventional colony (−18.7 day/birth) than in the SPF colony (−26.6 day/ birth). The reasons for the inverse effect of parity on PPA, or for its greater effect size in the SPF colony, were not known. However, the overall PPA effect was not due indirectly to increased female reproductive maturity, as measured by maternal age at conception (F = 0.475, df =1,77, P = 0.493).

Finally, regarding IBI, significant effects of colony type (F = 9.412, df =1,104, P = 0.003), maternal parity (F = 35.900, df = 1,104, P < 0.000), and dam age at conception (F = 38.188, df = 1,104, P < 0.000) were also observed. This model was quite robust and explained 31% of the variance. Based on this statistical model, the predicted effect sizes for the two levels of colony type differed by 64 days (SPF colony female mean expected IBI was 436 ± SE 16 days, compared to 372 ± SE 12 days for conventional colony females). This difference in effect sizes of over two months IBI (64 days) between colony types was not due to any effect of infant sex (F = 0.173, df = 1,103, P = 0.678). However, a comparison of maternal age and parity effects within each colony type was revealing. For the SPF, maternal parity reduced the IBI by 100 ± SE 25 days per birth, while maternal age at conception increased the IBI by 102 ± SE 21days per year of life. These two coefficients almost exactly balanced each other out. In contrast, in the conventional colony, maternal parity reduced the IBI by 99 ± SE 20 days per subsequent parity, while dam age at conception increased the IBI by only 72 ± SE 17 days per year of life. Thus, parity had a constant (negative) effect of decreasing IBI across both colonies, in that primiparous females experienced longer IBIs than multiparous females. But maternal age had a stronger effect in the SPF colony of increasing the IBI (predicted IBI was 30 days longer than conventional colony females). Considering all factors simultaneously from the same statistical model, the net result was that SPF dams had IBIs that were 28 days longer (413 ± SE 18 days) than conventional colony dams (385 ± SE 14 days; see Table 2).

Behavioral Observations of the SPF Colony

Within the SPF colony, a variety of mothering skills were observed among nursery-reared females, even among successive infants reared by the same mother over time. Most females (70%) exhibited 'fair' to 'excellent' mothering behaviors in caring for their infants. Six females showed variable levels of mothering behaviors over time. One female exhibited 'poor' to 'bad' mothering skills with her first three infants but successfully reared her fourth infant without incident. Conversely, another female exhibited 'excellent' mothering skills with her first two infants, but exhibited 'bad' mothering behaviors toward her third infant. One female was diagnosed with idiopathic epilepsy, which may have contributed to her complete absence of contact with her infant. Three females exhibited 'poor' to 'bad' mothering skills for all of their infants. Records did not consistently include contextual descriptions that indicated reasons for infant neglect, such as congenital defects, poor

lactation or recent changes in group social structure. Necropsy reports on deceased infants did not identify any pathological reasons for maternal neglect.

There were nine cases of infant death in the SPF colony over the study period. Causes for deaths prior to 180 days of age were not always identified, but were typically secondary to trauma. In some cases, maternal behavioral problems were identified. Records of four infants born in the SPF colony identified 'absent' maternal contact, as observed by SPF behavioral personnel. Two of these infants were removed from the SPF colony and successfully nursery-reared. The other two died within 48 hours of birth secondary to trauma. For 10 infants, abuse from either the mother or another group member was suspected as the cause of death or was the reason for removal and nursery-rearing. One of the breeding males was known to kidnap newborn infants. Kidnapped infants that were dragged through the play structures of the gang cage or corral commonly suffered lethal skull fractures. This typically occurred overnight, with SPF personnel finding a dead infant being carried by the dominant male the morning after a birth.

Discussion

The OUHSC BRR nursery-reared olive baboons were used to establish an SPF breeding colony. In order to develop the SPF colony, infants born in the OUHSC conventional colony were removed from their mothers within 12–48 hours after birth and reared in an SPF recruitment nursery until 18–24 months of age, then were integrated into harem groups and eventually indoor corrals of large breeding groups. Reproductive and infant outcome data during the formative years of the SPF baboon breeding program revealed a live birth rate indistinguishable from age-matched baboons in the conventional colony (90%) during the same time period. In addition, there were no statistical differences between pregnancy and maternal rearing outcomes between the two groups. Reproductive fitness and maternal care exhibited by the nursery-reared SPF colony females was therefore equal to that of the predominately mother-reared conventional colony females.

Reproductive parameters that differed significantly between the SPF and conventional colonies included age at first conception, PPA, and IBI. SPF females first conceived approximately six months sooner than their peers in the conventional colony. It is possible that infants in the SPF recruitment nursery experienced minimal nutritional variability, compared to mother-reared infants in the conventional colony. Conventional colony infants' access to nutrition would depend upon the variable health and social status of their mothers within the context of the social group. In contrast, uniform access to formula and (later) solid foods in the SPF recruitment nursery may have allowed nursery-reared females to grow and mature faster on average than the mother-reared females in the conventional colony. If true, SPF females would likely have also reached menarche at an earlier age than their conventional colony peers. However this could not be determined from the available data. Social rank may also have played a role in the accelerated growth maturation observed among SPF females. High social rank was correlated with reproductive success in wild olive baboons [Packer et al. 1995]. Unfortunately, rank data was not collected from either OUHSC colony, making it impossible to evaluate rank effects at this time. Questions concerning social rank must await detailed data collection on different measures of rank relationships and subsequent social network analysis [Lehmann and Ross 2011].

PPA and IBI are associated with maternal energy investment and infant growth rates in captive olive baboons [Garcia et al. 2009]. Furthermore, the length of IBI can be predicted by maternal rank [Garcia et al. 2006], and lower-ranking females tend to invest more time into each infant before they resume cycling. Records of female social rank within either OUHSC baboon colony were not available, thus reasons why SPF females experienced an

overall shorter PPA than age-matched conventional females was beyond the scope of this study. However, it may be pertinent that there were fewer numbers of sexually mature males present in the SPF colony compared to those in the conventional colony, and SPF colony staff periodically rotated adult males among social groups for breeding. The intermittent presence of adult males when females returned to sexual receptivity likely contributed to the prolonged IBI within the SPF colony.

In both OUHSC baboon colonies, primiparous females were more likely to abort than multiparous females, which conflicted with a recent report on reproductive productivity in a conventional *Papio hamadryas* breeding colony [Sunderland et al. 2008]. However, our findings were consistent with reports of captive rhesus macaques [Gagliardi et al. 2007; Hendrie et al. 1996], although Hendrie et al. (1996) found no such association between abortions and maternal parity in bonnet macaques (*Macaca radiata*). It is possible that the observed association between abortions and parity in the two OUHSC baboon colonies was related to a genetic propensity for early but unsuccessful pregnancy in their common founder generation. More likely, the difference between the Sunderland et al. (2008) results and the results reported here reflect different selection biases operating in these two observational studies [Rothman 2002]. Specifically, both pregnancy and early abortions may be more likely to be observed in an intensively managed SPF breeding colony.

In the SPF colony, the prevalence of documented abortions (8.1%) seemed high, while the number of stillbirths seemed low (1.6%), relative to the conventional colony (3.5% and 6.2%, respectively; see Table 2). However, the combined prevalence of abortions and stillbirths was identical 9.7% across both colonies (Table 2). The true number of abortions may have been higher, in particular early abortions (occurring within the first 30 days of gestation). Pregnancy was diagnosed by indirect observation, or when anogenital turgescence failed to occur at the expected time of a female's cycle. Preimplantation abortions may occur in 25% of baboon pregnancies, and an estimated 14.3% of pregnancies abort during the postimplanation period (days 10–22 of gestation) [Tardif et al. 2012]. Any temporary lack of cycling in OUHSC colonies early in pregnancy may have been attributed to other causes, such as transient illness or stress. Other tests to diagnose early pregnancy, such as chorionic gonadotropin levels or uterine ultrasound examination [Sunderland et al. 2008], were not routinely performed in the OUHSC breeding colonies. However, all adult cycling females were observed closely and stages were recorded frequently in both colonies. Therefore, it is unlikely a significant number of abortions beyond 30 days gestation or stillbirths were missed.

Accounts from health records revealed that one adult breeding male in the SPF colony practiced infanticide multiple times, which increased the infant mortality rate and decreased mother-rearing success in the SPF colony. Despite this, neither infant mortality nor mother-rearing success within the SPF colony differed significantly from the conventional colony. Furthermore, infants born to primiparous mothers are more likely to die in the neonatal period than infants to multiparous mothers, as documented here and in both captive baboon colonies [Sunderland et al. 2008] and in wild baboon populations [Cheney et al. 2006; Palombit et al. 2000]. In the wild, adult male baboons are known to commit infanticide consistent with their own reproductive interests and during unstable periods involving integration of extra-troop males [Buchan et al. 2003; Chalian and Meishvili 1990]. The infanticidal behavior exhibited by the OUHSC SPF male was directed toward its own offspring and the offspring of other males, and can probably be attributed to frequent changes made to the social structure of the breeding groups, as well as the presence of several primiparous mothers early in the SPF colony's breeding history.

The reproductive success of the SPF baboon colony was attributed to two key factors. First, all nursery-reared infants in the SPF recruitment nursery were in contact with other infants during the rearing process several hours each week, and were exposed to small social groups of cohorts early in life. Second, by two years of age, nursery-reared baboons were placed in larger social groups in the SPF colony. After the first five or six years, these social groups were composed of more diverse ages, which allowed younger females some opportunity to observe mother-infant behaviors from older females. Ultimately, the ability of NHP females to successfully reproduce and raise offspring can be difficult to attribute to a single factor, such as rearing environment, socialization history, or even genetics, because individual variation of mothering style has been well-documented in many different Cercopithecine species [Fairbanks 1996; Maestripieri 1998]. However, rhesus monkeys that experienced social isolation during early development exhibited significantly impaired reproduction and maternal abilities in adulthood [Harlow et al. 1966; Seay et al. 1964]. Thus the emphasis placed on social enrichment in the SPF recruitment nursery was likely a significant factor in the reproductive success of the SPF baboon colony.

In conclusion, reproduction and maternal abilities in an SPF baboon colony was not compromised by the nursery-rearing process. The SPF females had equivalent or better live birth rates, abortion/stillbirth incidence, and mother-rearing success of infants, compared to age-matched baboons from the OUHSC conventional baboon colony. In addition, SPF females conceived at an earlier age, exhibited shorter mean post-partum amenorrhea, and experienced longer interbirth intervals compared to conventional colony females. Our data was consistent with other reports which demonstrated that nursery-reared NHP infants do not exhibit inadequate social behavior as adults if vigorous efforts are made to promote and maintain healthy social interactions [Ruppenthal et al. 1976; Sackett et al. 2002; Shapiro et al. 1995; Worlein and Sackett 1997].

Acknowledgments

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Table 1

Mother Score System Utilized in the Baboon SPF Breeding Colony

Score	Description
1	Absent; No contact was observed between female and infant
2	Bad; Female showed little-to-no interest in her infant, or frequently exhibited abusive actions towards infant
3	Poor; Female was only somewhat interested in the infant, would pick up the infant only when approached by other animals or occasionally exhibited abusive actions towards infant
4	Fair; Female attempted to care for infant and infant seen nursing, but infant may be seen in an abnormal position with/without vocalization
5	Excellent; Female attempted to care for infant, held infant in ventral/ventral position, and infant observed to be clean, dry, quiet and frequently nursing

The scores were used to evaluate mother-infant interactions in the SPF breeding colony, and recorded in each female's health record. Typically, a score was assigned upon first observation of an infant the morning after birth, then 24-, 48-, and 72-hr later. These scores were used to evaluate the likelihood an infant would thrive if reared by the mother.

Table 2

Summary of Reproductive Data of SPF Colony Females and Age-Matched Conventional Colony Females

Parameter	SPF	Conventional
Sexually mature adult females	34	49
Average age at menarche (years)	3.27 ± SE 0.10	N/A
Adult females removed from colony	11	0
Females that conceived at least once	22	42
Average age at first conception (years)	4.22 ± SE 0.14	4.69 ± SE 0.09
Total pregnancies	62	113
Total live births	55[*] (90.2%)	102 (90.3%)
Total abortions	5 (8.1%)	4 (3.5%)
Total stillbirths	1 (1.6%)	7 (6.2%)
Total infant deaths before 180 days of age (Does not include abortions and stillbirths)	9 (16.4%)	10 (9.8%)
Total number of infants nursery-reared	7 (12.7%)	5 (4.9%)
Percentage (%) successful mother-reared infants	70.9%	79.2%
Percentage (%) male infants	51.8%	52.8%
Average PPA when infants were reared by their mother (days)	178 ± SE 9.9	205 ± SE 8.8
Total number of multiparous females	16 (72.3%)	30 (71.4%)
Average IBI of multiparous females (days)	413 ± SE 18	385 ± SE 14

[*] One (1) conception in the SPF colony was later born within the conventional colony due to a break in SPF status by the pregnant female. This birth was therefore not included in the final live birth rate.

Table 3

Birth Outcome by Rearing Condition and Maternal Colony Type

Pregnancy Outcome	Rearing condition of infants	SPF Mothers	Conventional Colony Mothers
Lived >180 days	Mother reared	39	57
	Nursery reared	7	5
Died <180 days	Mother reared	9	10
	Nursery reared	0	0
Abortion/Stillbirth		6	11