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ORIGINAL ARTICLE

Cesarean surgery and ovariohysterectomy in a precocial rodent *Octodon degus*

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ABSTRACT. The common degu (*Octodon degus*) is a trendy rodent pet in Europe and the USA, but is also widely used in scientific research. Information about degu housing, nutrition, behavior, disease diagnosis, and disease treatment is abundant in scientific literature. However, information on reproductive management, such as cesarean section, ovariohysterectomy, ovariectomy, and orchiectomy, is scarce and anecdotal. Our general objective was to develop a protocol for cesarean section and ovariohysterectomy for degus. Our results indicated that cesarean post-surgical survival was 100% for mothers and 97% for offspring, while ovariohysterectomy female postsurgical survival was 100%. Cesarean surgeries lasted an average of 61.82 min, while ovariohysterectomies lasted an average of 32.65 min. The initial recovery times for cesarean sections and ovariohysterectomies were an average of 8.18 and 5.53 min, respectively. The full recovery time for cesarean section was an average of 50.18 min, whereas that for ovariohysterectomies was an average of 15.38 min. These results suggest that both protocols are viable for use in veterinary clinics that use mid-level equipment. We discuss our results with data from other rodent species and rabbits and with orchiectomy and ovariectomy procedures practiced in degu. Finally, we discuss in detail four critical considerations for cesarean and ovariohysterectomy surgeries performed on small mammals such as degu.

Keywords: cesarean surgery; ovariohysterectomy surgery; common degu; *Octodon degus*.

INTRODUCTION

The common degu (*Octodon degus*), a caviomorph rodent endemic to Central Chile, has several characteristics that make it an exciting animal model. Degu has interesting life-history traits, including being long-lived (under laboratory conditions, ~ 8 years), having large litters, and giving birth to precocial pups (Rojas *et al*., 1982). Degu is a social breeder in which females share nests and offspring care, including nursing, for both their own and unrelated offspring (Ebensperger *et al*., 2004). Male degu can also provide offspring care (Ebensperger *et al*., 2010; Aspillaga-Cid *et al*., 2021). Degu has been widely used in laboratory experiments because it can be easily acclimatized to laboratory conditions (Weir, 1970; 1974), making it the most studied native Chilean species (Labra *et al*., 2021). Additionally, degu is an excellent model for biomedical research; degus has been used in studies of diabetes (Wright & Kern, 1992), amyloidosis (Nishi & Steiner, 1990), Alzheimer's disease (Castro-Fuentes & Socas-Pérez, 2012), and aging (Cuenca-Bermejo *et al*., 2020). Finally, degu is common as a pet and zoo in Europe and the USA (Jekl *et al*., 2010).

Due to the prevalence of degu living in captivity (houses, zoos, and research colonies), it is possible to find several studies that provide varied information relative to degu housing (Palacios & Lee, 2013), nutrition and behavior (Gutiérrez & Bozinovic, 1998; Edwards, 2009), disease diagnosis and treatment (Richardson, 2003; Jekl *et al*., 2010), and reproductive management and breeding (Palacios & Lee, 2013). However, only two studies have provided relevant information regarding the reproductive management of degu. The first study (Malbrue *et al*., 2019) assessed two orchiectomy techniques (pre-scrotal open technique vs. scrotal open technique) and one ovariectomy technique (bilateral technique). The second study corresponds to a case report of pregnancy failure, which concluded with the extraction of two dead fetuses and the uterus from a very young (3-month-old) female (Mancinelli *et al*., 2013). To date, studies relevant to female reproductive management such as ovariohysterectomy (OVH) and cesarean section (CS) are not available in the literature. Studying and describing these procedures is essential for implementing efficient reproductive management programs in captive settings such as research colonies, zoo colonies, breeding programs, and pet trade (Malbrue *et al*., 2019). Procedures such as OVH and CS have been described in other rodent species including hamsters (Fleischman, 1981), rats (Redobre, 2002), guinea pigs (Richardson & Flecknell, 2006; Prior, 1986; Jones, 1990), gerbils (Mighell & Baker, 1990) and rabbits (Richardson & Flecknell, 2006). These reports concluded that there are four critical aspects to consider during OVH and CS procedures: i) respiratory compromise due to pres-

sure of the visceral organs on the diaphragm, ii) difficulty in maintaining proper body temperature during the procedure due to decreased thermoregulatory ability under anesthesia, exacerbated by incision of the abdominal cavity and small body size, iii) suture dehiscence due to gnawing behavior, and iv) cessation or decreased motility of the small intestine (paralytic ileus) as a consequence of abdominal pain (Redobre, 2002; Richardson & Flecknell, 2006; Malbrue *et al*., 2019). Degu is a caviomorph rodent; thus, the chinchilla and guinea pig protocols have also been used for degu. However, degus is much smaller (170–250 g) (Ebensperger *et al*., 2004) than chinchillas (400–600 g) (Richardson, 2003) and guinea pigs (700–1100 g) (Terril & Clemons, 1998), and anesthesia and surgery are more complicated due to the difficulty of accessing the vascular and respiratory system function and because of the rapid loss of heat from such small-sized caviomorph rodents (Malbrue *et al*., 2019).

Relevant reproductive aspects of *degus*

Degu is a small-to medium-sized (ranging from 170 to 250 g) diurnal rodent that inhabits scrubland areas of arid central Chile (Ebensperger *et al*., 2004). Sexual maturity in degus occurs ~6 months after birth but can occur as early as 2 months or as late as 9 months of age (Rojas *et al*., 1982), with the primary mating season occurring during the late austral fall (June). Occasionally, degus undergoes a second breeding event as a result of post-partum estrus, with birth during late December and lactation extending through January (Ebensperger *et al*., 2013). After a gestation period of 87 ± 3 days (Rojas *et al*., 1982), females give birth an average of 3.42 ± 2.71 (SD) offspring, with a range of 0–10 offspring (Ebensperger *et al*., 2019). Degus has a chorioallantoic placenta (Mess, 2007), which corresponds to a haemomonochorial structure (Kanashiro *et al*., 2009). Degus has a long pregnancy period in rodents, likely because it produces precocial offspring (Long & Ebensperger, 2010). Offspring are born with open eyes and ears, well-developed incisors, an entire body covered with hair, long and stained nails, and large vibrissae (Reynolds & Wright, 1979; Rojas *et al*., 1982; Jekl *et al*., 2010). Lactation is relatively short, lasting for approximately 30 days, and corresponds to the most energetically demanding life-history stage for degu dams (Veloso & Bozinovic, 2000). In captivity, degus can live for 7 to 10 years (Edwards, 2009), females reproduce for four years, and males remain fertile until death (Palacios & Lee, 2013).

The main objective of this study was to describe a protocol for CS and OVH in degus. Our specific objectives were to determine: 1) percentage of maternal and neonatal survival, 2) duration of the procedure, and 3) time to initial and full recovery for both procedures. For the duration of both procedures, we determined whether surgeon expertise (i.e., measured as the order in which procedures were practiced, first last) and, in the case of CS, the size of the litter could be associated with the procedure duration. In addition, we provided descriptive data related to the reproductive traits of degu. Finally, based on our experience with degu CS and OVH, we discuss the critical points reported in other rodent species during CS and OVH.

MATERIAL AND METHODS

Study subjects and animal housing

The study was conducted between March 2011 and March 2012. A total of 38 pregnant females were included in the study (11 females with CS and 27 with OVH). CS females were two years old (born in 2009), and the procedure was performed at their second birth. OVH females were one-year-old (born in 2010) with one previous birth. To impregnate the females, we used two-year-old reproductive males (born in 2009) with records of reproductive success. All animals were born in captivity at the Universidad Austral de Chile (UACh) animal colony. The parents of these individuals were obtained from the animal colony of the Pontificia Universidad Católica de Chile (PUC) and corresponded to the third generation of captive animals born from wild specimens captured in Rinconada de Maipú, Chile (33°23'S, 70°31'W) in 2006. Each individual was maintained in a standard polycarbonate transparent rat box (45 × 23 × 21 cm) with hardwood chip bedding, water, and food (Cisternas® commercial rabbit pellets) provided *ad libitum*. The animals were provided with sticks, cardboard, and wood to gnaw. The vivarium room had an active ventilation system and an artificial photoperiod of 12:12 hour light-dark. The Ambient temperature and humidity were maintained at 18 ± 2 °C and 49% ± 3%, respectively.

Cesarean context

CS surgeries were performed in a behavioral ecology study (Correa, 2012), the objective of which was to determine whether intrauterine position (the position in utero occupied by each pup) relative to male siblings was related to differential exposure to androgens (for details, see Correa *et al*., 2013; Correa *et al*., 2016). CS was performed one day before the estimated parturition date (mean pregnancy period of 87 days from visible sperm plugs) (Rojas *et al*., 1982).

Cesarean surgery protocol

Pre-surgical management. We did not apply pre-surgical fasting, as we wanted to avoid hypoglycemia, and vomiting and regurgitation are unlikely in rodents (Redobre, 2002; Richardson & Flecknell, 2006). One hour before surgery, we treated the females with analgesics (tramadol 2 mg/kg of body weight, SC Tramadol Clorhidrato®, Sanderson Lab, Santiago, Chile) and fluids (10 ml 0.9% NaCl, SC) to reduce pain and improve hemodynamics (Redobre, 2002; Richardson, 2003).

Surgical procedure. Anesthetic induction was performed in an induction chamber (plastic box) with an oxygen flow of 1 L/min, and the initial percentage of isoflurane (Isofluorano USP®, Baxter Lab Santiago, Chile) of 2% gradually rising to 4% during the first minute. Once the animal was unconscious, it was removed from the chamber and placed

in a stretcher. Anesthesia was continued using an inhalation anesthesia machine (Surgivet/Anesco; model 100) and a face mask (non-rebreathing system Mapleson type B) specially designed to decrease nose size (a plastic perfume bottle cut and padded with gauze in the area in contact with the face). Anesthesia was maintained with an oxygen flux of 0.6 liter/min and 3% isoflurane throughout the surgical procedure.

To assess the depth of anesthesia, we squeezed the skinfold between the toes. Forceps were used to tighten the skin folds. If the animal did not move its leg, the absence of deep pain and the existence of a deep plane of anesthesia were assumed. Once anesthetized, we positioned the animal in dorsal recumbency, with the head and thorax raised at 45° to reduce visceral pressure (degus has a well-developed cecum) on the thorax and promote pulmonary ventilation (Redobre, 2002; Mancinelli *et al*., 2013). The arms and legs were maintained in a stretched position by using cotton ropes tied to a stretcher. After applying an ophthalmic ointment to maintain eye hydration, we covered the eyes of each female with a cotton hood (made by cutting the top of a baby sock), but left the nostrils exposed. Each female was placed in a slightly warm seed bag throughout surgery. Each degu was supported by seed bags that were placed on either side of the body. Only the degu head was left without moderate heat supply. The abdomen of the female was shaved with an electric razor and the skin was disinfected with iodinated alcohol (70%).

We initiated surgery with an abdominal midline laparotomy on the white line, exposing the gravid uterine horns one at a time (Figure 1). The pups were removed from the uterus one at a time, from the ovarian end to the cervical extreme of the uterine horn, starting with a horn with fewer pups. Using tissue scissors, we opened the fetal membranes and removed the pups by tearing the umbilical cord. Immediately after each pup was removed from the uterus, a second surgeon assisted the newborn by wiping the oronasal superficial secretions with soft gauze, gently shaking in short, up-and-down motions with the pup's head pointing downwards to eliminate nasal fluids, gently drying the pup's coat with a paper towel, and finally disinfecting and cauterizing the umbilical cord with a cotton swab soaked in a 10% iodine solution. Newborns were then placed in a box with bedding 60 cm beneath a red heat lamp. Female degus allonurse and provide maternal care indiscriminately to biological and foreign offspring (Ebensperger *et al*., 2006), thus we placed newborn pups with a second lactating female until the mother recovered from anesthesia.

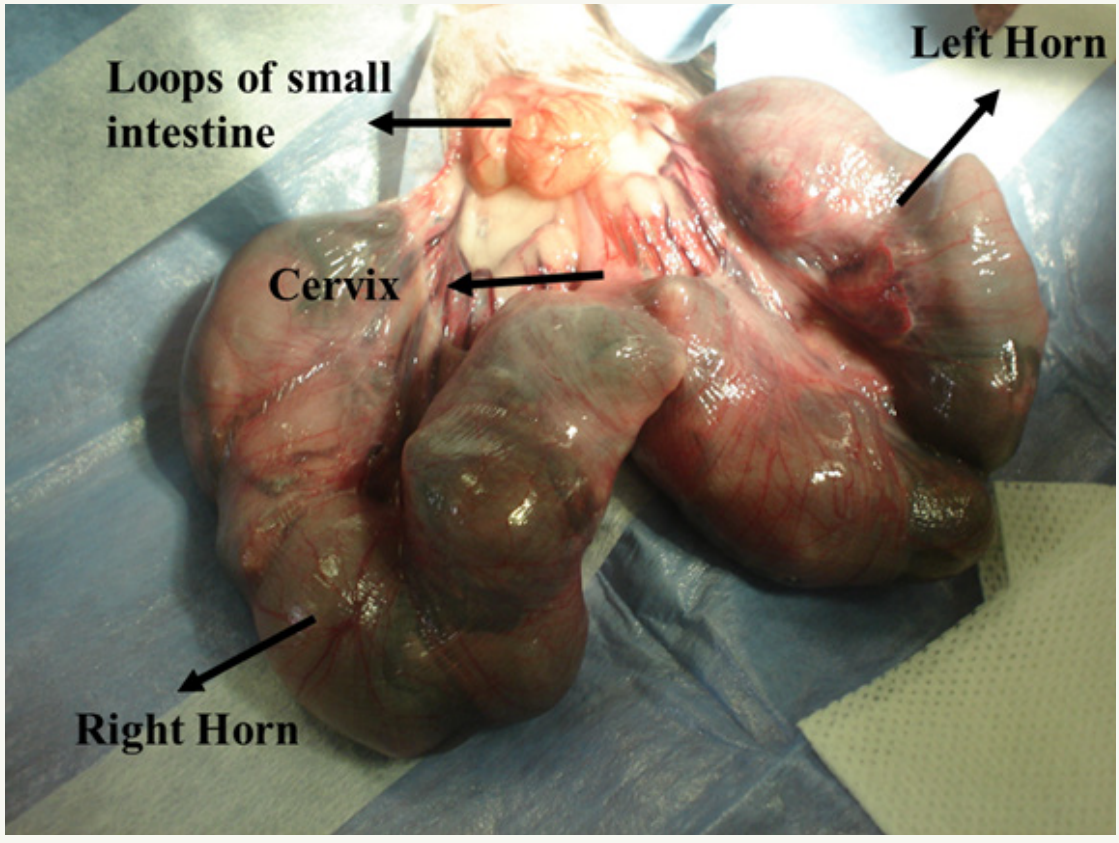

Figure 1. Gravid uterus of degu, exposed during a cesarean surgery. In addition to the cervix, the right horn and left horn of the uterus are indicated.

During surgery, we administered slightly warm and sterile intraperitoneal fluid (10 ml sterile 0.9% NaCl) to improve hydration and maintain abdominal visceral moisture (Redobre, 2002; Richardson, 2003). This procedure was repeated three times (total, 30 ml), with 20 minutes between each infusion period. After the removal of the pups, the uterus and ovaries were removed from the ovarian end to the cervix. Ligation of the uterine and ovarian stumps was performed with polyglycolic acid (Vycril®) 3-0, following the recommendations (Redobre, 2002; Richardson & Flecknell, 2006). Polyglycolic acid (Vycril®) 3-0 was also used for peritoneum and muscle sutures. We performed a discontinuous skin suture using nylon 3-0 attached to 23G needles. Anesthesia was closed when the skin suture was started. After finishing the skin sutures, the females remained on the face mask and received oxygen for 5–10 minutes (depending on the latency to wake up). Finally, the sutures were disinfected with iodinated alcohol (70%). Surgeries were performed by well-trained veterinarians (A.E, O.A.A, L.A.C) at the minor surgical pavilion of the Veterinary Teaching Hospital Facilities, Faculty of Veterinary Sciences, Universidad Austral de Chile.

Post-surgical management. Once the females woke up from the anesthesia, they were allocated to the same box with their litter and the nursing female. Wood chip bedding was used with pieces of tissue paper in each corner to provide a comfortable nest (Richardson & Flecknell, 2006). Once the two nursing females were together with the litter, a red heat lamp was placed 80 cm above the box to provide a warm environment (Richardson, 2003). The family was kept under a red heat lamp for one night, and the mother was offered an isotonic hydrating solution (Gatorade®) and palatable food (sunflower seeds and crushed oats) to encourage gut motility (Richardson & Flecknell, 2006). After surgery, all females were injected with an antibiotic (enrofloxacin, 5 mg/kg, SC Baytril®, Bayer Lab, Santiago, Chile) (Richardson, 2003), anti-inflammatory (ketoprofen 2 mg/kg, SC, Ketofen®, Merial Lab, Santiago, Chile), and analgesic (tramadol at the same dose as before surgery) every 12 hours for five days. Analgesics, anti-inflammatory drugs, and antibiotics were administered during the post-operative stage, as CS corresponds to invasive surgery that requires postoperative pain management and infection control, given the opening of the abdominal cavity. Postoperative pain was monitored for five days, during which analgesics and anti-inflammatory drugs were administered. The pain assessment was qualitative and involved analysis of the presence or absence of the following behaviors and postures: i) anorexia, ii) hunched posture, iii) bristly fur, iv) contraction of the abdominal muscles, which are indicative of discomfort and pain in rodents and rabbits (Richardson & Flecknell, 2006), and v) ocular secretions with a milky appearance that corresponds to a specific sign of stress and discomfort in degus (Correa, personal communication, March, 2012). The suture line was monitored and disinfected once daily with iodinated alcohol (70%). While suture dehiscence due to gnawing can be an issue in rodents, we did not see any evidence of this in degus; therefore, we did not use soft Elizabethan collars made of cloth (Redobre, 2002; Richardson & Flecknell, 2006). The nylon suture was removed six days (range, 5–7 days) after surgery. One person gently restricted the female, while the other removed the suture by using blunt scissors. However, chemical sedation is not required. Females and pups were monitored daily for the first 10 days and twice at night during the first two days after surgery. The substitute mother remained in the group until three days after surgery. Various food items, including fruits, honey cereals, sunflower seeds, crushed oats, and both rat and rabbit pellets, were offered during the post-surgical period.

Ovariohysterectomy context

OVH surgeries were performed as part of a behavioral ecology study (Correa, 2012), in which the objective was to evaluate whether intrauterine position determines litter traits in adulthood, including the size of the litter (see Correa *et al.*, 2016). For this purpose, we needed to know if there was reabsorption of embryos in the uterus, which can be evaluated by counting the scars that remain on the uterine mucosa, indicating failed implantation in first-time mothers (Krackow, 1992; Zielinski *et al.*, 1992). A total of 27 OVH surgeries were performed, in which we removed the uterus and ovaries of one year-old females after their first pregnancy and birth. After a typical gestation, parturition, and lactation period, the pups were weaned at 49 d of age. Females were then separated from their pups and left alone for ~41 days with *ad libitum* food and water, which allowed them to recover from reproductive processes. OVH surgery was performed at 90 days postpartum.

Ovariohysterectomy surgical procedure

Pre-surgical management. Females were treated with an analgesic (tramadol 2 mg/kg, SC) 1 h before surgery. The protocols for anesthetic induction, anesthesia, positioning of the degus on the surgical bed, and thermoregulatory variables were the same as those used for the CS procedure described above.

Surgical procedure. Skin preparation was identical to that for CS, but the abdominal midline incision was shorter (~1.5 cm). The small intestine was then gently displaced to expose the cervix. Once the cervix was identified, bifurcation of the horns was followed to reach the ovary. Uterine and ovarian stump ligations were performed as outlined in the CS protocol. Once the ovaries and uterus were removed, slightly warm and sterile saline fluid was administered intraperitoneally (5 ml 0.9% NaCl). A second dose of intraperitoneal fluid (5 ml 0.9% NaCl) was administered immediately before the last stitch to close the peritoneum and muscle. Peritoneal, muscular, and skin sutures were applied as described for CS. Recovery and postprocedural management were identical to those of CS. Similarly, OVH surgeries were performed by the same professionals and at the same facilities as the CS surgeries. During recovery, females were housed in standard rat boxes with the same bedding material as

in the CS protocol. In this study, we did not use red heat lamps because the females were housed in a room with a controlled temperature of 18–22°C. Once the females were fully awake, they were offered an isotonic hydrating solution (Gatorade®) to drink and palatable food (honey cereals, sunflower seeds, crushed oats, apple pieces, and rat pellets).

Procedure Durations, Recovery Times, And Survival Of Mothers And Pups

The duration of CS and OVH was defined as the time between the first abdominal incision and when the female was rotated from dorsal to ventral recumbency for post-surgical recovery (Malbrue *et al.*, 2019). The initial recovery time was defined as the time between ventral recumbency and the first leg movement. Full recovery time was defined as the time between the first leg movement and when the female was able to stand and walk in a coordinated manner. Neonatal and maternal survival were determined at two time points: i) once the CS and OVH were over, and ii) at weaning. These data are presented as percentages ((number of individuals surviving/total number of pups per litter) × 100). Finally, for CS, we determined i) the litter size, ii) male percentage of the litter, iii) female percentage of the litter, iv) number of pups per uterine horn, v) pup body weight, vi) litter weight, and vii) maternal reproductive investment (MRI). MRI was calculated as ((((litter weight at birth + uterus and membrane weight)/maternal weight before CS) × 100). As the CS procedure provided data on the intrauterine position (IUP) of each pup, we analyzed whether the IUP (cranial end, middle on, and caudal end of the uterine horn) is associated with the body weight of the pups.

Statistical analyses

We conducted descriptive statistical analyses for i) CS duration correlated with litter size, ii) CS duration correlated with the order in which different CS were performed (i.e., the last CS surgery was significantly shorter than the first CS surgery), and iii) OVH duration correlated with the order in which different OVHs were performed. For these determinations, we conducted a Spearman's correlation analysis. To analyze the potential effect of IUP on pup body weight, we performed a one-way ANOVA, with IUP (cranial end, middle, and caudal end) as the independent variable and pup body weight as the dependent variable. Before carrying out a one-way ANOVA, we confirmed that the dependent variable had a normal distribution using the Kolmogorov-Smirnov test. Tukey's test was used for a posteriori analyses. Statistical analyses were performed using STATISTICA 7 software (StatSoft). All data are reported as mean ± SD.

RESULTS

Maternal and pup survival rates

For the CS surgeries, we measured 83 pups distributed across 11 litters. All pups were extracted alive from the uterus, except for one mummified pup, which probably died because of umbilical cord compression (Figure 2b). At the end of CS, the maternal and neonatal survival rates were 100% and 97.3%, respectively. Of the 83 pups born by CS, three died shortly after being extracted. These three pups came from two large litters (mother 161, one male pup dead, litter size 10; female 612, two male pups dead, litter size 10). All three pups that did not survive showed signs of delayed development. The pups remained with their mothers until natural weaning (~49 days), and no pups died during the lactation stage; thus, the mother and pup survival at weaning was 100%. Relative to OVHs, maternal survival was 100%.

Procedure duration

The CS procedures took, on average, 61.82 ± 8.62 min. The fastest CS surgery lasted 51 min, while the slowest CS surgery took 79 min (n= 11, Table 1). CS duration and litter size were positively correlated (Spearman correlation= 0.92, $P<0.05$), CS duration was not correlated with the order in which different CS surgeries were performed (Spearman correlation= –0.33, $P>0.05$). The OVH procedures had an average duration of 32.89 ± 4.26 min. The fastest OVH lasted 26 min, whereas the slowest lasted 42 min (n= 27; Table 2). In this case, OVH duration and order were negatively correlated (Spearman correlation= -0.39, $P<0.05$), such that early OVH surgeries were generally performed more slowly than later OVH surgeries.

Times to initial and full recovery

The average time to initial recovery for CS surgeries was 8.18 ± 2.79 min with a range of 4–13 min (n=11). The average full recovery time was 50.18 ± 41.00 min. The high variability observed in this variable was associated with one female patient (612), who presented with a full recovery time of 171 min. When excluding this extreme value, the time to full recovery was 38.10 ± 9.13 min with a range of 21–52 min (Table 1, n=10). For OVH surgeries, the average time to initial recovery was 5.59 ± 2.08 min with a range of 2–10 min (n=27). The average time to full recovery was 15.11 ± 5.82 min, with a range of 7–27 min (Table 2, n=27).

Descriptive data relative to reproductive traits

For CS surgeries, the average litter size was 7.55 ± 1.63 (ranging 5–10 pups, n=11). The average percentage of males per litter was 53.8 ± 20.8% (33.3-100%), whereas the average percentage of females per litter was 46.2 ± 20.8% (0-66.7%). Left uterine horns had 3.90 ± 1.44 pups (ranging 1–6, n=11), whereas right uterine horns had 3.63 ± 1.28 pups (ranging 2–6, n=11). Thus, the pups were homogeneously distributed between the horns. Details of each litter type are presented in Table 3. The average pup body weight at CS was 10.19 ± 1.14 g (ranging from 8.20–12.40 g, n= 83). while average litter weight was 75.90 ± 13.53 g (ranging 58.00–106.40 g, n=11). The average maternal reproductive investment was 26.6 ± 3.6% (20.8–32.3). Details of the reproductive investment of each female are presented in Table 4. The results of one-way ANOVA indicated that IUP use was associated

Table 1. Descriptive data regarding surgery duration and times to initial and full wake up from cesarean surgeries in female degus.

Mother ID	Order	Litter size	Cesarean duration (min)	Time to initial recovery (min)	Time to full recovery (min)
56	1	9	71	11	44
61	2	7	61	9	33
161	3	10	79	11	52
246	4	7	60	4	21
841	5	5	51	9	35
10A	6	6	55	8	41
811	7	7	57	6	37
612	8	10	72	13	171
H40	9	8	59	5	49
827	10	6	54	8	39
427	11	8	61	6	30
Average		7.55	61.82	8.8	50.18
Standard deviation		1.63	8.62	2.79	41.00

with pup body weight (ANOVA, F (2.80) = 5.376, p= 0.006). Tukey's posteriori analysis showed that pups located at the cervical end of the uterine horn were heavier (mean, 10.784 g) than those located in the middle (mean, 9.581 g) of the uterine horn (Figure 3).

DISCUSSION

In this study, we outlined the detailed protocols for CS and OVH surgeries in degus, including pre-surgical, surgical, and post-surgical management. These details expand on previously reported orchiectomy, ovariectomy, and OVH procedures in degus (Mancinelli *et al*., 2013; Malbrue *et al*., 2019). Compared with the available information from other rodent and rabbit species (Redobre, 2002; Richardson & Flecknell, 2006), our protocols differed in four major aspects. First, we did not consider the intravenous route for the administration of fluids and drugs because degus are too small, and rodent cannulation techniques (caudal and jugular veins) are unreliable (Redobre, 2002; Richardson & Flecknell, 2006). Degus has a very short neck and caudal skin autotomy (spontaneous tail self-mutilation as an anti-predator strategy) occurs when the tail is manipulated (Shargal *et al*., 1999). Intravenous routes have also not been used in orchiectomy, ovariectomy, or OVH procedures performed in degus (Mancinelli *et al*., 2013; Malbrue *et al*., 2019). Second, we used a face mask instead of an endotracheal tube to maintain anesthesia, as recommended in the anesthetic protocol for other rodent species (Redobre, 2002; Richardson & Flecknell, 2006). Maintenance of anesthesia by mask was the chosen methodology for orchiectomy, ovariectomy, and OVH procedures previously performed in degus (Mancinelli *et al*., 2013; Malbrue *et al*., 2019). Third, we used tramadol to provide analgesia, although it has not been used in previous degu orchiectomy, ovariectomy, or OVH procedures (Mancinelli *et al*., 2013; Malbrue *et al*., 2019). Mancinelli *et al*. (2013) used buprenorphine to provide analgesia for OVH procedures, whereas Malbrue *et al*. (2019) used butorphanol tartrate for analgesia during orchiectomy and ovariectomy surgeries in degus. Our results indicate that tramadol is an effective analgesic in degus, as we did not observe any evidence of post-surgical acute pain, such as anorexia, hunched posture, bristly fur, contraction of the abdominal muscles (Richardson & Flecknell, 2006), or ocular secretions with a milky appearance (Correa, personal communication, March 2012). Degu mothers also displayed normal post-partum behaviors including eating, drinking, and nursing. Although tramadol is not the first choice of analgesic in other small mammals such as rabbits (Hedenqvist, 2008), our results suggest that this drug could be an effective analgesic for degus. Fourth, nylon was used for skin sutures instead of skin staples, as recommended for rodents and rabbits to decrease suture dehiscence from gnawing (Redobre, 2002; Richardson & Flecknell, 2006). However, in previously reported OVH, orchiectomy, and ovariectomy procedures in degus, the skin was closed with sutures and sometimes with surgical glue as a second barrier to close the skin (Mancinelli *et al*., 2013; Malbrue *et al*., 2019). No suture dehiscence was observed among the OVH (n=27), and CS (n=11) surgeries performed in this study, as Mancinelli *et al*. (2013) and Malbrue *et al*. (2019) also did not detect suture dehiscence during their surgical procedures. We observed that mothers licked but did not gnaw the stitches, and that pups suckled without

Table 2. Descriptive data regarding surgery duration and times to initial and full wake up from ovariohysterectomy surgeries in female degus.

Mother ID	Order OVH	OVH duration (min)	Time to initial recovery (min)	Time to full recovery (min)
368	1	39	7	8
415	2	35	5	13
Short tail	3	37	5	25
417	4	42	7	15
405	5	41	7	26
447	6	38	6	7
424	7	32	3	11
370	8	29	4	11
418	9	35	4	21
411	10	27	6	9
324	11	32	8	13
427	12	29	2	9
421	13	32	5	19
429	14	28	6	10
305	15	35	4	16
61A	16	33	10	27
61B	17	28	5	21
848	18	31	5	12
White ear	19	29	2	9
446	20	28	8	17
401	21	36	3	10
404	22	26	7	22
428	23	34	4	11
448	24	31	10	14
437	25	36	7	16
H5	26	33	6	21
506	27	32	5	15
Average		32.89	5.59	15.11
Standard deviation		4.26	2.08	5.82

any problem or interest in the stitches. Therefore, we suggest that good surgical techniques and gentle tissue handling are sufficient for preventing suture dehiscence.

Additionally, in comparison to our CS and OVH protocols, previous OVH, orchiectomy, and ovariectomy procedures in degus: i) used sevofluoerane as an anesthetic (Mancinelli *et al*., 2013), ii) used a subcutaneous route to hydration during surgery (Mancinelli *et al*., 2013; Malbrue *et al*., 2019), iii) administered local anesthetic blocks (Malbrue *et al*., 2019), iv) permanently controlled degu body temperature (Mancinelli *et al*., 2013; Malbrue *et al*., 2019), v) used meloxicam to manage inflammation (Mancinelli *et al*., 2013; Malbrue *et al*., 2019), vi) did not use antibiotics during pre-surgical, surgical, or post-surgical management (Malbrue *et al*., 2019), and vii) had problems finding ovaries during ovariectomy via the flank, likely as consequence of the high volume and surface area of degu

Table 3. Descriptive data of degu litters obtained by cesarean section.

Mother ID	Litter size	Male/female pups ratio	Male pup percentage	Female pup percentage	N° of pups in left horn	N° of pups in right horn
56	9	3/6	33.3	66.7	6	3
61	7	4/3	57.1	42.9	1	6
161	10	4/6	40	60	5	5
246	7	5/2	71.4	28.6	5	2
841	5	3/2	60	40	3	2
10A	6	2/4	33.3	66.7	3	3
811	7	3/4	42.9	57.1	3	4
612	10	7/3	70	30	5	5
H40	8	4/4	50	50	5	3
827	6	2/4	33.3	66.7	3	3
427	8	8/0	100	0	4	4
Average	7.55		53.75	46.25	3.91	3.64
Standard deviation	1.63		20.83	20.83	1.45	1.29

Table 4. . Descriptive data regarding degu litter weight and maternal reproductive investment. Maternal reproductive investment was calculated as ((litter weight at birth + uterus and membranes weight)/maternal weight before CS) x 100.

Mother ID	Female body weight (g) before cesarean	Female body weight (g) after cesarean	Uterus weight (g)	Maternal Reproductive investment (%)	Litter weight (g) at birth	Mean offspring body weight (g) at birth
56	373.9	264.2	15.5	25.1	78.3	8.7
61	372	232.7	17.1	25.5	77.7	11.1
161	360.7	273.8	15	26.8	81.7	8.2
246	383	246.3	14.5	21.6	68.2	9.7
841	393.5	297.3	20.2	20.8	61.8	12.4
10A	301.4	217.9	15.4	24.4	58	9.7
811	279.5	199.2	10.4	29.7	72.7	10.4
612	380.5	187.8	16.4	32.3	106.4	10.6
H40	358.4	260.2	16.3	28.6	86.1	10.8
827	291.5	204.6	14.2	26.8	63.8	10.6
427	307.6	194.2	15.3	31.1	80.3	10
Average	345.64	234.38	15.48	26.61	75.91	10.20
Standard deviation	41.83	36.60	2.35	3.65	13.53	1.15

intestines (Malbrue *et al*., 2019). However, similar to Mancinelli *et al*. (2013) and Malbbrue *et al*. (2019), we also utilized heat sources throughout the entire surgery to maintain degu body temperature (Mancinelli *et al*., 2013; Malbrue *et al*., 2019) and administered analgesic and anti-inflammatory medications during the pre-and post-operative stages (Mancinelli *et al*., 2013). Finally, similar to Mancinelli *et al*. (2013), we positioned the degus with the thorax elevated during the surgical steps, which required them to lie on their backs.

As our first objective was to report survival rates related to our surgical protocols, our protocols resulted in high maternal and neonatal survival rates (100% and 97.3%, respectively). As reported in the Results section, the three mortality events corresponded to underdeveloped individuals within a very large litter. The asymmetry of development in the littermates of recently born degu pups is a common phenomenon (Rojas *et al*., 1982) (Figure 2c), which is also observed in guinea pigs, which are the closest related domestic species to degus (Scott, 1937).

Our results indicated that individuals in the middle of the uterine horns were lighter than those in the cervical ends of the uterine horns (Figure 2a,c, and Figure 3). Individuals in the ovarian ends of the uterine horns had an intermediate body weight but were not statistically different from those in the middle and cervical ends of the uterine horns. This pattern has been previously described in domestic pigs (Dziuk, 1992), European rabbits (Bautista *et al*., 2015) and Sprague Dawley laboratory rats (D'Errico *et al*., 2021), but in different ways than in degus. In Sprague-Dawley rats, individuals in the middle of the horn were lighter than those in the cervical and ovarian ends, and the horn (left, right) also affected individual body weight, with the lightest individuals located in the middle of the left horn (D'Errico *et al*., 2021). In domestic pigs, individuals in the ovarian end are heavier than those in the middle or cervical end of the uterine horns (Dziuk, 1992), whereas in European rabbits, individuals located at both ends of the uterine horns are heavier than those in the middle (Bautista *et al*., 2015).

From these studies and our results, only one pattern emerged: the individuals located in the middle of the uterine horns were light. Dziuk (1992) suggested that lower body weight in these individuals could be a consequence of high fetal density, leading to less space for growth, while Bautista *et al*. (2015) also suggested that differences in pup body weight, depending on the IUP, could be a consequence of differences in vascular supply and placental efficiency. Raz *et al*. (2012) suggested that individuals at both ends of the uterine horns receive more blood supply and, therefore, more nutrients, having an advantage to grow, which may explain our findings.

The second objective was to calculate the duration of the CS and OVH procedures. Our results indicate that these average times (CS 61 min and OVH 32 min) are reasonable. It is difficult to compare these times with those of similar species, as we have only found anecdotal reports of CS and OVH in different rodent species (Fleischman, 1981; Prior, 1986; Jones, 1990; Mighell & Baker, 1990) and rabbit species (Richardson & Flecknell, 2006). Therefore, we only can compare our results with the ovariectomy procedure performed previously in degus (Malbrue *et al*., 2019), which reported an average duration of 12.56 ± 4.09 min (considering only the surgical time) for an ovariectomy using the bilateral flank technique. As this duration is shorter than that of our OVH protocol via a midline approach, we suggest using the ovariectomy protocol from Malbrue *et al*. (2019) if the objective is only to sterilize the females without removing the uterus. We observed a positive correlation between the litter size and CS duration. The lack of correlation between CS surgery order and duration and the negative correlation between the order of OVH surgeries and duration suggest that surgeon expertise can help decrease OVH, but not CS duration. We suggest that these relationships are a consequence of OVH being very similar between each degu, whereas CS is more variable as female degus vary in litter size.

Our third objective was to report that the time to initial and full recovery from anesthesia was relatively short in degus (average initial: CS, 8 min; OVH, 5 min; average full:38 min; OVH, 15 min). These results are similar to those reported by Malbrue *et al*. (2019), who found that the average ovariectomy recovery time was 14.14 ±3.12 min. These fast recovery times are not surprising as degus, similar to other small mammals, exhibit rapid metabolism and drug elimination (Zhao *et al*., 2016).

Finally, in relation to the reproductive traits of degu, we highlight that degu mothers make high maternal investments. Our results indicated that the summed litter, uterus, and membrane weights corresponded to 1/5 to 1/3 of the mother's total body weight. This trait is notable, as close caviomorph relatives of degus (chinchillas and guinea pigs) generally deliver smaller litters, but with well-developed pups (chinchillas average two offspring, ranging 1–4 (Kuroiwa & Imamichi, 1977); guinea pigs average two offspring, ranging 1–5 (Peaker & Taylor, 1996)). However, degus delivers larger litters (average six, range 1–10) (Ebensperger *et al*., 2019), and at the same well-developed pups (Rojas *et al*.,1982), which implies a higher energy expenditure. In terms of surgical management, this trait could be relevant because removal of 1/5 to 1/3 of female body weight could cause acute decompression of abdominal organs, blood redistribution, and changes in abdominal pressure. Therefore, during CS, we administered intraperitoneal fluid three times, exposed only one horn at a time, and started pup extraction with a uterine horn containing fewer pups.

In conclusion, relative to our four critical points, we used previous information to control for i) respiratory compromise, ii) body temperature fluctuations, iii) suture dehiscence, and iv) reduced intestinal motility during reproductive surgery in degus. (Redobre, 2002; Richardson, 2003; Richardson & Flecknell, 2006) The individuals included in this study did not encounter any of the four critical problems listed above, and we want to highlight that degu are good patients during all stages of the detailed surgeries.

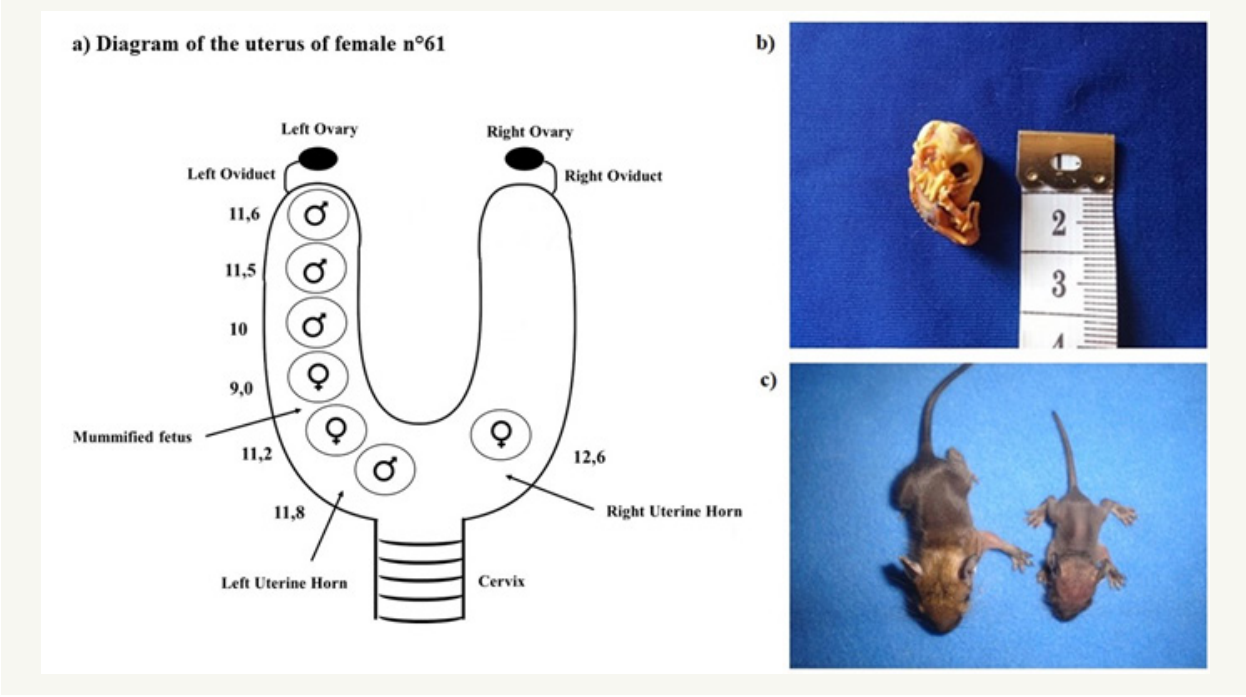

Figure 2. a) Diagram of the uterus of female n°61, which includes the real weights of the offspring extracted by cesarean section, the real fetus distribution, and the position in which mummified was located. Males and females are indicated with man and woman symbols. b) Photograph of mummified pup with cm scale. c) Example of asymmetry in body size and developmental levels of degu littermates. The pup on the left side of the photo corresponds to the 12.6 g female that was alone in the right horn. The pup on the right side of the photo corresponds to the 9.0 g female that was in fourth position, counting from the ovary to the cervix, in the left horn.

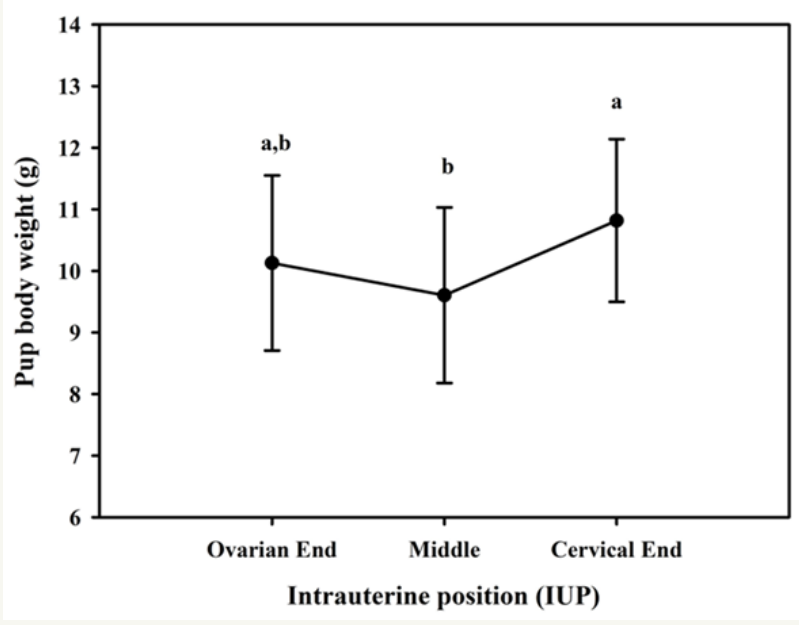

Figure 3. Intrauterine position and pup body weight at cesarean. Letters represent significant differences between groups using a Tukey posteriori test with $p < 0.05$.

Competing interests statement

The authors declare that they have no competing interests.

Author contribution

Conception: Loreto A. Correa and Mauricio Soto-Gamboa. Data acquisition: Ángelo Espinoza, O. Alejandro Aleuy, and Loreto A. Correa. Data analysis and interpretation: Loreto A. Correa. Original draft: Loreto A. Correa. Revisions: Ángelo Espinoza, O. Alejandro Aleuy, and Mauricio Soto-Gamboa.

Ethical statement

In this study, we followed all protocols, animal handling techniques, and suggestions by the Ethics Committee of the Universidad Austral de Chile (report 03/09) and followed the Chilean Ethical Legislation required by CONICYT. Animal handling, injections, and surgeries were performed by veterinarian staff (A. E., O.A.A, and L.A.C).

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