Tamil Nadu Forest Department

Advanced Institute for Wildlife Conservation

(Research, Training & Education)

Vandalur, Tamil Nadu.

Report on

APPLICATION OF INFRARED THERMOGRAPHY AS A DIAGNOSTIC TOOL IN CAPTIVE AND WILD ELEPHANTS

Scheme: **Modernization of Forest Force**

August 2024

Tamil Nadu Forest Department
ADVANCED INSTITUTE FOR WILDLIFE CONSERVATION
(Research, Training & Education)
Vandalur – 600 048. Tamil Nadu.

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‘APPLICATION OF INFRARED THERMOGRAPHY AS A DIAGNOSTIC TOOL IN CAPTIVE AND WILD ELEPHANTS’

Project funded by the Government of Tamil Nadu
under the scheme
‘Modernization of Forest Force (MoFF)’

Centre for Animal Care Sciences

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Project Scientist	:	Dr. Kumar, K.
Junior Research Fellow	:	Mr. Madeswaran, R.
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ABSTRACT

Asian elephants are a symbol of strength and pride all over the Indian subcontinent. However, captive elephants, maintained under human care for conservation and tourism efforts, face certain physiological, psychological and pathological issues. Infrared thermography has been proved through various studies to be successful in providing repeatable and reliable results in recording the thermoregulation patterns and surface temperature variations of various animals and identifying health issues. Hence, the applications of infrared thermography as a diagnostic tool in captive and wild elephants were studied in this project, centred around the elephants housed at the elephant camps of Anamalai and Mudumalai Tiger Reserve. The study formulated the normal thermography associated with captive elephants and the issues that cause deviation from normality. The study also successfully identified and tracked injuries and ailments such as inflammations, wounds and abscesses based on surface temperature variations. The monitoring of reproductive events like oestrus and pregnancy proved difficult due to time constraints but musth conditions were identifiable. The study was also able to shed light on how infrared thermography could play a role in wild elephant surveillance and monitoring. In conclusion, the study identified a variety of methods in which infrared thermograph can be a valuable addition to captive elephant management.

Keywords: Infrared thermography, captive elephants, diagnostic tool, thermoregulation

INTRODUCTION

The earliest proboscidean, dating back to the early Eocene epoch approximately 55 million years ago, underwent significant evolutionary developments, including an increase in body and tusk size, as well as the development and extension of the trunk to give rise to today's two extant genera - *Loxodonta* and *Elephas* (Shoshani, 2006). Both the genus *Loxodonta* and *Elephas* originated in East Africa. However, despite this shared origin, *Loxodonta*, represented by the living African elephants, appears to retain more primitive and generalised features compared to *Elephas*, represented by the living Asian elephants (Maglio, 1973; Shoshani & Tassy, 1996). Asian elephants have a more recent common ancestry with mammoths (genus *Mammuthus*) than with African elephants (Fleischer *et al.*, 2001). The genus *Loxodonta* has two extant species, the African bush elephant (*L. africana*) and the African forest elephant (*L. cyclotis*), while the genus *Elephas* has one extant species, the Asian elephant (*E. maximus*). Furthermore, three subspecies exist within Asian elephants - Indian elephant (*E. m. indicus*), Sri Lankan elephant (*E. m. maximus*) and Sumatran elephant (*E. m. sumatranus*) (Wilson & Reeder, 2005). The Borneo elephant (*E. m. borneensis*) has been proposed as the fourth subspecies based on DNA analysis but is yet to be recognised (Fernando *et al.*, 2003).

Across the Indian subcontinent, elephants possess historical, cultural, social and biological importance. As a keystone species, it plays a significant role in creating and maintaining forest cover; however, its dwindling numbers pose a serious threat to several ecosystems (Poulsen *et al.*, 2018). Captive elephant camps were established during the British colonial days to engage the animals in logging activities; however, in recent days, the camps primarily engage in tourism-related activities, aiming to raise awareness among the general public about the importance of elephants to the ecosystem (Fowler & Mikota, 2008).

As giant herbivores adapted to consume enormous quantities of fodder and regularly migrate for water and mates, camp-housed elephants face their unique share of problems. Unlike free-ranging elephants, camp elephants are restricted in movement and grazing. They are also prone to infections like tuberculosis, herpes virus infection, tetanus, encephalomyocarditis, salmonellosis, and babesiosis. Captive elephants often experience foot issues due to insufficient exercise, prolonged standing on hard surfaces and exposure to contamination from standing on dung (Ghimire *et al.*, 2022; Miller *et al.*, 2015). Due to such reasons, it is important to regularly monitor the health and well-being of camp-housed elephants. In addition to routine preliminary testing of blood, serum, or urine, infrared thermography can also be considered a potential diagnostic tool evidenced by the multitude of studies conducted on a variety of domestic and wild animals.

Infrared thermography (IRT), also known as thermal imaging, involves capturing and creating an image of an object using infrared radiation emitted from the object. Infrared radiation, part of the electromagnetic spectrum, is generated by any object having a temperature above absolute zero (-273°C). It is a non-contact and non-intrusive method that allows us to visualize thermal energy. The energy emitted by a body primarily depends on its surface temperature. Therefore, IRT can be seen as a two-dimensional method for measuring temperature. Although initially developed for military use, IRT has branched into various other fields, including medical imaging, thermal mapping, archaeology, chemical imaging, unmanned aerial vehicle (UAV) surveillance, and agriculture (Meola & Carlomagno, 2004). IRT has also found its use in the veterinary field, mainly used to monitor thermoregulatory patterns.

In veterinary medicine, thermography has been widely used in horses to detect inflammation, and identify musculoskeletal issues like hairline fractures, tendon and ligament injuries, joint disease, and infections (Colahan *et al.*, 1991). Thermographic studies have also been conducted on a variety of wild animals such as apes (Dezecache *et al.*, 2017 and Heintz *et al.*, 2019), primates (McFarland *et al.*, 2020 and Nakayama *et al.*, 2005), racoons (Dunbar & MacCarthy 2006), penguins (Duncan *et al.*, 2016), cassowaries (Eastick *et al.*, 2019), bovines (Mota-Rojas *et al.*, 2021), large felids (Stryker 2016) and seals (Mauck *et al.*, 2003) to learn about a variety of subjects ranging from thermoregulation patterns, behavioural changes, disease diagnosis, etc. In certain instances, IRT has successfully identified design flaws in zoo enclosures for captive animals, such as Asian elephants, sable antelopes, and Mishmi takins. These design flaws have been linked to irregular thermoregulatory behavior in the animals (Hilsberg 1998; Hilsberg-Merz 2008). Therefore, in addition to its diagnostic purposes, IRT has proven valuable in managing zoos and other captive animal facilities by helping to ensure optimal enclosure conditions. Thermographic studies have also been conducted in elephants (Avni-Magen *et al.*, 2017; Cena & Clark, 1973; Phillip & Heath, 1992) since their status of being the largest land mammals generates much interest in researchers regarding the metabolic processes that maintain homeostasis in these mega-herbivores.

It was found that heat dissipation in elephants mainly occurs through their ear pinnae, which are highly vascularised and have a large surface-to-volume ratio (Wright, 1984). It was observed that the rate of ear flapping was proportional to the rise in ambient temperature, indicating the versatility of the ear pinnae to spread and flap according to the environment (Buss & Estes, 1971). Of the three living species of elephants, the African bush elephant (*L. africana*) has the largest ear flaps, owing to the hotter climate it lives in, followed by the African forest elephant (*L. cyclotis*) and the Asian elephant (*E. maximus*) (Narasimhan, 2008). Thermal windows are another important aspect of thermoregulation that is often studied, referring to specific areas on an animal's body surface that regulate heat exchange with the environment, adjusting through changes in exposure and blood flow (Cooper & Withers, 2003). Thermal windows achieve this by regulating blood flow through vasoconstriction and vasodilation into these regions (Šumbera *et al.*, 2007). In elephants, thermal windows are not restricted to the ear flaps but also include poorly-haired areas like the eyes, nose, mouth, and shoulder (Hilsberg, 2001). Additionally, infrared thermography is best used for animals such as elephants, rhinoceroses, hippopotami and giraffes as the absence of long hair/thick coat makes diagnostic interpretation much easier (Hilsberg-Merz, 2008).

IRT has the advantage of being a non-invasive, contactless and real-time method to assess animals compared to other imaging techniques like ultrasonography, endoscopy, and radiography. Hence, the possibilities of using IRT to assess the primary health of elephants based on surface temperature variations are abundant. With this background, the present study was designed to study the applications of infrared thermography as a diagnostic tool in captive and wild elephants.

OBJECTIVES

1. Developing normal thermograms of captive Asian elephants
2. Identification of surface injuries and foot ailments in Asian elephants by use of thermography
3. Monitoring of reproductive events such as oestrus and pregnancy in Asian elephants by use of thermography

REVIEW OF LITERATURE

Infrared thermographic studies have been conducted in elephants, both African and Asian, since the late 1900s.

Cena & Clark (1973) studied an African elephant kept at a cool ambient temperature and found that the temperature of the elephant's ears matched that of the ground. The observations suggested that the energy losses were balanced by solar heat gain and that the ears dissipated low levels of metabolic heat. They also theorized that vasoconstriction in the ears minimizes total energy loss when the elephant is below its thermoneutral temperature.

Williams (1990) studied the surface temperature profiles and surface area measurements of African and Asian elephants to calculate standard equations for convective, conductive, and radiant heat transfer. The results showed that free convection and radiation transfer accounted for 86% of total heat loss. Heat transfer across the ears, a critical thermal window at high ambient temperatures, represented nearly 8%. The surface area of the animals and metabolic heat production were proportional to body mass. However, the thermal conductance of the elephants was three to five times higher than predicted. This high thermal conductance was attributed to the absence of fur.

Phillip & Heath (1992) used infrared thermography to study four female African elephants and found that one side of the ear accounted for almost 4.5% of the animal's total heat loss. They also observed that the temperature distribution patterns across the ear pinna varied with ambient temperature due to the elephant's ability to control blood flow through dilation or constriction of blood vessels. They postulated that, apart from evaporation, the elephant's heat loss needs can be met by the vasomotion of the ear pinnae under various conditions.

Hilsberg (2002) reported several case studies of African and Asian elephants housed in a zoological park, demonstrating the successful use of IRT in identifying issues such as inflammation, lameness, and infections. These problems often resulted from captivity conditions, including prolonged leg chaining, lack of comfortable substrates and enclosures, in-fighting, and rough handling.

Church *et al.* (2009) presented a case study on a captive female Asian elephant exhibiting uneven gait and difficulty in eating. Infrared thermography was used to identify and localize the inflammation in the right forelimb, which prevented the elephant from bearing its entire body weight on its forelimbs. Additionally, they discovered an improperly positioned molar affecting the sinus area, causing the eating issues.

Weissenböck *et al.* (2010) studied thermal windows in six African zoo elephants and observed two important phenomena. Firstly, they identified that elephants have specific areas on their bodies, independent thermal windows, which are highly vascularised and help regulate body temperature. Secondly, distinct and sharply defined hot sections were observed on the elephants' ear pinnae, indicating localized areas where heat is emitted. The frequency of thermal windows also increased with increasing ambient temperature and body weight. They theorized that the elephant reacts flexibly regarding heat loss due to its ability to restrict blood flow to its thermal windows.

Weissenböck *et al.* (2012) studied how elephants adapted heterothermy (storing heat during the daytime and dissipating it during cooler night hours) since diurnal heat storage mechanisms were favoured by animals of large body sizes like camels. Body temperatures of captive Asian elephants housed in Thailand (natural ambient temperature) and Germany (cold ambient temperatures) were recorded. The results showed that mean daily temperatures in Thailand oscillated more than those recorded in Germany due to increased day temperatures and decreased night temperatures. Hence, it was seen that elephants also adapted the characteristic features of heterothermy seen in desert animals.

Rowe (2012) used thermography to measure the skin surface temperatures of female African and Asian elephant ear pinnae before and after exercise, estimating heat gains and losses across various ambient temperatures. In hot environments, walking in the full sun led to radiant heat gain in vasodilated pinnae, while behavioural choices like seeking shade and being active at night increased heat loss through vasodilated pinnae.

Avni-Magen *et al.* (2017) monitored Asian elephants over three months, during which they developed pathological inflammatory lesions in their ears. A strong correlation was found between clinically diagnosed inflammatory lesions and the areas identified as problematic by the thermal camera. Thermograms showed a temperature difference of approximately 2°C, with higher radiation in clinical areas and lower radiation in non-clinical areas. The results indicated that the thermal camera could detect temperature increases in the elephants' ears before clinical identification.

Lefebvre *et al.* (2023) investigated the adaptive capability of captive Asian elephants to colder climates by taking thermal images of the elephants during January and February in Ontario, Canada. The thermograms of the ears showed frequent variability in surface temperature, presenting as thermal windows. These thermal windows appeared most often in the distal and then medial regions of the ear. The pattern of these thermal windows supports the idea that increased blood flow is used as a method of warming. The study suggested that the species might be better adapted to lower ambient temperatures than previously thought.

MATERIALS AND METHODS

Places of the Study

The study used the camp elephants maintained at Anamalai Tiger Reserve (ATR) and Mudumalai Tiger Reserve (MTR). In ATR, elephants are housed in two camps namely Kozhikamuthi (10° 44' 53.8" N; 76° 84' 88.5" E) and Varagaliyar (10° 41' 92.9" N; 76° 86' 66.1" E) whereas in MTR, there are two elephant camps, Theppakadu (11° 57' 91.2" N; 76° 58' 40.3" E) and Abhyaranyam (11° 55' 71.1" N; 76° 56' 19.5" E).

The Elephant Rehabilitation Centre (ERC), MR Palayam, Tiruchirapalli (11°3' 10.872" N; 78°48'45.864" E) was also chosen as a place of study since it predominantly housed elephants under medical care. The team also studied certain animals housed at Arignar Anna Zoological Park (AAZP), Vandalur, Tamil Nadu.

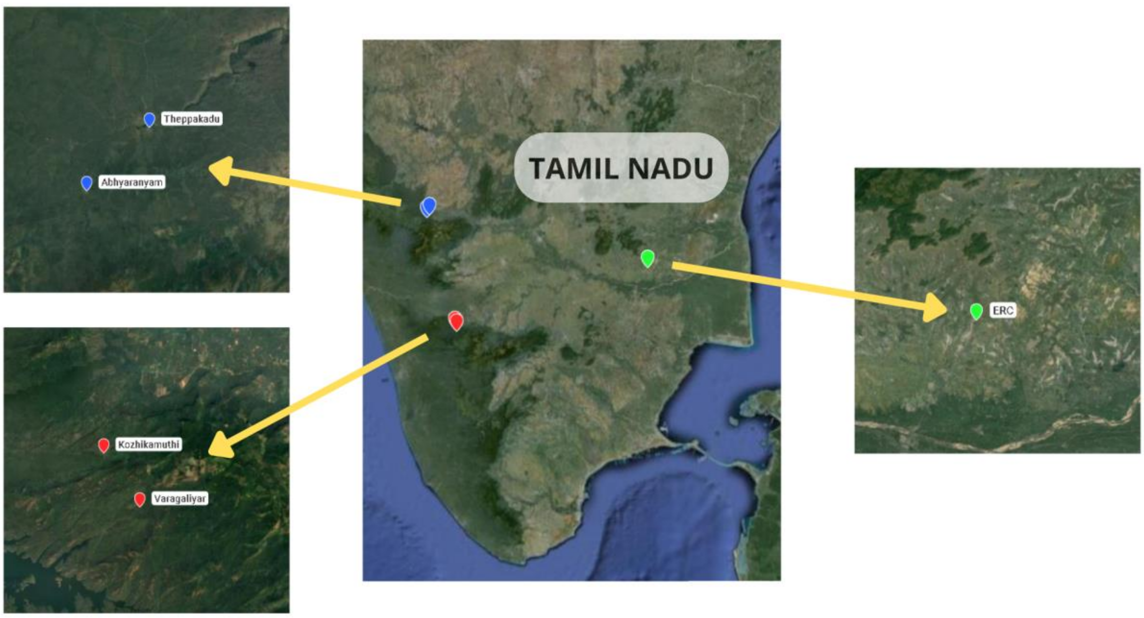


Figure 1. Location Map of Theppakadu and Abhyaranyam Elephant Camps in MTR, Kozhikamuthi and Varagaliyar Elephant Camps in ATR and ERC, Tiruchirapalli.

Data collection procedure

Infrared images (thermograms) of the elephants were captured using a FLIR E54 Advanced Thermal Imaging Camera (Teledyne FLIR, USA). It has 320 × 240 pixels IR resolution and a 4" LCD touch screen with 640 × 480 pixels. With a detection range of 120°C to -20°C, the camera resolves with an accuracy of ±2°C. It also has a 5 MP digital camera with a built-in LED lamp to capture standard digital images. The thermal camera automatically calibrated parameters, including emissivity (set at 0.98 per manufacturer's recommendation), reflected temperature, subject-camera distance, and air humidity according to the circumstances.

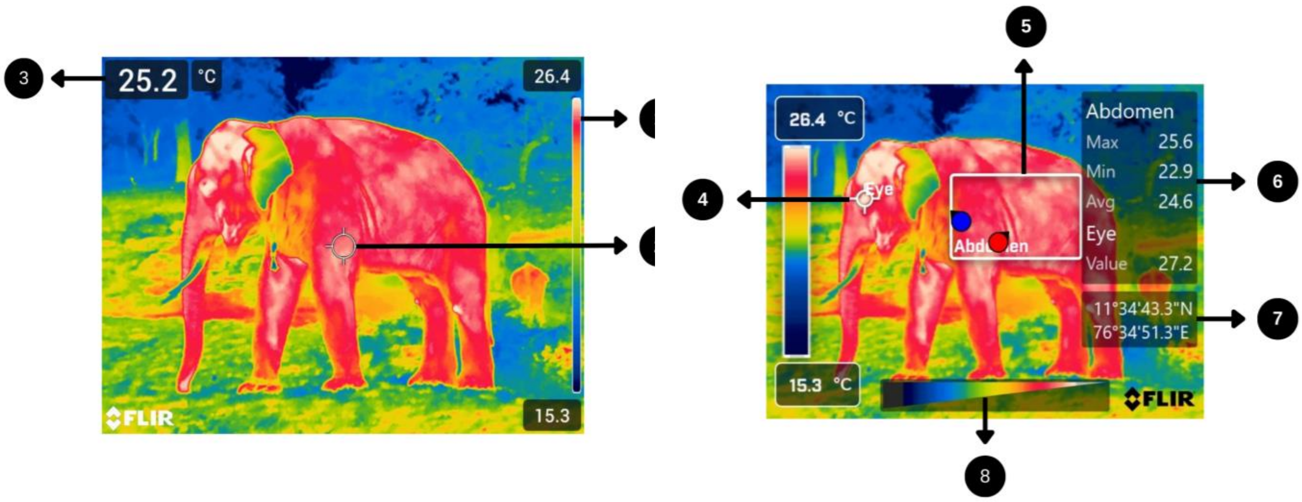
Figure 2. FLIR E54 Advanced Thermal Imaging Camera.

Infrared thermal images (thermograms) of camp elephants were captured periodically from October 2023 to May 2024. Thermograms were recorded generally in the mornings (6 to 9 A.M.) and evenings (4 to 7 P.M.) to minimise the effect of the sun's heat on the elephant. The elephants were allowed to acclimate for 5-10 minutes in shade, out of direct sunlight, before their thermograms were recorded. To capture full-body images of the elephants, the camera was positioned 10-20 meters from the animal. When required to observe a particular body part in focus, the thermograms were captured close to the elephant. Thermograms of wild elephants were opportunistically captured when the team encountered wild herds during their routine work.

The thermograms were analysed using the software FLIR Thermal Studio (v4.0.30319), while statistical analyses were performed using GraphPad Prism (version 8) and Microsoft Excel (version 2406).

Understanding a Thermogram

Thermograms captured by the thermal camera are analysed and scrutinised using FLIR Thermal Studio and then exported as images for interpretation. The following examples help us understand what the thermograms represent.



A **B**

Figure 3. Examples of a typical thermogram; before (A) and after (B) thermographic analysis.

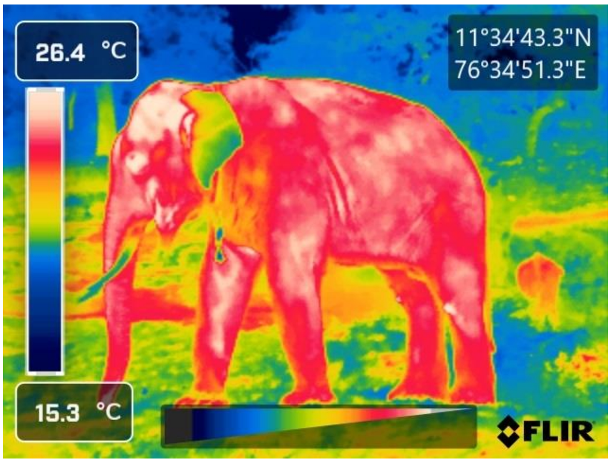
A typical thermogram captured in the thermal camera (Figure 3A), before being analysed in the software, appears with the following components:

1.	Temperature scale	-	the maximum and minimum temperatures of the image contained in the thermogram are represented in degrees Celsius, degrees Fahrenheit, or Kelvins. The colour gradient in the scale corresponds to the temperatures observed in the thermogram.
2.	Centre spot	-	indicates the centre of the thermogram captured.
3.	Temperature of the centre spot	-	indicates the temperature of the centre spot.

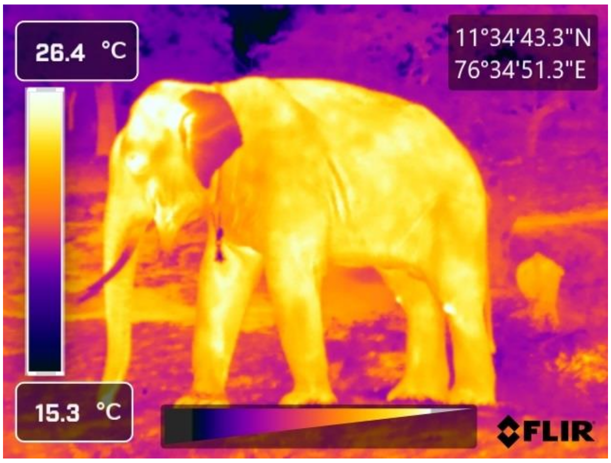
A thermogram analysed through the software and exported as an image (Figure 3B) contains the following components:

4.	Spot	-	indicates the temperature of a particular spot.
5.	Selection area	-	a selected area (can be a line/rectangle/ellipse) where its average/maximum (hotspots)/minimum (coldspots) temperatures are calculated.
6.	Measurements table	-	displays the temperatures corresponding to the spots/selections.
7.	Geolocation of the image	-	latitude and longitude represented in DMS format.
8.	Histogram scale	-	a visual representation of the temperature data (colours) contained in the thermogram.

Thermograms can be captured in different colour palettes according to the needs of the thermographer. Some of the commonly used colour palettes are pictured in Figure 4.



A



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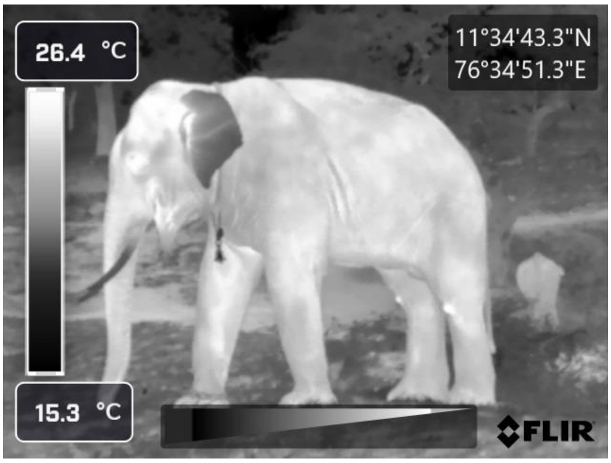

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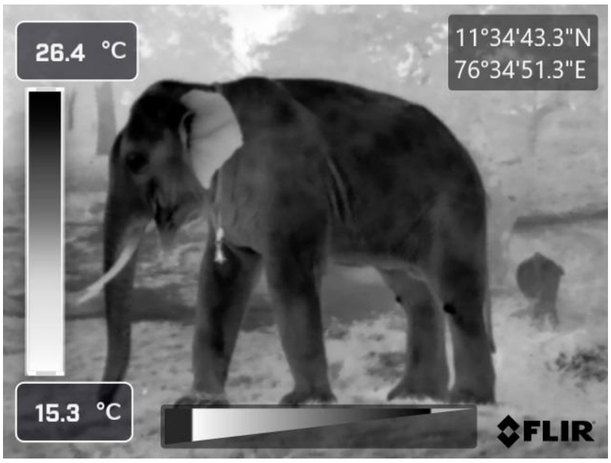


D

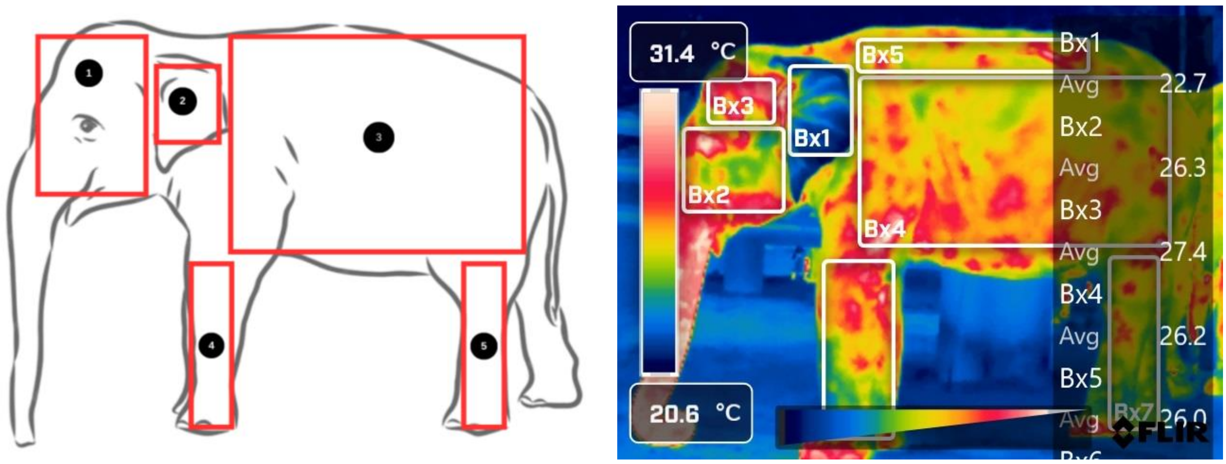
Figure 4. Thermograms recorded in different colour palettes: A - Rainbow (RGB), B - Iron, C - Gray (white hot) and D - Black hot.

OBSERVATIONS AND DISCUSSION

A total of 54 elephants were involved in this study. In ATR, 24 elephants (16 males and 8 females) were studied whereas in MTR, 19 elephants (14 males and 5 females) were studied. In addition, 11 female elephants from ERC were studied in this study. The general details of the elephants involved in the study are provided in Tables 1, 2 and 3.

A) DEVELOPING NORMAL THERMOGRAPHY

To analyse the normal thermography, healthy elephants of ATR and MTR elephant camps were placed 10-20 metres away from the thermal camera to record thermograms of their profile under shady conditions away from direct sunlight during early mornings or late evenings. The body parts chosen for thermographic analysis are pictured in Figure 5. The eye was also included in the temperature calculations of the head, in addition to being analysed independently.



A B

Figure 5. A - Pictographic representation of the body parts chosen for the observation of average surface temperature. 1 - Head, 2 - Ear, 3 - Torso, 4 - Forelimb and 5 - Hindlimb; B - A representative thermogram analysed using Thermal Studio.

Surfaces like the trunk and tail were not considered for measurements as they show frequent and irregular temperature variations. Certain regions like the eyes, oral cavity, opening of the ear canal, genitals, and anus always show increased radiation when compared to the other parts of the body since they essentially reflect the internal core temperature of the animal.

Head

Male elephants showed an average head surface temperature of 28.47 ± 2.52 °C while female elephants showed an average head surface temperature of 28.73 ± 2.74 °C, exhibiting a coefficient of variation of 0.65%. It can be seen that males and females do not differ by a large margin and show similar mean temperatures. Welch's t-test conducted between the head surface temperatures of male and female elephants revealed that there was no statistically significant difference between the two sexes (P = 0.8025 at 95% CI). A combined average of 28.54 ± 2.54 °C was calculated for both male and female elephants. The head surface temperatures of the elephants are listed in Table 4, while the graphical representation of the data is pictured in Figure 6.

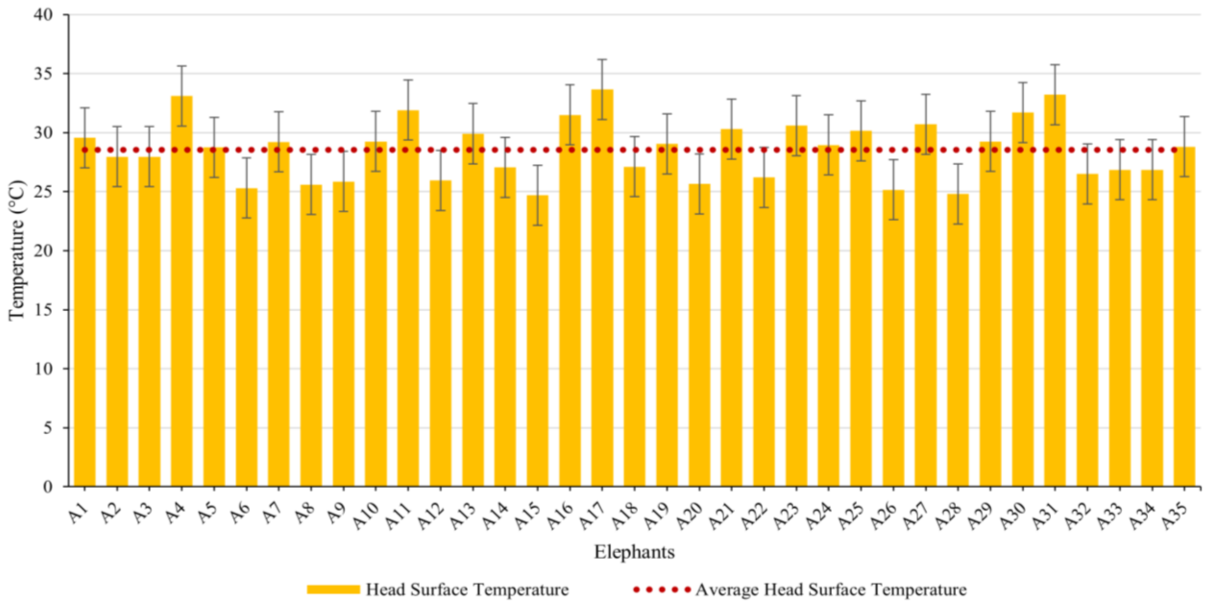


Figure 6. Variations in the temperatures of elephant head surfaces (Mean ± SD) and the average surface temperature of the head.

Ear

The temperature of the surface area "ear" refers to the thermograms captured of the anterior ear pinna. It was observed that the ears showed the most variance concerning the overall surface temperature of the elephants. This highlights that the large ear pinnae of elephants serve as the main centres of thermoregulation in elephants. Males showed an average ear surface temperature of 26.12 ± 3.32 °C while females showed a slightly lower average ear surface temperature of 25.91 ± 3.98 °C, exhibiting a coefficient of variation of 0.58%. Welch's t-test conducted between the ear surface temperatures of male and female elephants revealed that there was no statistically significant difference between the sexes (P = 0.8865 at 95% CI). A combined average of 26.07 ± 3.44 °C was calculated for both male and female elephants. The ear surface temperatures of the elephants are listed in Table 4, while the graphical representation of the data is pictured in Figure 7.

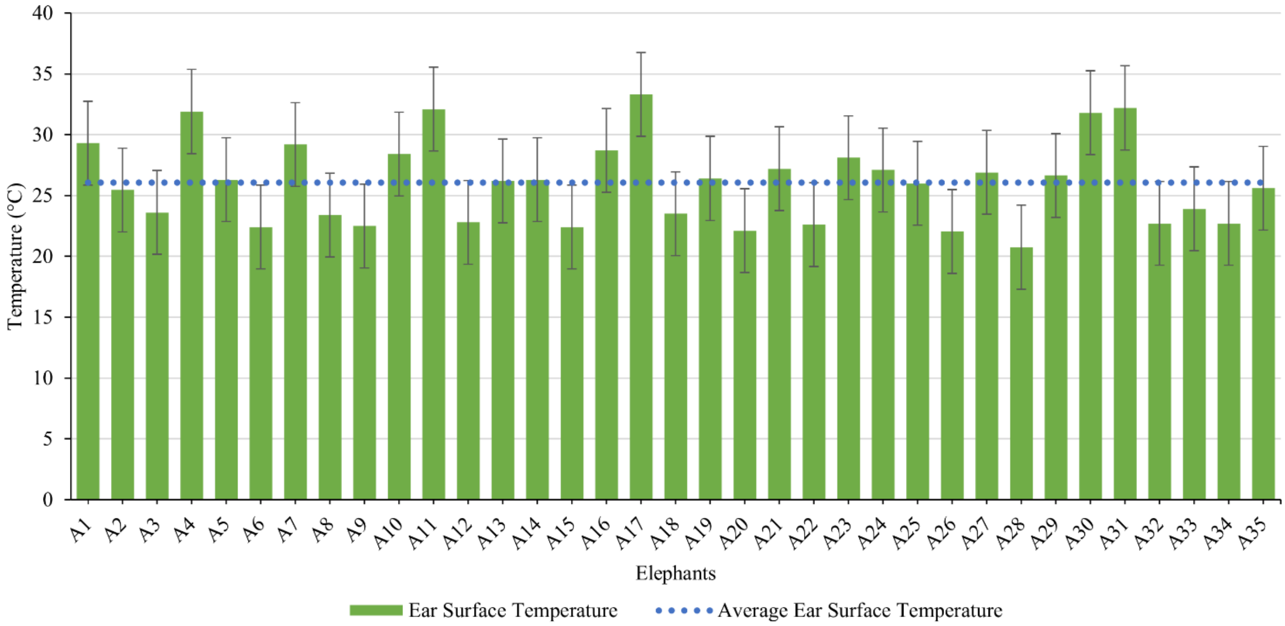


Figure 7. Variations in the temperatures of elephant ear surfaces (Mean ± SD) and the average surface temperature of the ear.

As observed from the above data, the ear is significantly cooler than the rest of the body surface and serves as the primary source of thermoregulation. Elephants were observed to flap their ears more frequently as the ambient temperature increased, showing a proportional relationship. The distal region of the ear flap was always the first to cool down, with the cooling effect spreading inwardly (towards the ear canal) as the heat is gradually dissipated from the body (Figure 8), resulting in the ear veins being prominently visible as warm bands in cooler ears (Figure 9).

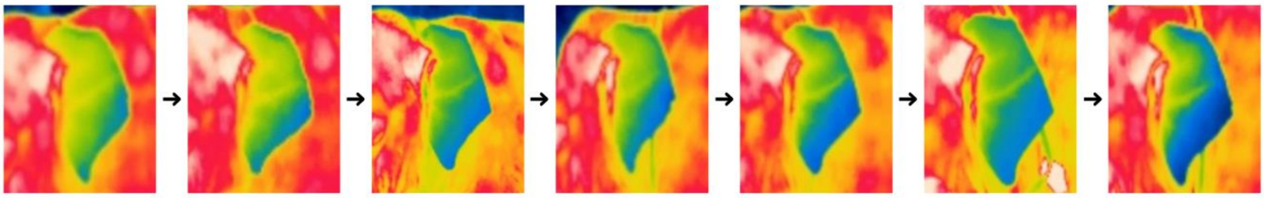


Figure 8. The left ear of a male elephant shows the progression of the thermal pattern (hotter to colder; left to right) from the distal to the proximal region of the ear pinna over 15 minutes.

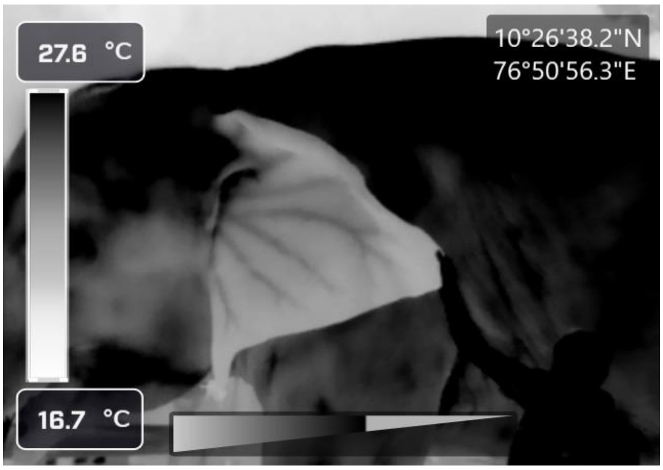


Figure 9. Thermogram of the left ear of a female elephant in the 'black hot' colour palette. Note the lateral auricular artery and its branches appearing warmer against the cool ear.

Torso

Temperature measurements across the torso show variations within individuals due to issues such as localised inflammation, wounds and uneven exposure to sunlight but care was taken to choose thermograms for analysis that exhibited uniform body temperatures. The uniformity of the surface temperatures of the torso was also influenced by thermal windows which are discussed later ("Thermal Windows").

Male elephants showed an average torso surface temperature of 27.99 ± 2.68 °C while females exhibited a slightly higher average torso surface temperature of 28.41 ± 3.08 °C, exhibiting a coefficient of variation of 1.03%. Welch's t-test conducted between the torso surface temperatures of male and female elephants revealed that there was no statistically significant difference between the sexes (P = 0.7264 at 95% CI). Studies conducted in humans have revealed that despite men having a 23% higher resting metabolic rate than women (Arciero *et al.*, 1993) women exhibit higher core temperature (0.2-0.5°C higher) than men, theorised to be the effect of hormonal variations (Baker *et al.*, 2020; Kim 1998). Similar results have also been in laboratory rodents (Sanchez-Alavez *et al.*, 2011; Yang *et al.*, 2007). It could be theorised that these female elephants exhibited slightly elevated surface torso temperatures due to similar reasons although it should be noted that there were no statistically significant differences between the sexes. A combined average of 28.1 ± 2.75 °C was calculated for both male and female elephants. The torso surface temperatures of the elephants are listed in Table 4, while the graphical representation of the data is pictured in Figure 10.

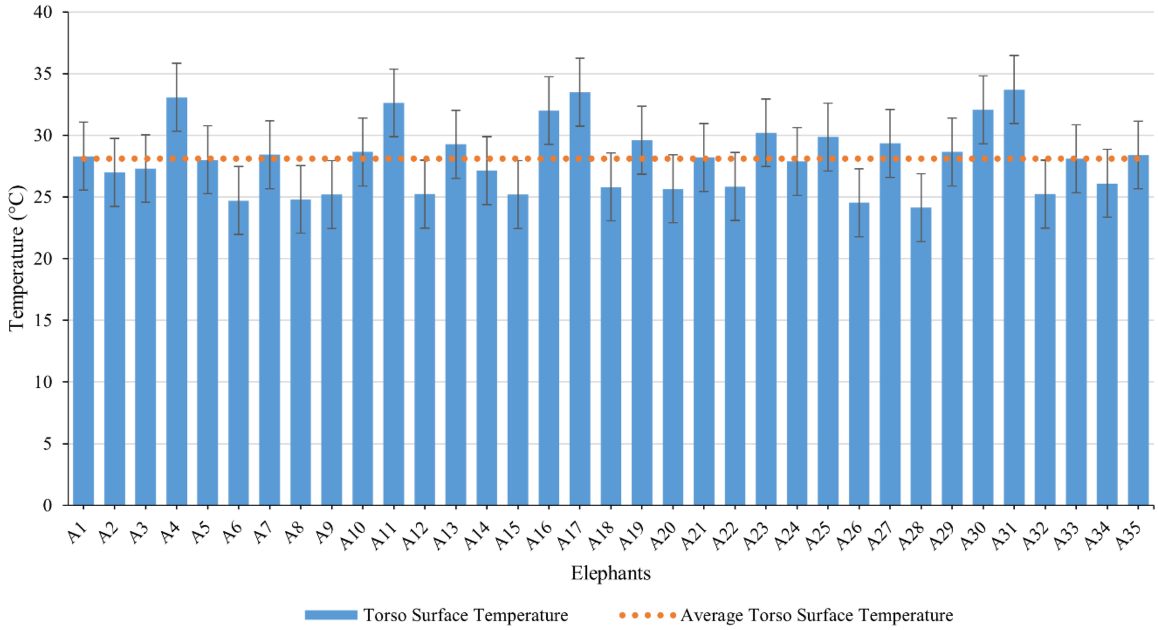


Figure 10. Variations in the temperatures of elephant torso surfaces (Mean ± SD) and the average surface temperature of the torso.

Forelimbs and Hindlimbs

When seen as a combined average for both males and females, the surface temperatures of forelimbs (27.88 ± 2.56 °C) and hindlimbs (27.54 ± 2.73 °C) did not show much variation but differences did exist between the sexes. In both forelimbs and hindlimbs, females (28.16 ± 2.96 °C and 27.91 ± 3.28 °C respectively) exhibited slightly higher surface temperatures than males (27.78 ± 2.46 °C and 27.41 ± 2.57 °C respectively), possibly exhibiting an extension of the temperature variation observed in the torso. A coefficient of variation of 0.96% and 1.26% was observed between males and females for forelimbs and hindlimbs, respectively. Welch's t-test conducted between the forelimb ($P = 0.7341$ at 95% CI) and hindlimb ($P = 0.6896$ at 95% CI) surface temperatures of male and female elephants revealed that there was no statistically significant difference between the sexes. The forelimb and hindlimb surface temperatures of the elephants are listed in Table 4 while the graphical representation of the data is pictured in Figure 11. Abnormalities in the limb surface temperatures due to physiological issues are detailed later ("Lameness and other Foot Ailments").

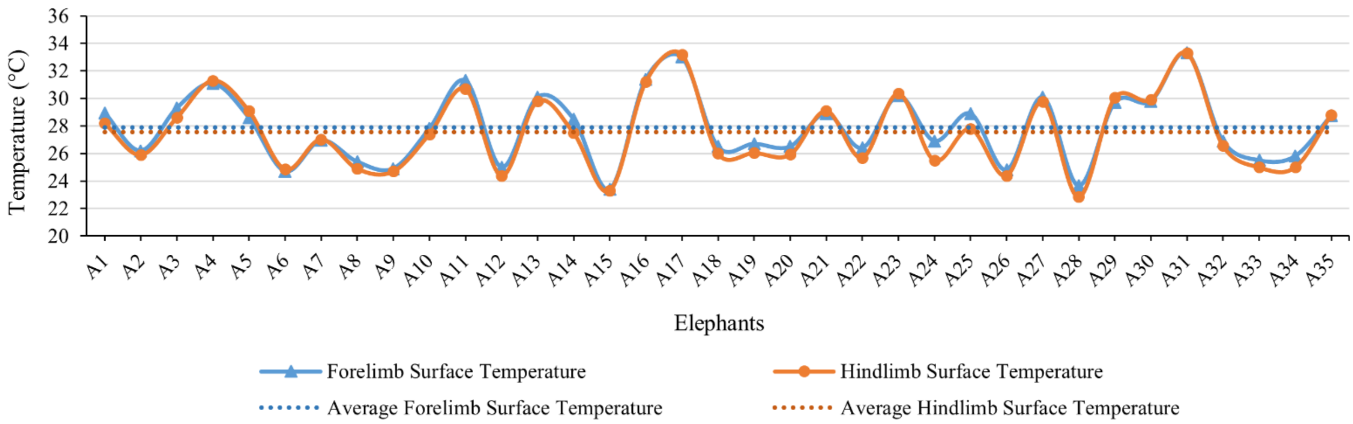
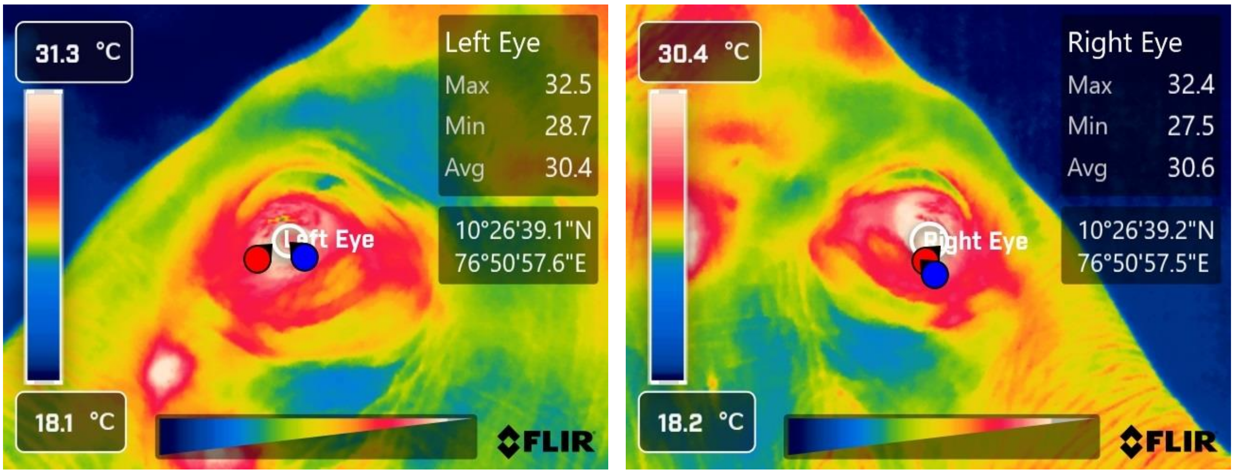


Figure 11. Variations in the forelimb and hindlimb surface temperatures of elephants and the respective average values.

Eye

Applications of IRT in ophthalmology had been well documented in human beings (Gulias-Cañizo *et al.*, 2023), while in the veterinary field, ocular temperature had been studied to assess stress levels in dogs (Budny-Walczak *et al.*, 2024), sheep (Arfuso *et al.*, 2022) and horses (Aragona *et al.*, 2024; Ijichi *et al.*, 2020). With this background, thermograms of the eyes of apparently healthy captive elephants (without any ocular disorders) of ATR were captured in close proximity to analyse temperature variations. The maximum temperature (hotspot) of the eye was accounted for to represent the right and left eye temperatures of individual male and female elephants, which are listed in Table 5.



A B

Figure 12. Representative thermograms analysed using Thermal Studio showing the left (A) and right (B) eyes of a male elephant without any ocular disorders.

It was observed that the right eye showed an average temperature of 32.61 ± 0.39 °C while the left eye showed an average temperature of 32.53 ± 0.87 °C (a coefficient of variation less than 0.17%). Paired t-test conducted between the left and right eye temperatures revealed that there was no statistically significant difference between them (P = 0.8035 at 95% CI). Generally, the temperatures fall within the ranges of 32.22-33°C for the right eye and 31.66-33.41°C for the left eye. A graphical representation of the data is pictured in Figure 13.

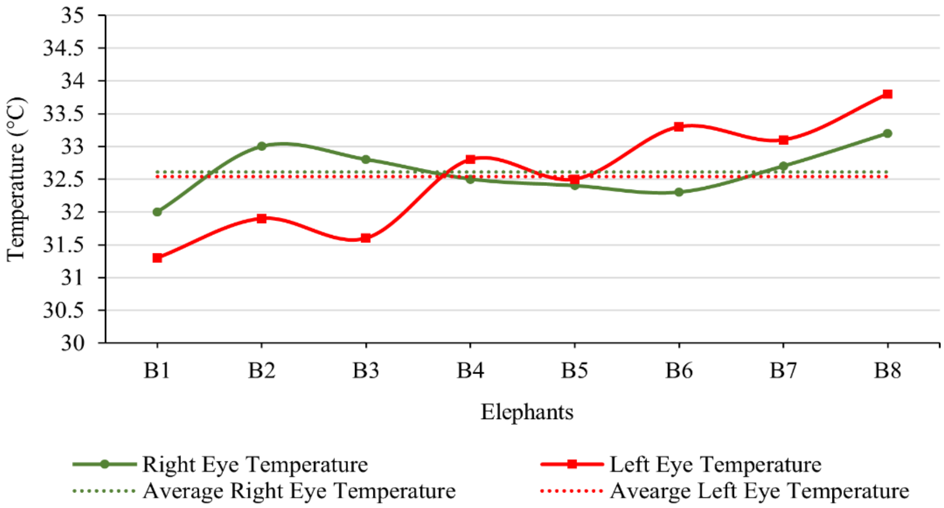
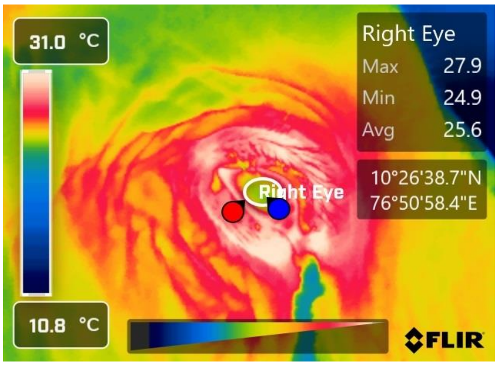


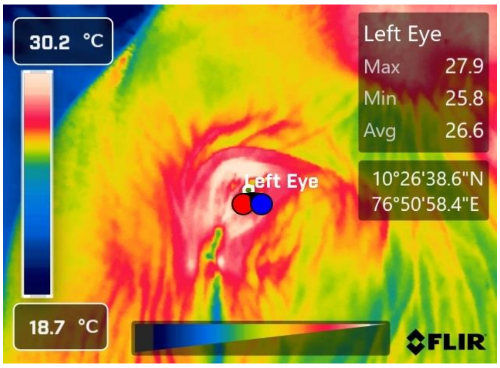
Figure 13. Variations in the right and left eye temperatures of elephants and the respective average values.

Thermograms of elephants suffering from ocular disorders were also recorded but not included in the calculations mentioned above. Some of them are listed below.



A

B

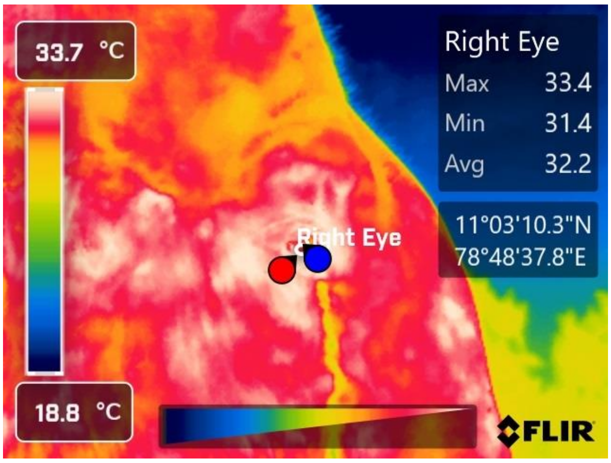


C

D

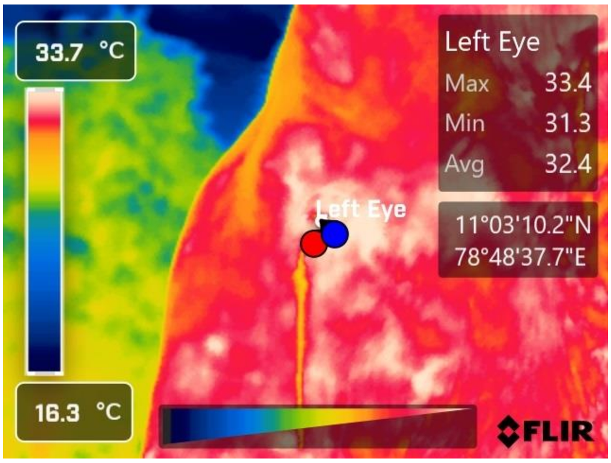
Figure 14. Elephant Sivagami: A & B - Right eye and C & D - Left eye.

Elephant Sivagami (Female, 74 years) showed decreased radiation in both eyes compared to the values calculated from healthy elephants. A maximum temperature of 27.9°C was observed in both right and left eyes, well below the calculated averages (Fig. 14). Both eyes appeared cloudy and opaque, with a white discharge exuding during the time the thermogram was recorded. The elephant keepers reported that the elephant had reduced vision in both eyes, as indicated by the low temperatures.



A

B



C

D

Figure 15. Elephant Kirathi: A & B - Right eye and C & D - Left eye.

Elephant Kirathi (Female, 64 years), at the time of capturing the thermograms, suffered from bilateral uveitis (inflammation of both eyes) and was under treatment for the same. Both eyes showed a maximum temperature of 33.4°C, which corroborated with the maximum temperature calculated previously (Fig. 15). Both eyes also exhibited whitish secretions, along with symptoms similar to conjunctivitis

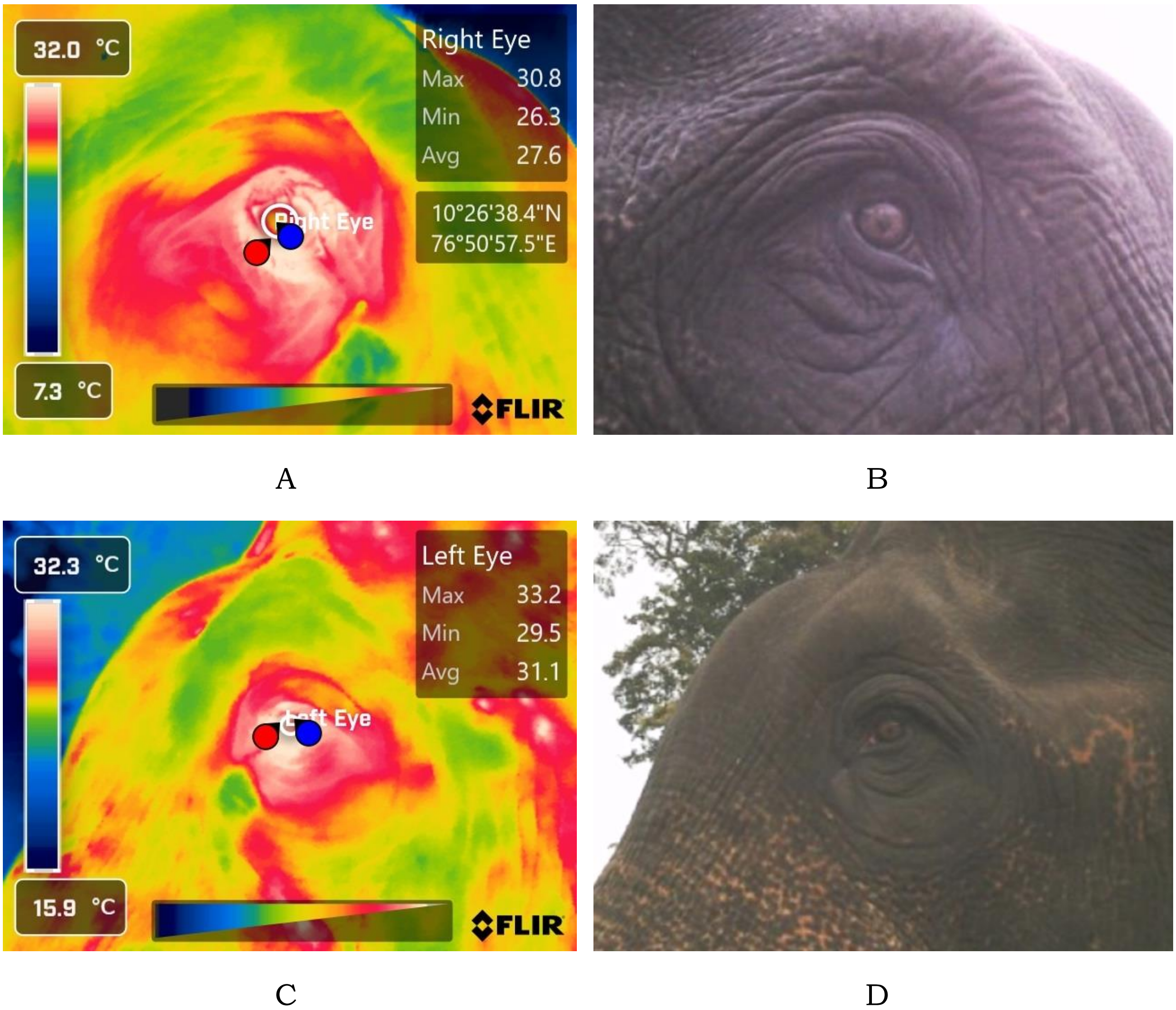
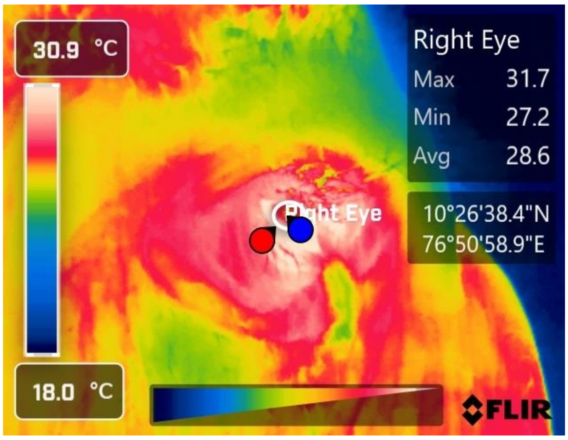


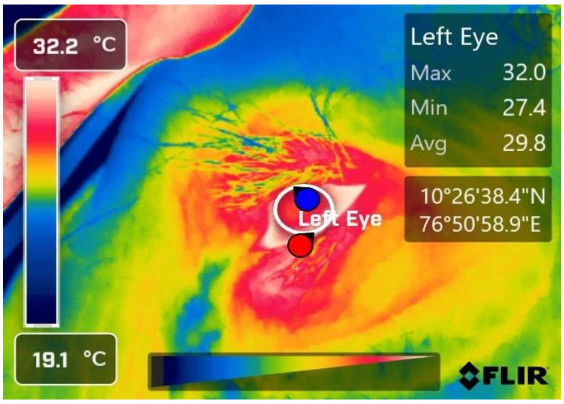
Figure 16. Elephant Chinnathambi: A & B - Right eye and C & D - Left eye.

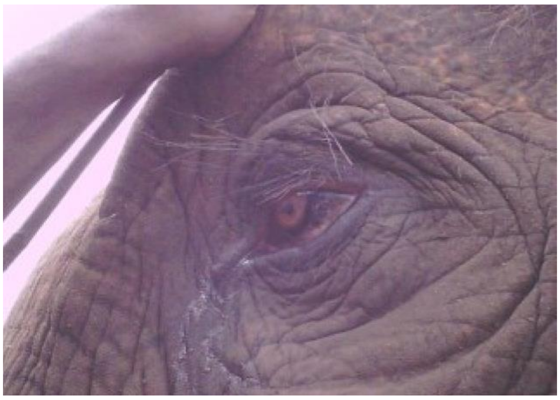
Elephant Chinnathambi (Male, 27 years) was partially blind in its right eye, as informed by the caretakers. The thermographic analysis confirmed this and showed a maximum temperature of 30.8°C in the right eye and 33.2°C in the left eye (Fig. 16). According to our reference intervals, the temperature of the right eye fell below the lower limit, while the left eye temperature was within the average range.



A

B





C

D

Figure 17. Elephant Deivanai: A & B - Right eye and C & D - Left eye.

Elephant Deivanai (Female, 15 years) had previously experienced ocular injuries due to negligence and abuse in captivity and showed significant improvement following appropriate rehabilitation and medical treatment. Both eyes functioned normally and displayed no abnormal radiation during the study (Fig. 17).

Age-wise comparison

As observed from the previously recorded surface temperatures it is clear that the male and female captive elephants of ATR and MTR do not show a significant variation between the sexes. Additionally, a comparison was done between different age groups to check whether age as a factor imparted a difference in surface temperatures. Elephants were classified according to previously stated references (Arivazhagan & Sukumar, 2008) with slight modifications to fit our availabilities. Elephants were classified into five groups – juvenile (1 to 6 years old), sub-adult (7 to 15 years old), young adult (16 to 25 years old), adult (26 to 50 years old) and senior adult (51 years old and above). Average surface temperatures of the head, ear, torso, forelimbs and hindlimbs corresponding to the five age groups are listed in Table 6 and the graphical representation of the data is illustrated in Figure 18.

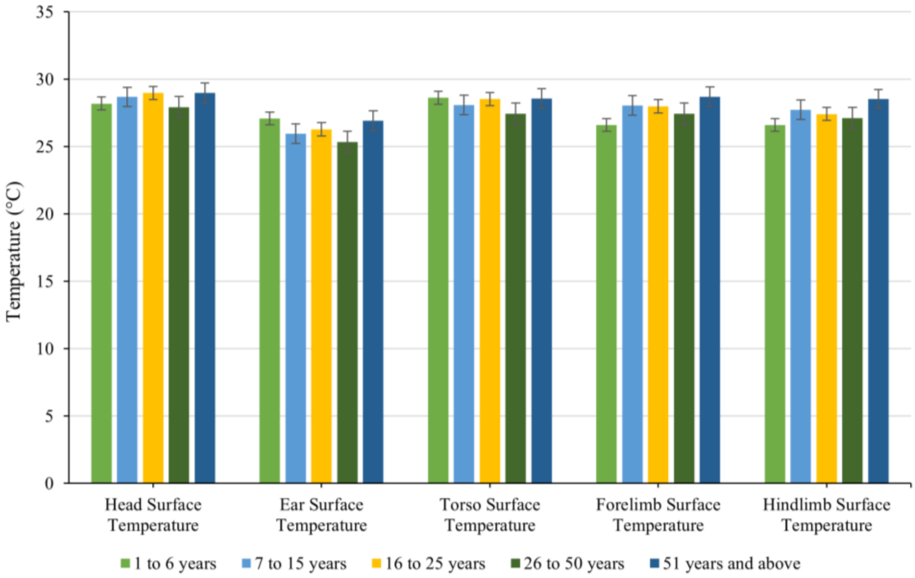


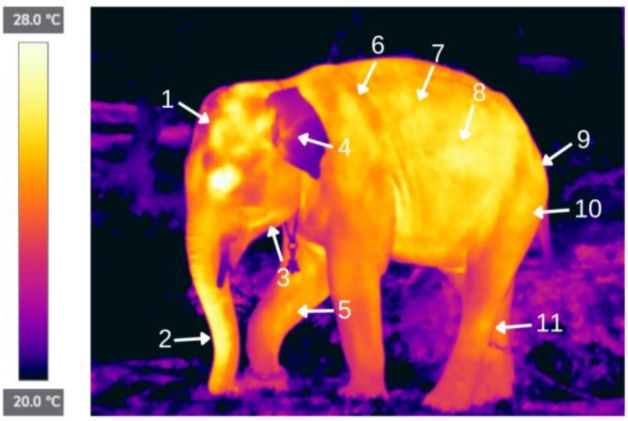
Figure 18. Average surface temperatures of different body parts corresponding to different age groups

Welch ANOVA and post hoc Dunnett's T3 multiple comparison test conducted to compare the five body parts with the five age groups revealed that there were no statistically significant differences between the two parameters. Certain studies have indicated that temperature differences exist between calves and adults (Lefebvre *et al.*, 2023; Weissenböck *et al.*, 2012) but in this current study, no significant difference could be observed, arguably due to unequal sample size in the respective age groups.

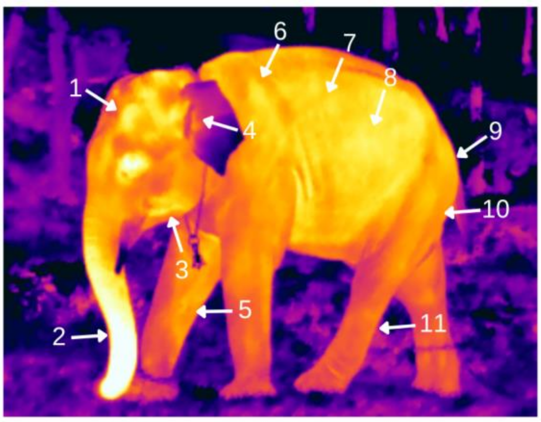
Thermal Windows

Thermal windows are defined by Weissenböck *et al.* (2010) as distinct, independent hot spots (minimum visible as a dot-shape on thermograms) on the animal's surface whose temperature differs from its surrounding regions. In this study, three healthy male elephants of varying ages from MTR were observed to assess thermal windows. Observations were made before their morning bath and 15 minutes after the bath, allowing time for the elephants to acclimate to their surroundings and facilitating the visualization of thermal windows on the thermograms. Thermal windows were chosen manually through visual inspection using the Thermal Studio software, with the utmost care taken to avoid confusing wounds/inflamed areas with thermal windows, as these conditions also exhibit localised radiation.

Elephant Raghu (7 years): Results of the paired T-test conducted for the eleven thermal windows observed before and after the bath revealed that there was no statistically significant difference between the two sets of values (P = 0.9664 at 95% CI). It has been observed that younger elephants exhibit more thermal radiation than adults (Lefebvre *et al.*, 2023; Weissenböck *et al.*, 2012). Therefore, it can be theorised that the temperature difference was not significant enough since the young animal generally exhibited higher thermal radiation. Moreover, the most variation in temperature was observed in the trunk region, which is highly vascularised and more prone to temperature fluctuations. The datasets for the thermal windows are listed in Table 7. The thermograms of the before and after bath images and the graphical representation of the data highlighting the temperature differences are pictured in Figures 19 and 20, respectively.



A



B

Figure 19. Thermal windows on elephant Raghu; A - Before bath & B - After bath.

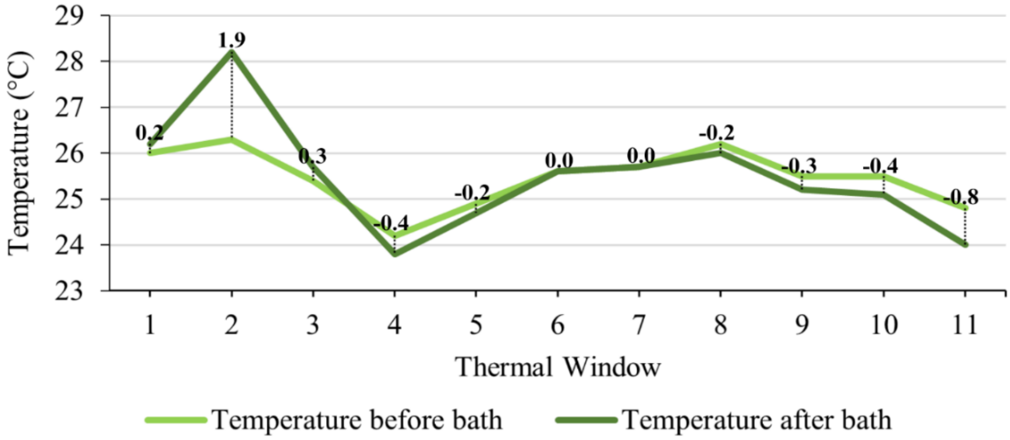


Figure 20. Variations in the thermal windows before and after bath temperatures of elephant Raghu. The differences in temperature are highlighted above the value points.

Elephant Krishna (12 years): Results of the paired T-test conducted for the seventeen thermal windows observed before and after the bath indicated a statistically significant difference between the two sets of values (P = 0.0022 at 95% CI). In contrast to the data obtained from Raghu, the current dataset exhibits greater variation, which is attributed to factors such as increased age, body surface area, and metabolic processes. The datasets for the thermal windows are listed in Table 8. The thermograms of the before and after bath images and the graphical representation of the data highlighting the temperature difference are pictured in Figures 21 and 22.

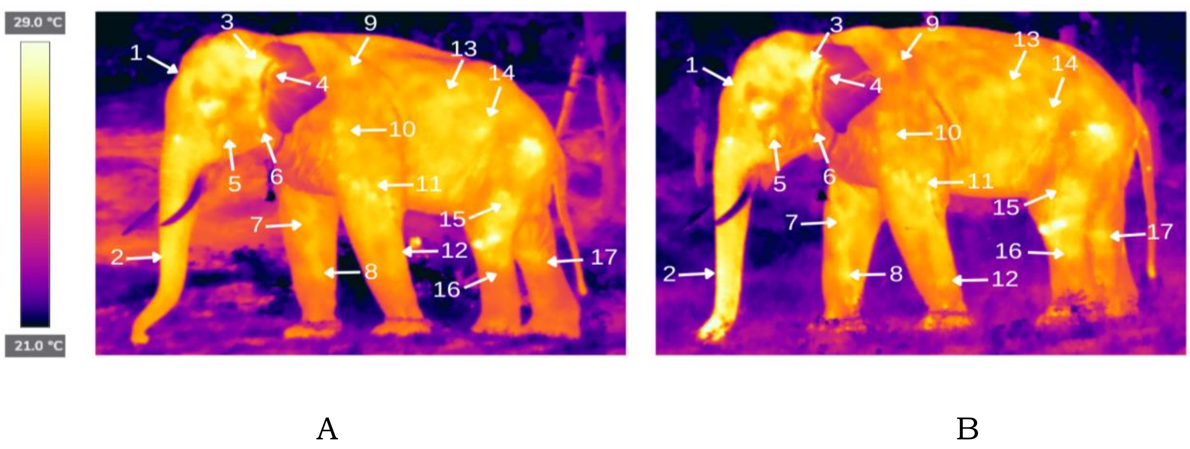


Figure 21. Thermal windows on elephant Krishna; A - Before bath & B - After bath.

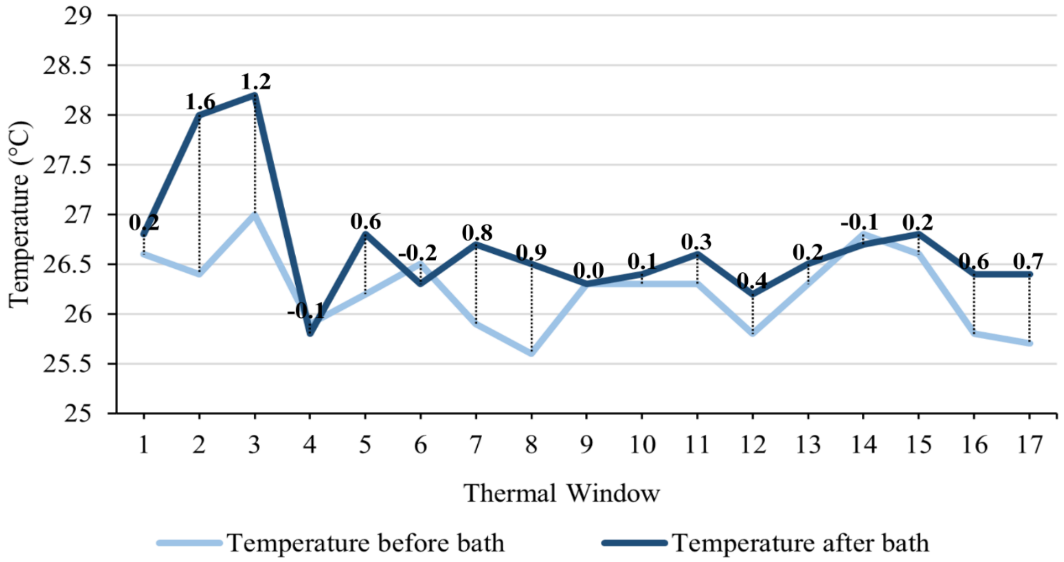
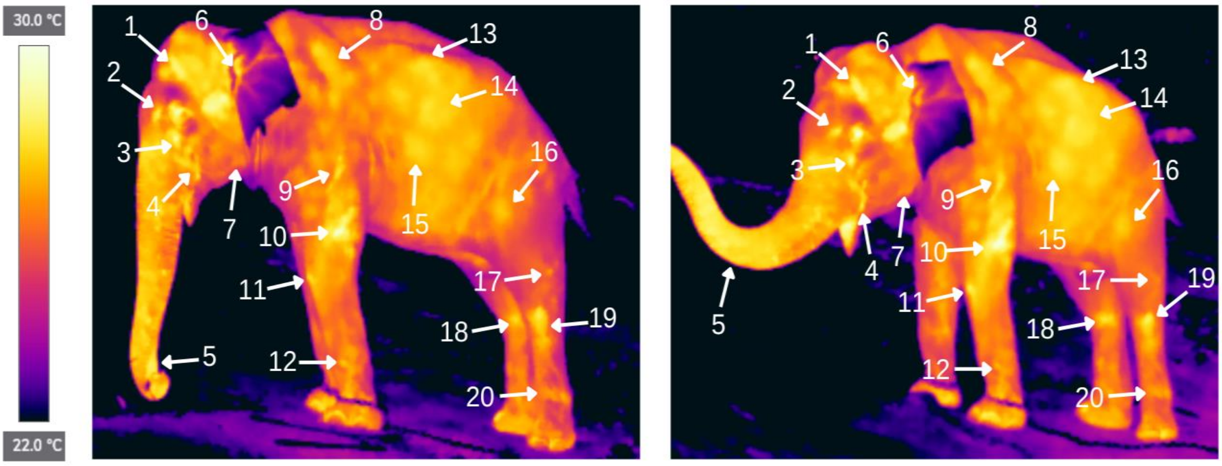


Figure 22. Variations in the thermal windows before and after bath temperatures of elephant Krishna. The differences in temperature are highlighted above the value points.

Elephant Udhayan (25 years): Results of the paired T-test conducted for the twenty thermal windows observed before and after the bath indicated a statistically significant difference between the two sets of values (P = <0.0001 at 95% CI), which is greater than that observed in Krishna. A higher number of thermal patterns was observed in Udhayan than in Krishna and Raghu, which matches with the observations made by Lefebvre *et al.* (2023), where it was observed that more thermal windows were recorded in older elephants. It is also worth noting that Udhayan was in the initial stages of musth (no behavioural changes at the time of recording the thermogram), wherein the metabolic activity, hormonal changes, and associated thermoregulatory behaviours (LaDue, 2022) could influence the thermal windows. The datasets for the thermal windows are listed in Table 9. The thermograms of the before and after bath images and the graphical representation of the data highlighting the temperature differences are pictured in Figures 23 and 24.



A B

Figure 23. Thermal windows on elephant Udhayan; A - Before bath & B - After bath.

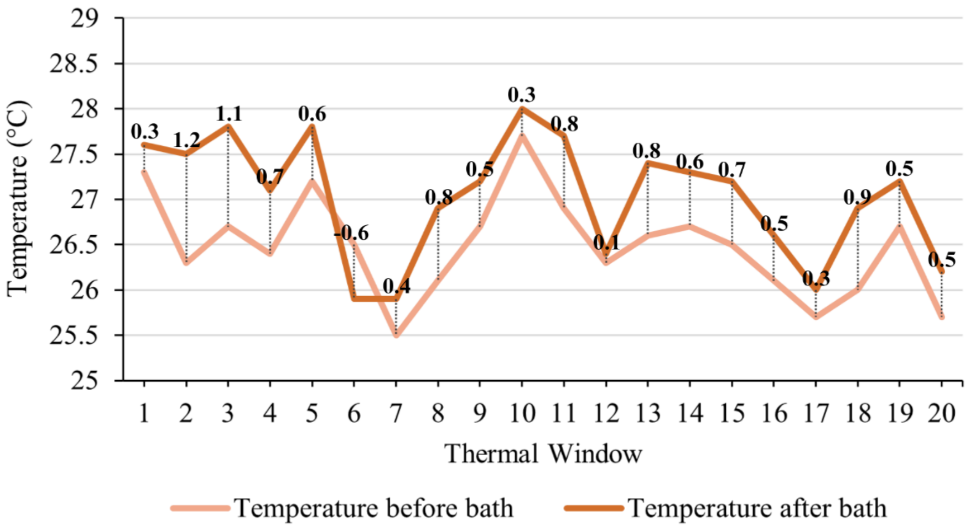


Figure 24. Variations in the thermal windows before and after bath temperatures of elephant Udhayan. The differences in temperature are highlighted above the value points.

Effect of Ambient Temperature on Thermographic Analysis

One major issue faced while recording thermograms was avoiding the interference of ambient temperature, primarily sunlight, on the animal's surface. Since IRT captures the radiation emitted by an object, the surface temperature may be skewed when an animal stands under direct or intense sunlight. Consequently, the resulting thermogram may not accurately represent the animal's actual thermal patterns. Most of the infrared thermographic studies cited in this study were conducted in places that experience colder ambient temperatures than rest of Tamil Nadu. In those outdoor conditions, the effect of external forces like sunlight-induced heating is reduced, and the thermograms more accurately capture the thermal patterns of the animal.

To address this issue, the thermograms of the elephants were consistently captured early in the mornings (6 to 9 A.M.) and late in the evenings (4 to 7 P.M.). Wherever possible, the elephants were positioned under the shade of enclosures, buildings or trees and given a few minutes to acclimate to their surroundings before capturing the thermogram. Thermograms recorded under sub-optimal conditions were not accounted for when analysing the normal thermography of elephants. The effects of high ambient temperature in IRT are illustrated in the results obtained from the thermograms recorded in ERC during January and May 2024 are presented below.

During the study, Tiruchirapalli experienced average temperatures ranging from 25°C to 43°C. This was significantly higher compared to ATR (15°C-22°C) and MTR (19°C-27°C), which are hill stations with consistently cool weather throughout the year. The thermograms that were captured in ERC to study the normal thermography of the elephants were found to be biased due to the high ambient temperature. This bias caused the images of the elephants to appear "cooler" in comparison to their habitat (Fig. 25).

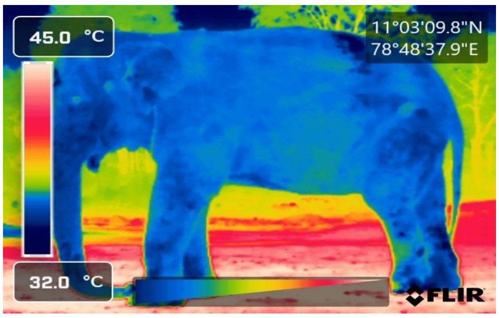


Figure 25. Thermogram of an elephant captured at ERC in May 2024. Note the temperature scale and the high ambient temperature of the surroundings.

ERC houses only female elephants, and the surface temperature values calculated for these elephants appeared higher than the average surface temperatures of female elephants from ATR and MTR. When assessing the average surface temperatures of the head, ear, torso, forelimb and hindlimb of the eleven elephants of ERC, the calculated results amounted to 32.26 ± 2.48 °C, 31.46 ± 2.92 °C, 32.39 ± 2.72 °C, 32.20 ± 2.57 °C, and 31.95 ± 2.54 °C respectively (Table 10). These results indicated an increase of 3.5°C to 5.5°C from the averages calculated from the female elephants of ATR and MTR. The graphical representation of the data highlighting the difference in the surface temperatures of elephants housed at ERC and ATR & MTR are pictured in Figures 26.

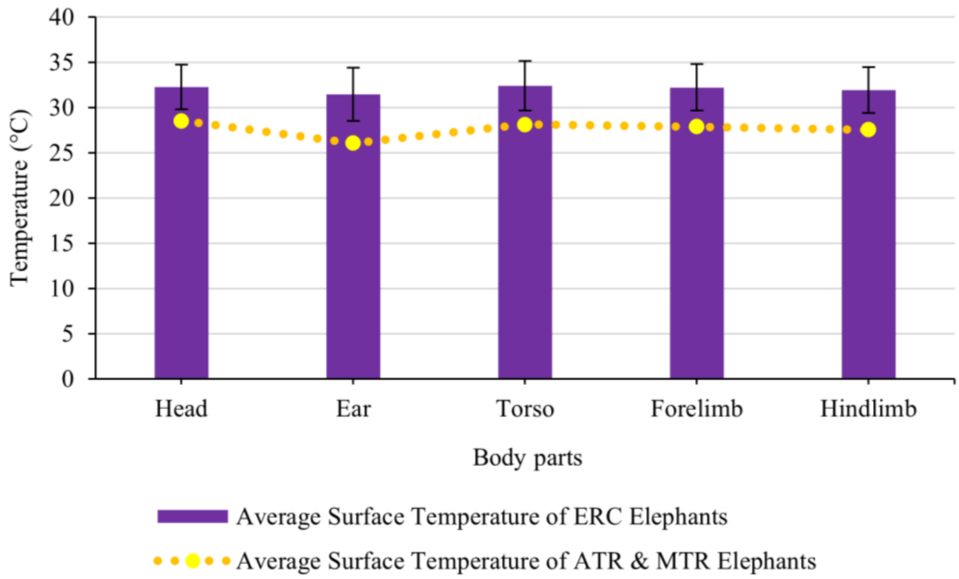


Figure 26. Variation in the average surface temperatures of elephants housed at ERC (mean ± SD) and ATR & MTR.

A key factor that can affect a thermogram's accuracy is a phenomenon known as "thermal loading". This occurs when surrounding areas/objects absorb and retain the sun's radiation much longer than usual, leading to high thermal contrast when capturing the thermogram. Such thermal loading can introduce a bias, positive or negative, when assessing the condition of our subject (Garner *et al.*, 1995). The thermal camera is programmed to automatically set and adjust the temperature scale of the thermogram based on the total radiation the camera detects in the frame. If the scale was to be adjusted to the temperature ranges seen in ATR and MTR (~30°C to 20°C), the surroundings were seen to oversaturate the image and affect the visual interpretation of the elephants' temperature readouts (Fig. 27).

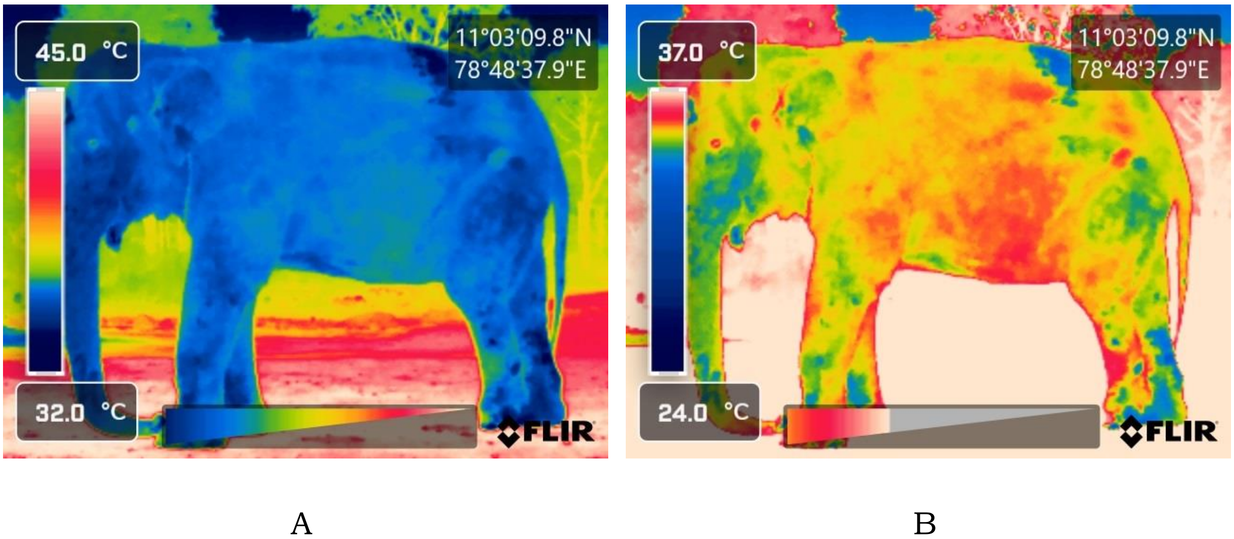
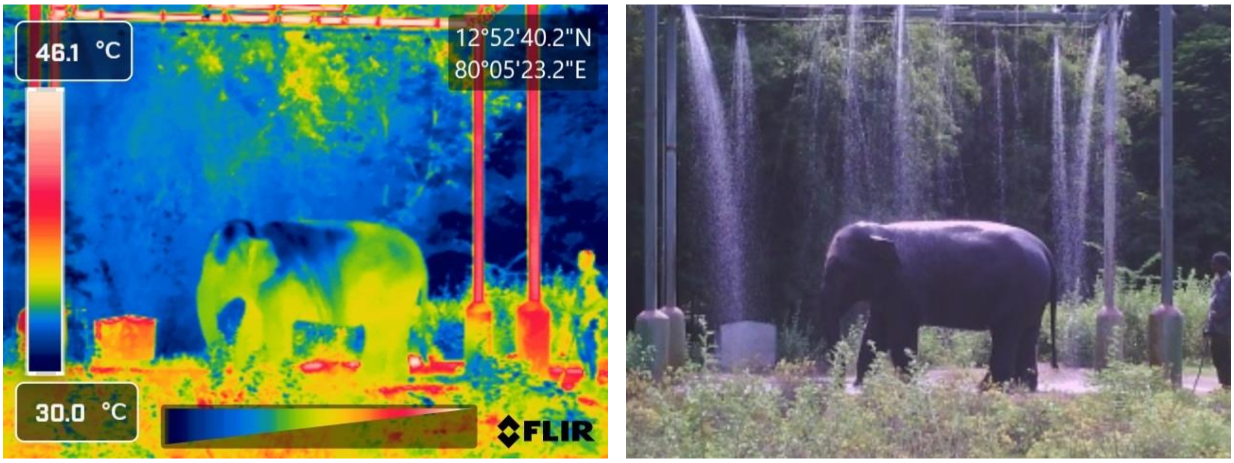


Figure 27. Thermograms of an elephant from ERC; A - temperature scale set by the instrument automatically based on the surroundings, B - temperature scale manually adjusted to match the thermograms captured in ATR and MTR.

Hence, a thermographer must be familiar with the anatomy and physiology of the animal, and also consider the ambient temperature and the environment in which the animal is situated. The average surface temperatures measured for the elephants of ERC should not be viewed as erroneous or indicative of problems with their thermoregulation. Although these temperatures differ from those of the elephants at ATR and MTR, they accurately reflect the environmental conditions in which the elephants of ERC reside in. Interpretation of such thermograms should be done with consideration of these perceived limitations.

Like sunlight, rainfall is also a significant interfering factor, primarily due to the instrument's lack of waterproofing. Secondly, rainfall on the elephants' skin reduces the surface temperature (Fig. 28), rendering the readings unreliable. Hence, care was taken to ensure that the elephants were dry before recording the thermogram, particularly after an elephant had been bathed.



A B

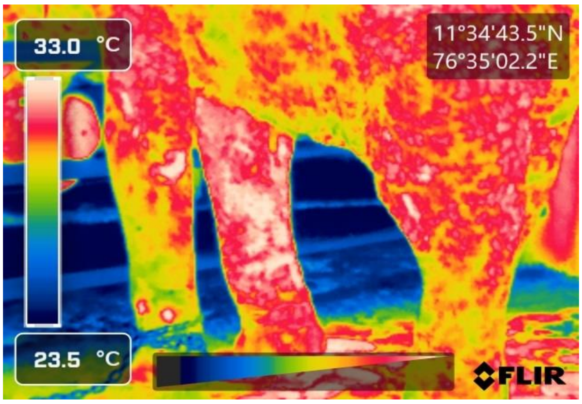
Figure 28. A female elephant at AAZP bathing in the shower. Note the temperature difference in the areas showered with water.

B) Identifying surface injuries and foot ailments

Despite their thick skin and large size, pachyderms like elephants still need regular skin care and hygiene. In the wild, elephants care for their skin by regularly bathing, coating it with dust and mud, and rubbing off dry/dead skin against trees and rocks. In captivity, their skin needs similar attention, which can be provided through human interaction (regular bathing and scrubbing) or by offering environmental conditions (foliage and substrates to brush against) that mimic their natural habitats (Fowler & Mikota, 2008). However, despite routine care, captive elephants are more prone to infections and injuries due to a myriad of reasons, such as restricted movement and grazing, insufficient exercise, infighting, prolonged standing on hard surfaces, improper animal handling, and exposure to contaminants from the substrate (Ghimire *et al.*, 2022; Miller *et al.*, 2015). To identify such issues, IRT was employed on the captive elephants of ATR, MTR and ERC.

Inflammation

Inflammation is defined as the body's protective response to harmful stimuli like pathogens, damaged cells, or irritants. It involves immune cells and chemical mediators to remove the cause of injury, clear out damaged tissues, and initiate repair. Classic signs include redness, heat, swelling, pain, and loss of function. Vasodilation and increased permeability of the blood vessels at the site of inflammation are responsible for the heating and swelling of the region (Kasper *et al.*, 2015). IRT is capable of identifying these changes.

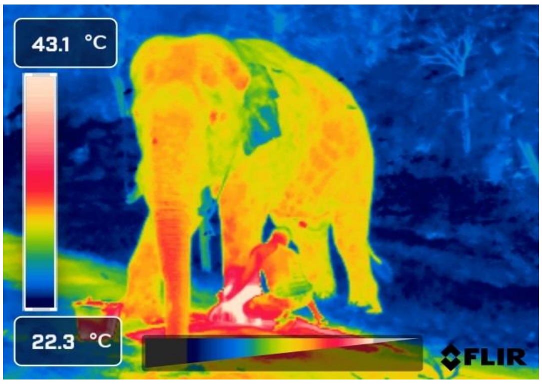


A

B

Figure 29. Elephant Masini: Right forelimb showing inflammation.

Elephant Masini (Female, 16 years) has consistent issues with its right forelimb due to previous abuse and mistreatment. Visually, the right leg looked swollen compared to the left leg. On the thermograms, the inflamed right leg showed an average surface temperature of 31.45°C, while the left leg showed an average surface temperature of 30.45°C (Fig. 29).



A

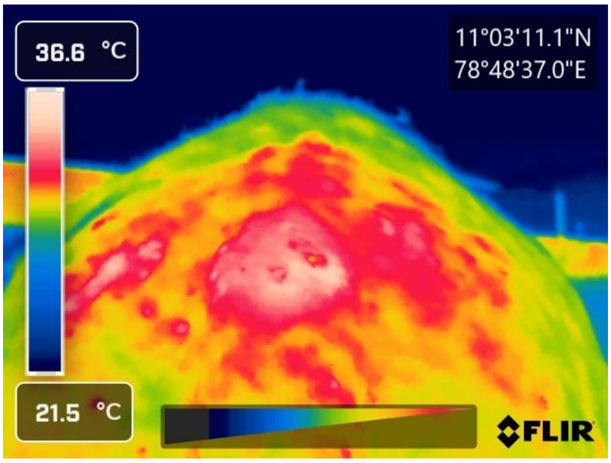
B

Figure 30. Elephant Cherambadi Shankar: hot compress being applied to the inflamed limbs by the caretaker.

Elephant Cherambadi Shankar (Male, 37 years) suffered from diarrhoea and dehydration during the study, resulting in swollen limbs (Figure 30). The elephant keeper reported that, along with medication, the elephant's legs were treated with hot compresses in a salt solution as instructed by the veterinarian.

Wounds

A wound is a broad term for any injury where the skin is torn, cut, or punctured. Wound healing also has an inflammatory phase, during which the blood vessels vasodilate and edematous fluid leaks into the tissue, causing swelling. Both phenomena cause a localised increase in radiation capable of being visualised through IRT.



A B

Figure 31. Elephant Malachi; wound at the base of tail region.

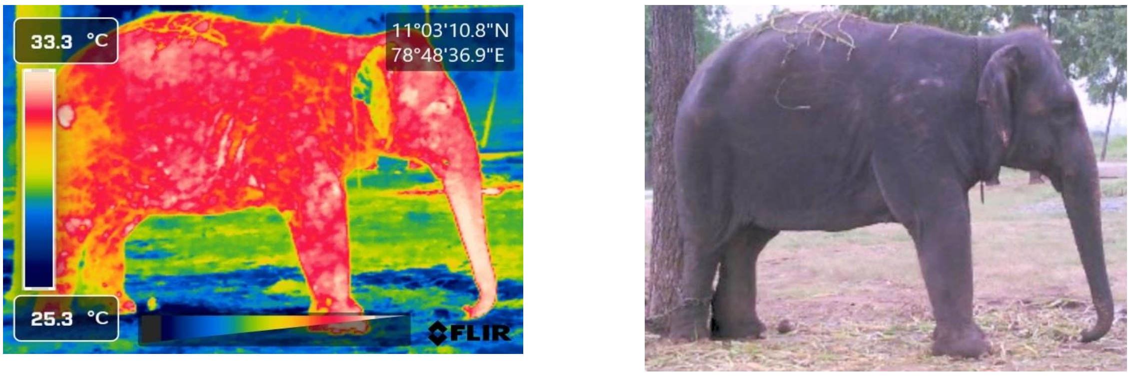
Elephant Malachi (Female, 38 years) had a group of small injuries around its hindquarters near the base of the tail. This injured region exhibited an average surface temperature of 33.5°C while the unaffected areas showed 30.8°C (Fig. 31).

A B

Figure 32. Elephant Kirathi: wound at the base of tail.

Elephant Kirathi had a wound on the base of its tail. The wound showed an average surface temperature of 32.9°C, while the surrounding areas showed 31°C (Fig. 32) at the time of recording the thermogram

A B



C D

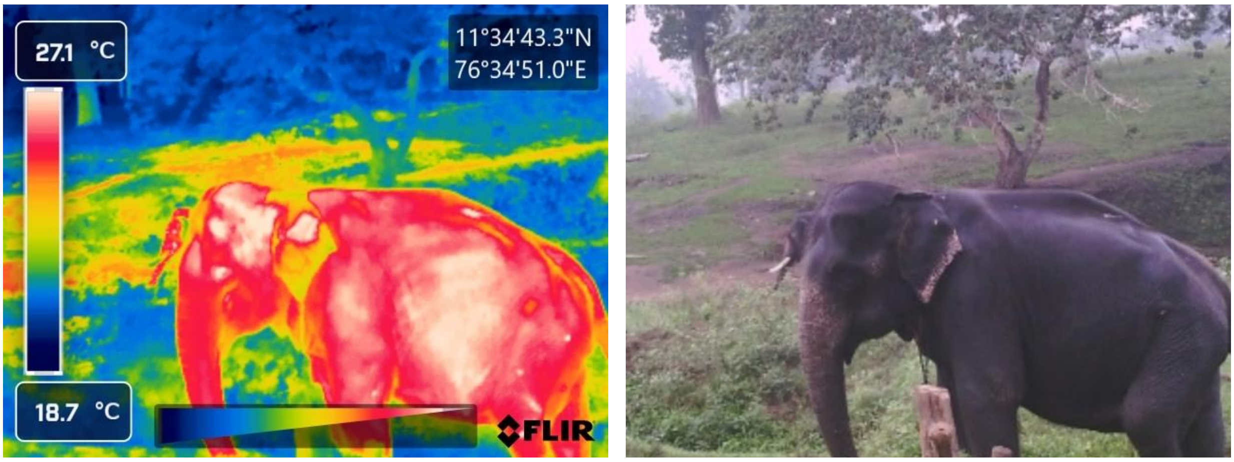
Figure 33. Elephant Rupali: pressure sores on the left (A & B) and right (C & D) hindquarters of the body.

Pressure sores (also known as pressure ulcers, bedsores, or decubitus ulcers) are injuries that affect the skin and the underlying tissue due to sustained pressure. These sores commonly develop on body parts that support weight and remain in contact with a surface for long duration, such as the heels, elbows, hips, and tailbone (Bhattacharya & Mishra, 2015). In Figure 33, elephant Rupali (Female, 23 years) exhibited increased radiation from two regions, particularly on both its left and right hindquarters. Both regions corresponded with the area where the hip bone and knee come in contact with the ground while the animal rises and lies down. The pressure sores exhibited average surface temperatures in the range of 34.4°C to 32.1°C while the neighbouring regions exhibited average surface temperatures in the range of 31.4°C to 30.5°C.

Abscess

An abscess is a localised collection of pus within body tissues, typically caused by a bacterial infection. The immune response to infection accumulates dead tissue, bacteria, and white blood cells, forming pus. Abscesses can develop in various parts of the body, including the skin, gums, and internal organs, and are characterised by swelling, redness, warmth, and tenderness. Treatment usually involves draining the abscess and may include antibiotics to clear the infection (Bowman, 2022).

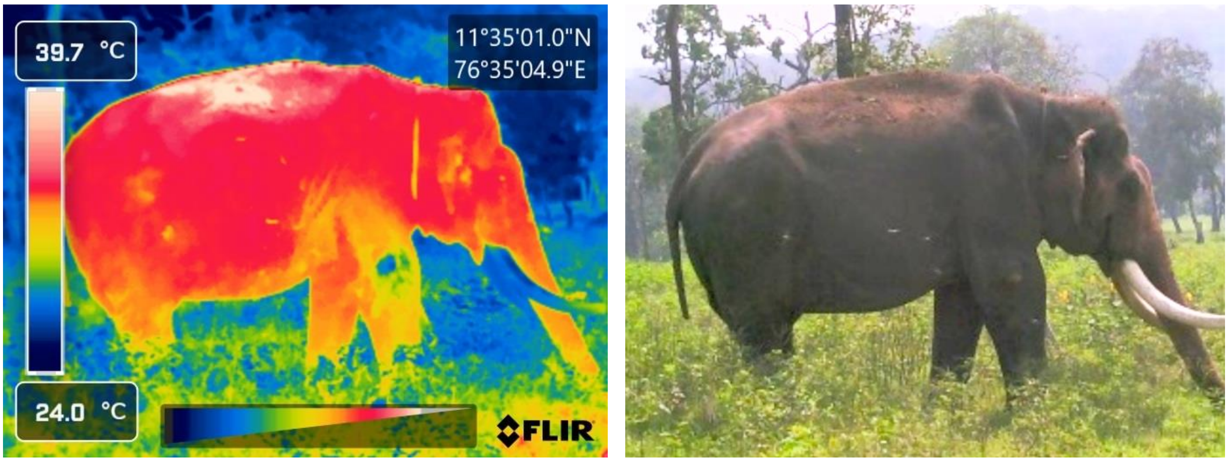
Abscesses go through a 'before' and 'after' ripe stage of development. Following an infection, the area becomes inflamed, and a pocket of pus begins to form. Upon reaching full maturity (ripe condition), the abscess accumulates more pus and dead tissue, indicating that it is ready to be drained. After drainage, the abscess loses volume, inflammation reduces, and the new tissue begins to form (Baiu & Melendez, 2018). Thermograms of surface-level abscesses before and after ripening are pictured below.



A B

Figure 34. Elephant Kamatchi: ear abscess at ripe stage.

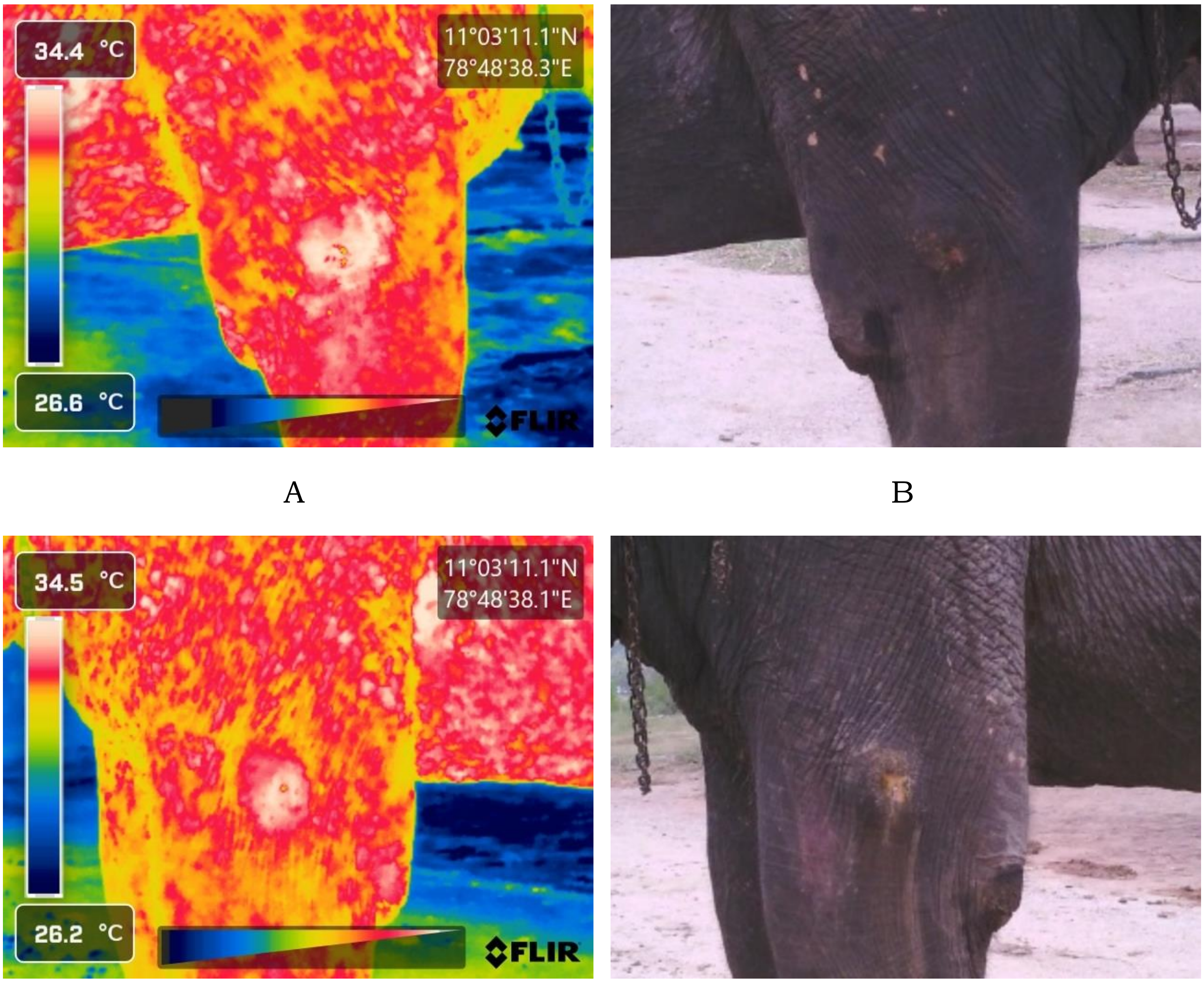
Elephant Kamatchi (Female, 64 years) showed an abscess in its left anterior ear pinna. Visually, the abscess looked fully swollen (ripe) and ready to be drained. The abscess showed a maximum surface temperature of 27.57°C, while the surrounding areas did not exceed 25°C (Figure 34). At the time of capturing the thermogram, the animal was observed scratching that region with a stick and eventually breaking the abscess later on.



A B

Figure 35. Elephant Anna: broken abscess in the right forelimb.

Elephant Anna (Male, 65 years) had an abscess on its right forelimb. The abscess had been undergoing treatment for an extended period of time, and at the time the thermogram was captured, it had recently been drained (Figure 35). The drained abscess showed a lower temperature (30°C) than its adjoining areas (32.8°C) due to the presence of pus and other exudate fluid that lowered the surface temperature.



C D

Figure 36. Elephant Indira: abscess on the right (A & B) and left (C & D) forelimb.

Elephant Indira (Female, 62 years) had abscesses on both the right and left forelimbs around the elbow region. The abscesses showed an average surface temperature in the range of 33.6°C to 34.8°C while the unaffected areas showed temperatures in the range of 31.5°C to 33.6°C (Fig. 36).

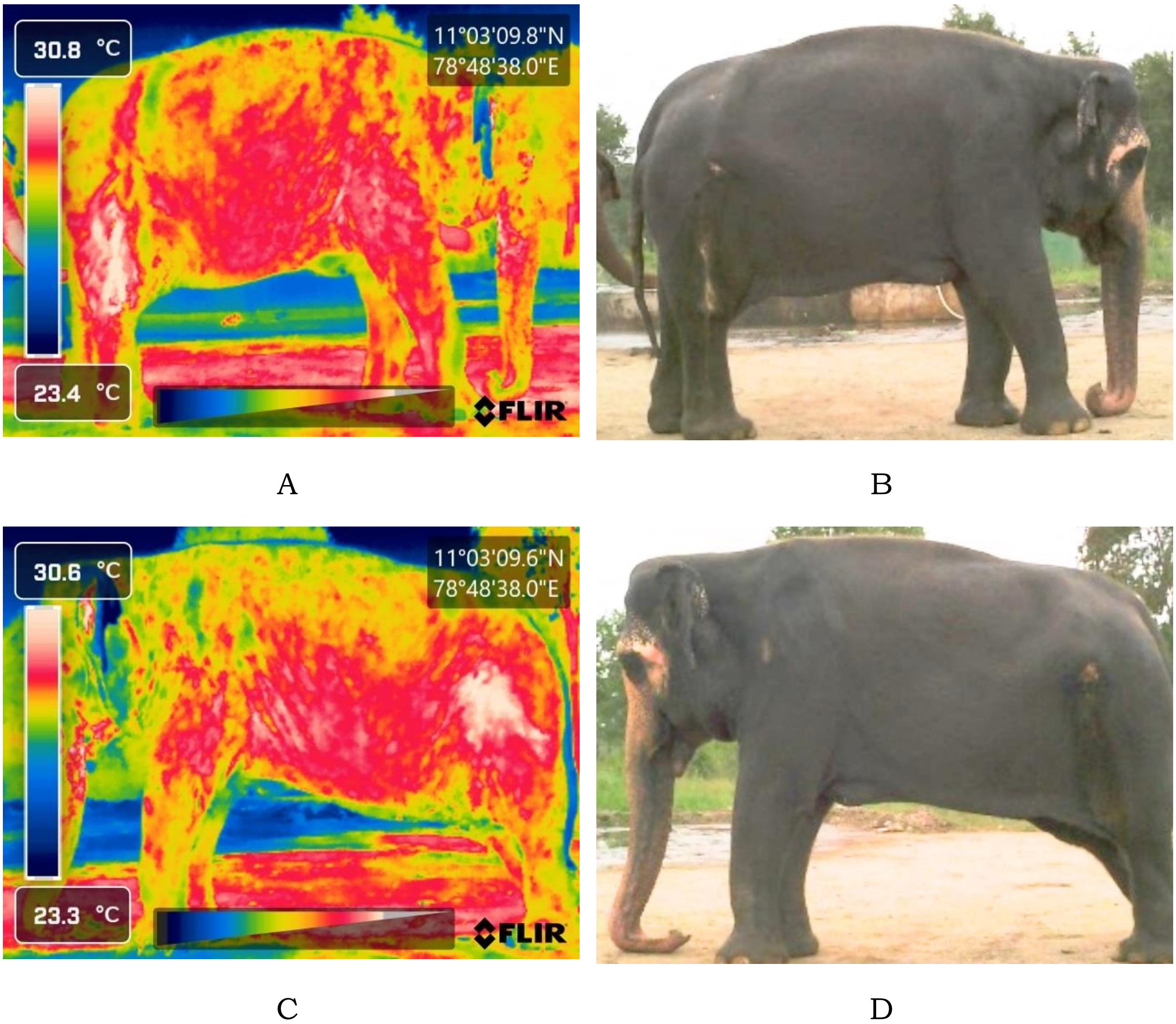
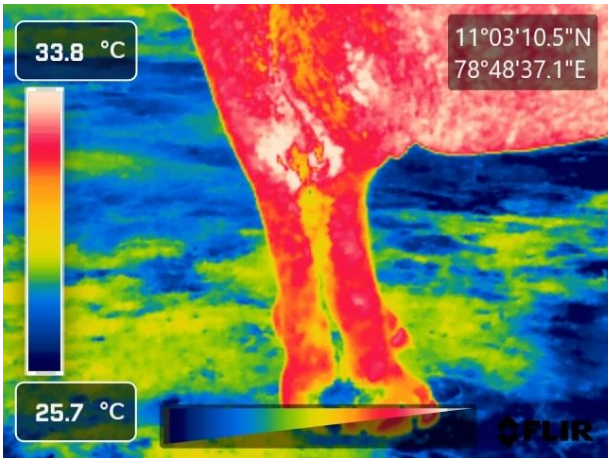
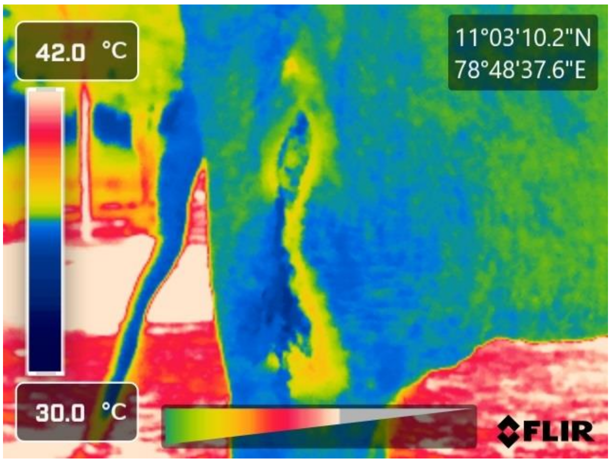


Figure 37. Elephant Santhiya: thermograms of the profile show the extent of radiation created by the abscess.

Elephant Santhiya (Female, 48 years) suffered from abscesses on both its left and right hindquarters, with the one on its right hindlimb more extensive and severe. The irradiated regions on the thermograms show the extent of the area affected by the abscesses (Fig. 37).



A B

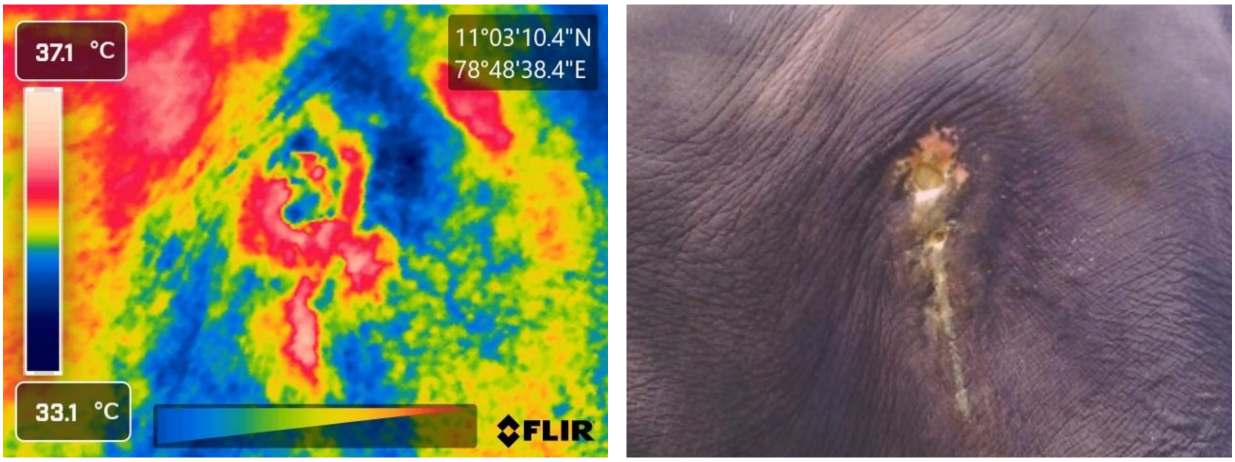


C D

Figure 38. Elephant Santhiya: Progression of the healing of the abscess on the right hindquarters. Images captured on January 2024 (A & B) and May 2024 (C & D).

Figures 38A and 38B show thermograms of the abscess on the right hindquarters captured in January 2024. The abscess had been regularly drained and cleaned by the caretakers but was still leaking pus-like fluid. The wounds were not healed, revealing exposed muscle underneath.

Figures 38C and 38D show thermograms captured in May 2024. Visually, the wounds appeared to be more healed compared to before, with no exudate fluid present. The wounds were regularly dressed and medicated by the caretakers under the supervision of the veterinarian. During the first visit, the wounds exhibited an average surface temperature of 32.7°C. In contrast, during the latter visit, the temperature increased to 36.7°C, indicating the clearing of pus and the progression of wound healing.



A B

Figure 39. Elephant Santhiya: abscess in the left hindquarters.

Figure 39 shows the thermogram captured of the abscess on the left hindquarters. This abscess was smaller than the one on the other side but still appeared exposed. The thermogram showed that the exposed area in the middle appeared "cold" and exhibited 35.3°C, compared to the surrounding inflamed region, which showed 35.68°C. These temperatures were comparable to the 35.15°C exhibited by the surrounding unaffected regions, indicating that the healing process was still underway.

Lameness and other Foot Ailments

In the wild, elephants' foot pads cushion their steps and protect their sensitive foot structures from punctures. These foot pads are generally thick and wrinkled on the bottom. In captivity, the condition of their feet and the required foot care may vary. Captive elephants typically do not need as thick a pad for protection from environmental hazards. However, inadequate activity, unsuitable substrates, or irregular foot care can cause the footpads and nails to become overgrown, wounded, or infected.

A B

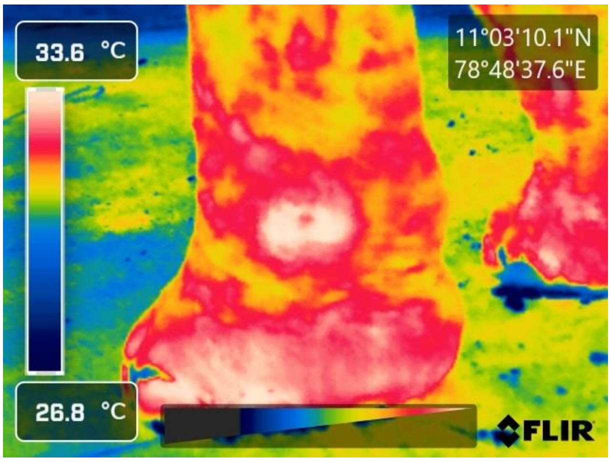
Figure 40. Elephant Gomathi: lameness observed in the right hindlimb.

Elephant Gomathi (Female, 70 years) was observed by its caretakers to exhibit an uneven gait and did not distribute its weight evenly across the hindlimbs. The right hindlimb appeared more withered than the left hindlimb (Figure 40). Corroborating this, the thermogram of the right hindlimb exhibited a lower temperature (29.1°C) than the left hindlimb (30.1°C), indicating a presumed decline in blood flow.

A B

Figure 41. Elephant Gomathi: nail crack observed in the left forelimb.

Gomathi also had a cracked nail in its left forelimb. The cracked region exhibited an average temperature of 35.5°C while the other healthy nails exhibited an average temperature of 36.06°C. The rest of the foot did not appear inflamed and showed an average surface temperature of 34.2°C (Fig. 41).



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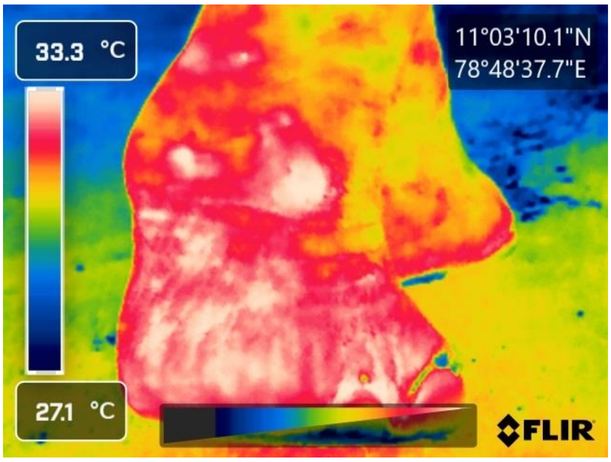


C

D

Figure 42. Elephant Kirathi: foot abscesses in the left (A & B) and right (C & D) hindlimbs.

Elephant Kirathi suffered from foot abscess on both the left and right hindlimbs. The infected areas exhibited a maximum temperature in the range of 33°C to 34°C while the unaffected areas upwards exhibited 31°C to 32°C (Fig. 42). The areas below the abscess also appeared inflamed and showed elevated temperatures, ranging from 31°C to 33°C.

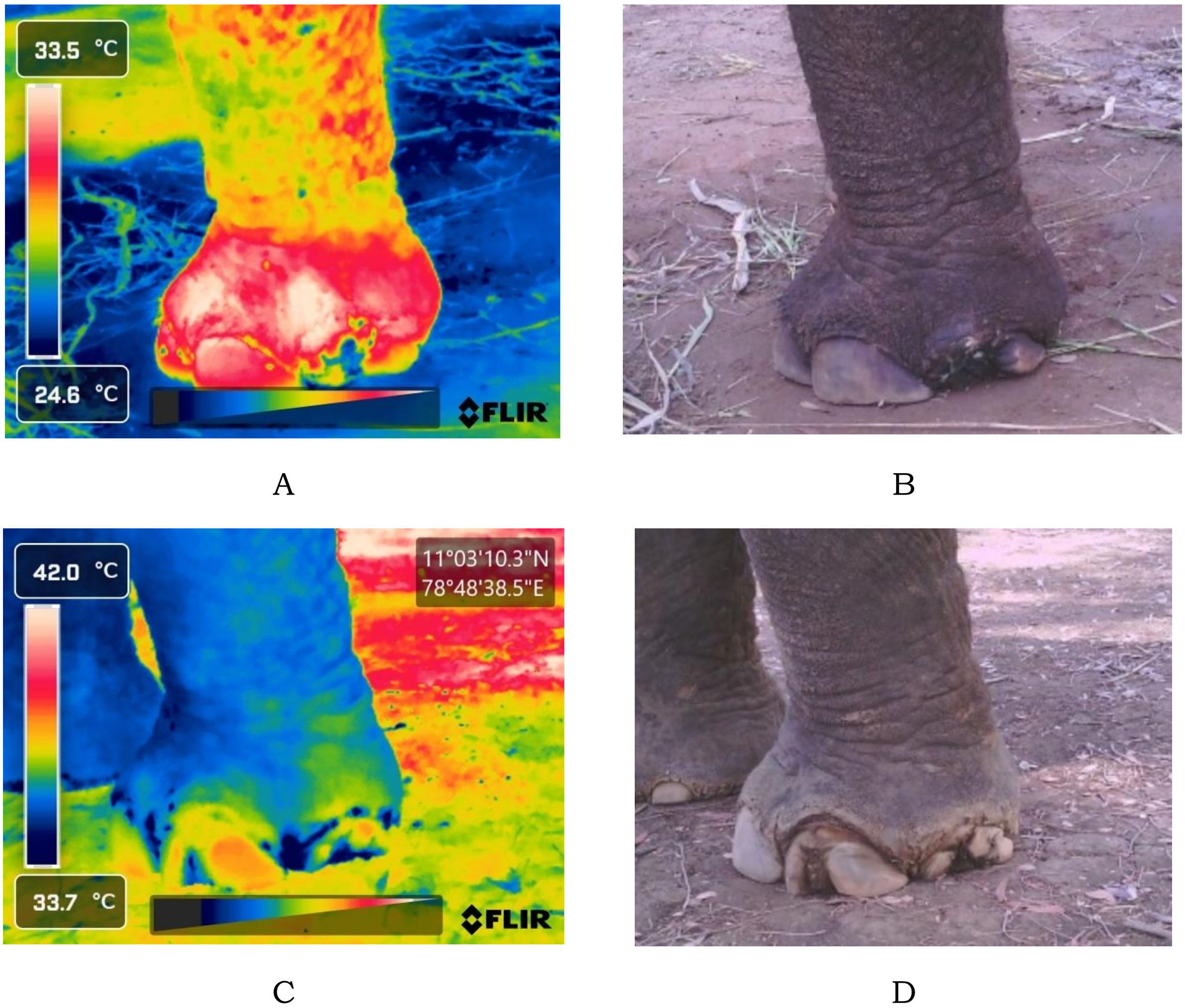


Figure 43. Elephant Jainy: progression of nail infection on the left forelimb. Images captured on January 2024 (A & B) and May 2024 (C & D).

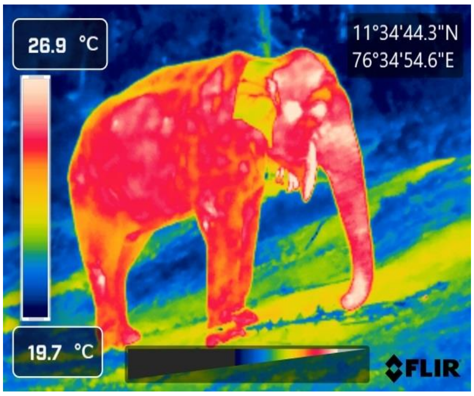
Elephant Jainy (Female, 60 years) had a nail removed from its left forelimb due to an infection. Figures 43A and 43B shows the thermogram of the infection captured in January 2024. The infected area exhibited a temperature of 28.7°C while the ankle region exhibited an average surface temperature of 31.35°C, indicating inflammation. The unaffected upper portions exhibited lower surface temperatures (29.3°C). Figures 43C and 43D show the thermogram of the infection captured in May 2024. The infection appeared to have subsided, exhibiting a temperature of 36.5°C, while the surrounding areas showed 35.9°C indicating a smaller temperature difference than previously recorded. However, the adjacent nail had developed a crack over time and exhibited a higher temperature (37.4°C) compared to the infected nail.

C) Monitoring reproductive events

Reproductive events like pregnancy have been successfully observed in domestic animals like horses using IRT (Bowers *et al.*, 2009). Radiation related to pregnancy has been detected in captive wild animals like elephants, rhinoceroses, and giraffes using IRT. However, identifying oestrus using IRT has been reported only once. (Hilsberg-Merz, 2008). The relationship between musth and infrared thermography has not yet been reported.

Musth

Musth, the sexually active period in bull elephants, is characterised by heightened aggression and sexual behaviour, drainage from the temporal glands, urine dribbling and increased androgen secretion. This period can last from a few weeks to several months (Mikota *et al.*, 1994). The temporal gland, also known as the musth gland, is located midway between the eye and ear on either side of the face. When not in musth, it is about the size of a human fist, with a small opening for its duct. During musth, the gland enlarges more than double its normal size, resulting in a noticeable swelling with a visible patch of fluid. The body temperature tends to be elevated during the time of musth (Rajaram, 2008).



A

B

Figure 44. Elephant Udhayan pictured during October 2023. Note the high radiation emitted from the temporal gland.

During the team’s initial visit to MTR (October 2023), elephant Udhayan was in the initial stages of musth. The elephant keeper mentioned that the musth was delayed by a few weeks and that the elephant was behaving normally. The team observed that the elephant did not exhibit signs of aggression, the temporal area was not significantly swollen, and there was no visible secretion of musth fluid.

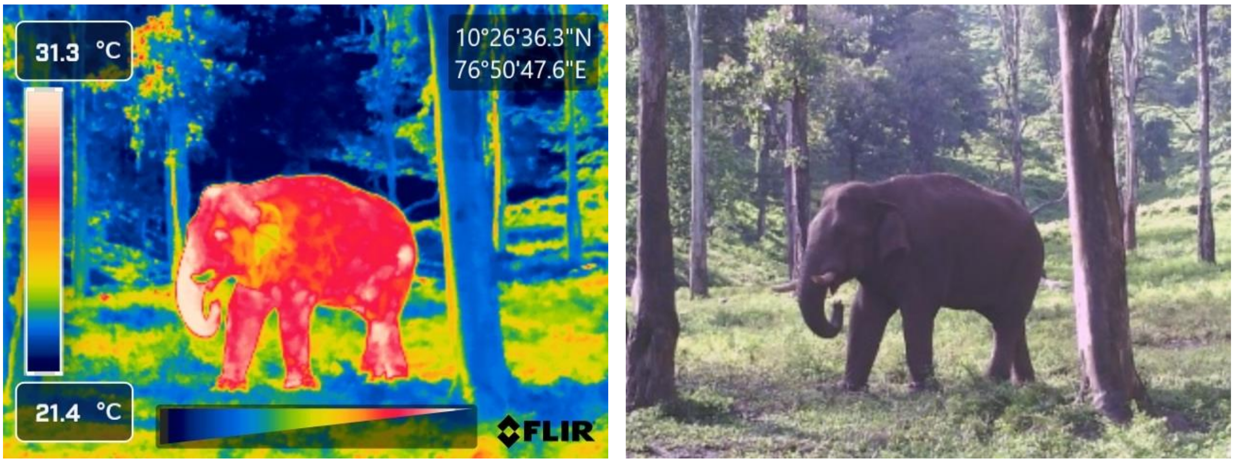
However, the thermograms revealed that the region corresponding to the temporal gland showing increased radiation. It exhibited an average surface temperature of 27.6°C (29°C at the hottest spot), while the surrounding regions showed an average surface temperature of 25.5°C (Fig. 44). Despite the elephant having not yet entered full-fledged musth and was still exhibiting normal behaviour, the thermograms showed that the processes associated with musth were underway and that the typical symptoms of musth were expected to appear soon.

During the team’s subsequent visit to MTR (March 2024), Udhayan was in the midst of full-fledged musth. The elephant was constantly chained and kept isolated from the other camp elephants. The elephant keepers informed that Udhayan was exhibiting behavioural signs of musth, such as tugging at its chains, lunging at other elephants/humans, and kicking up and tossing soil over itself. The temporal gland was noticeably swollen and musth fluid secretion was apparent. Thermograms could only be recorded from a distance owing to safety issues. It was observed that the area corresponding to the temporal gland showed an average surface temperature of 31.4°C while the surrounding regions showed an average surface temperature of 30.3°C (Fig. 45). The elephant keepers informed that the musth was extending beyond its usual period, which could be an effect of the delay in the onset of musth.

A B

Figure 45. Elephant Udhayan pictured in March 2024.

Elephant Chinnathambi was nearing the end of its musth period during October 2023. Thermograms captured of the elephant revealed that the area corresponding to the temporal gland showed an average surface temperature of 26.8°C, which was not abnormal and comparable to the surrounding areas (Fig. 46).



A B

Figure 46. Elephant Chinnathambi pictured during March 2024.

Oestrus and Pregnancy

Elephants are non-seasonal and polyoestrous breeders. In the wild, female elephants reach maturity at 10 to 12 years of age (Perry, 1953;

Sukumar, 1995). In captivity, pregnancy has been reported in females as young as four years for Asian elephants and seven years for African elephants. Elephants have the longest spontaneous oestrous cycle among mammals, lasting 12 to 18 weeks (Hess *et al.*, 1993 for Asian elephants; Plotka *et al.*, 1988 for African elephants), as well as the longest gestation period of 18 to 22 months (Fowler & Mikota, 2008). Elephants can breed throughout the year under favourable conditions, though there is evidence of some seasonal patterns. In wild African elephants, conception and births predominantly occur during the rainy season, when food and water are plentiful (Craig, 1984), while captive Asian elephants, living in their natural climatic conditions, birthed most during the cool season from December to March (Mar 2002).

Interacting with the veterinarians and elephant keepers of ATR and MTR, it was learnt that the birth of an elephant in camp had not occurred in over a decade and that the females rarely mate with the resident male elephants. Even having mated, they have not led to successful pregnancies. Furthermore, the mating habits of the females with wild males could not be monitored.

During the team's initial visit to ATR (October 2023), elephant Abinaya (Female, 19 years) was observed to be in heat and displayed courtship behaviour with the elephant Muthu (Male, 23 years). Elephant keepers mentioned that Abinaya and Muthu had mated multiple times over the course of a month. It has been observed in horses (Bowers *et al.*, 2009), elephants, and rhinoceroses (Hilsberg-Merz, 2008) that pregnant females exhibit higher radiation in their flank regions during their later stages of pregnancy when the foetus is well-grown and pressing against the side of the abdomen, leading to an increase in temperature in that region. The thermograms (Fig. 47) showed that both the right and left lower flank regions of Abinaya showed an average surface temperature of 29.7°C, which was consistent with the adjoining areas and did not appear abnormal.

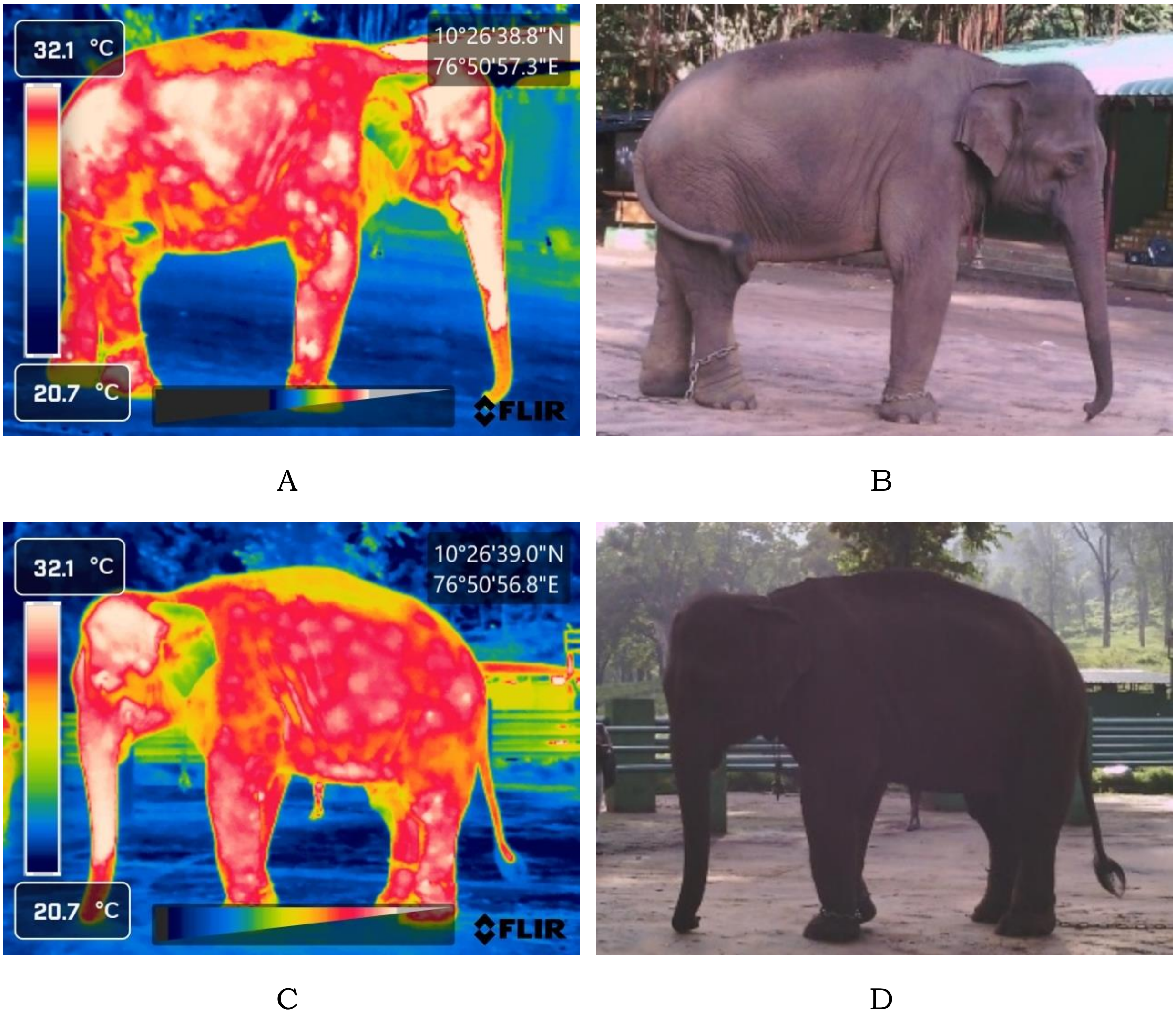
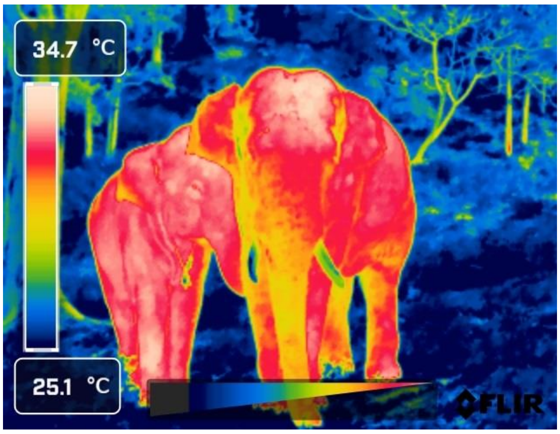


Figure 47. Right (A & B) and left (C & D) profile thermograms of elephant Abinaya.

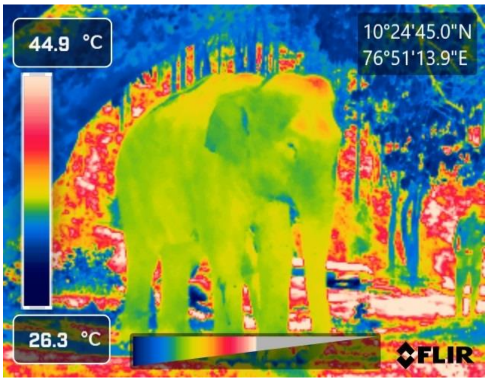
The pair (Fig. 48), however, displayed classic signs of elephant courtship behaviour such as trunk touching and caressing, vocalisations, and following and guarding each other, among other playful interactions (Leong *et al.*, 2003; Moss, 1983; Poole, 1987; Poole & Moss, 1989).



A B

Figure 48. Elephants Abinaya (L) and Muthu (R) exhibiting courtship behaviour.

During the team's subsequent visit to ATR (March 2024), Abinaya ceased socialising with Muthu and started behaving normally. Thermograms did not show increased radiation in the flank region (Fig. 49) which could mean that the elephant was not pregnant. However, even if it was pregnant, it would be too early in the pregnancy for the foetus to show considerable growth and emit noticeable radiation.



A B

Figure 49. Thermogram of elephant Abinaya captured during March 2024.

Tracking reproductive events like oestrus and pregnancy was challenging in this current study as both phenomena are unpredictable and require regular observation to make conclusive remarks. Another issue was the lack of female elephants of breeding age and the restrictions on male elephants during musth. Moreover, the long gestation period of almost two years mandates a longer study period to draw significant conclusions regarding the usefulness of IRT in tracking pregnancy.

Wild elephant encounters

During the team's visit to ATR in December 2024, a wild elephant herd was spotted near a watering hole near Topslip, Ulandy Range. The team visited the place accompanied by the Forest Veterinary Assistant Surgeon, ATR, and Forest Range staff.

Outwardly, the herd was not visible, as it was covered by foliage and undergrowth. However, IRT revealed multiple elephants camouflaged among the trees (Figure 50). Among them, a particular female elephant appeared to be standing amid the herd, seemingly protected by the other elephants. It was speculated that this female might be pregnant, but due to safety concerns, the team refrained from approaching closer and observed from a safe distance.

Figure 50. Screenshots from the thermographic video captured of a wild elephant herd near Topslip, Ulandy Range.

In March 2024, the team had the opportunity to participate in an operation in Bannari Range, Sathyamangalam Tiger Reserve (STR). There, a female elephant had been seen lying by the side of the road in exhaustion, with its calf (female, around five months old) roaming nearby. Despite the veterinarians' efforts, the mother did not survive, and it was decided that the calf would be reunited with another female from its herd.

A

B

C

D

Figure 51. Screenshots from the thermographic video captured of the reunification of the abandoned calf with another female near Bannari Range, STR. A - Abandoned calf dropped off from the vehicle; B - Female and its calf seen across the road inspecting the abandoned calf; C - Female elephant taking the abandoned calf under its protection; D - Elephants retreating to their herd.

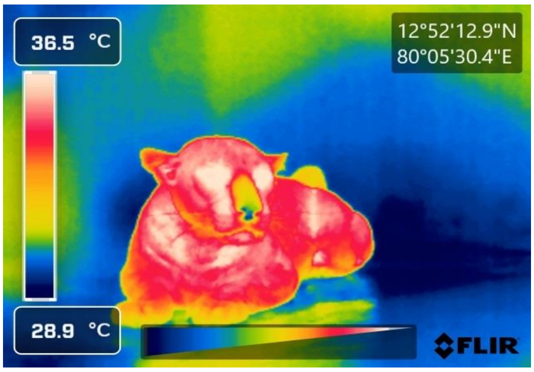
The relocation of the abandoned calf took place between 11 PM and 3 AM, in total darkness. The team accompanied the forest veterinarians, forest officers and mahouts to track the herd from which the mother and calf had been separated. After locating the herd and identifying a potential female from that herd for the calf, a plan was formulated to reunite the calf. Once the calf was released from the vehicle, the selected female, who had an older male calf of its own, rushed to the abandoned calf and took it under its protection. The trio were then seen returning to the forest and rejoining the herd (Fig. 51).

The thermographic video helped to visualise and identify the elephants in sub-optimal lighting conditions without disturbing the animals. Furthermore, Figure 51 shows that the abandoned calf exhibited the highest radiation, as expected of a youngling (Lefebvre *et al.*, 2023; Weissenböck *et al.*, 2012). It was also observed that the female elephant's ear exhibited high radiation. It has been reported that human beings experiencing stressful conditions have increased core body temperature due to elevated heart rate, blood pressure, and metabolic rate (Marazziti *et al.*, 1992). A similar parallel could be drawn in this situation, suggesting that the female elephant was stressed. In contrast, the older male calf's ear appeared cool, indicating it was not presumably stressed. This observation could be further studied in conditions such as elephants engaged in kumki operations or subjected to long travel periods.

Other phenomena observed through IRT

Apart from these observations made in the captive elephants of ATR, MTR and ERC, certain unique phenomena were observed in other animals, which are listed below:

- Thermograms recorded of Indian leopard (*Panthera pardus fusca*), Bengal tiger (*P. tigris tigris*) and Asian palm civet (*Paradoxurus hermaphroditus*) at AAZP showed that the snout area appeared cooler compared to the surrounding regions by a margin of 2°C to 5°C (Figure 52). This was because the rhinarium, informally known as a wet nose or wet snout, is the nose's hairless, moist and cool surface. This structure is especially prominent in animals such as dogs, cats, and other mammals that rely heavily on their sense of smell (Gläser & Kröger, 2017).



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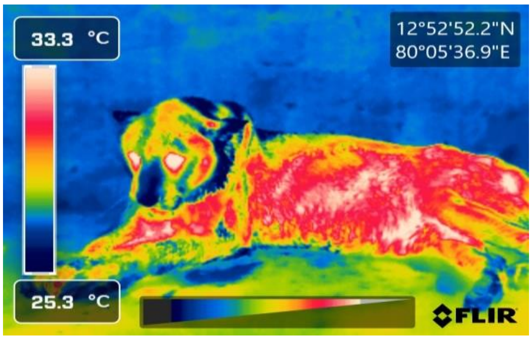

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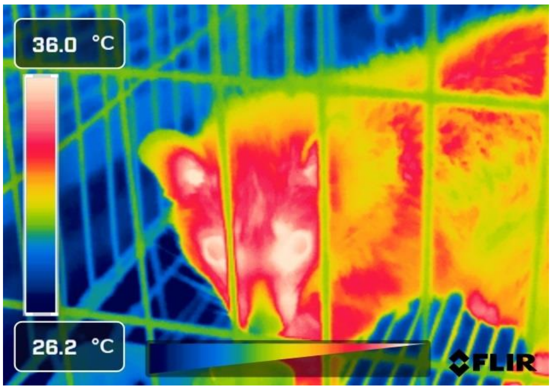

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F

Figure 52. Thermograms of animals with rhinarium; A - Indian leopard, B - Bengal tiger and, C - Asian palm civet.

- Thermograms of free-ranging spotted deer (*Axis axis*) at AAZP and AIWC were recorded when the males had and did not have velvet covering their antlers. Velvet is a soft, vascularized tissue rich in blood vessels and nerves, supplying nutrients and oxygen for the rapid growth of antlers in deer. The velvet supports growth until the antlers harden, at which point the blood supply is cut off, causing the velvet to dry up and shed (Suttie & Harris, 2000). The velvet contributed to temperature differences ranging from 0.1°C to 0.5°C (Fig. 53). Velvet covered antlers appeared warm on the thermograms while antlers without velvet appeared cool, like any bony structure.

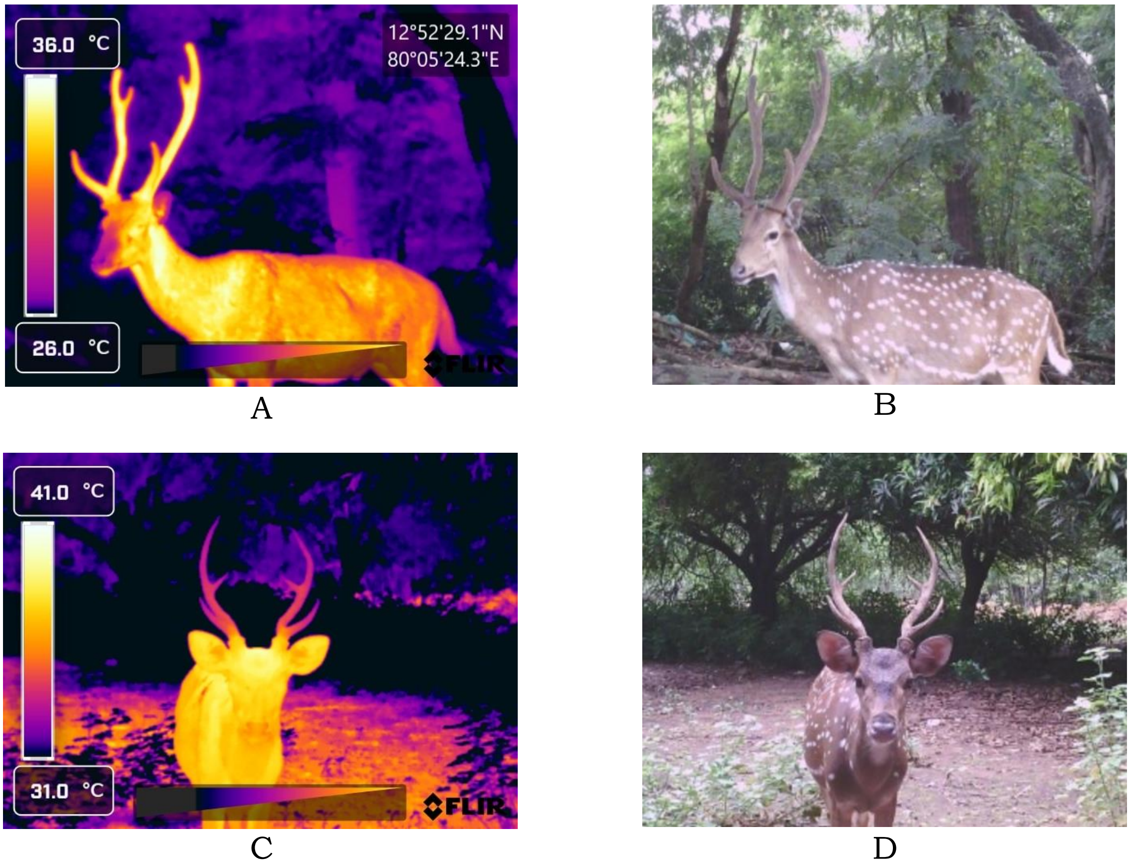
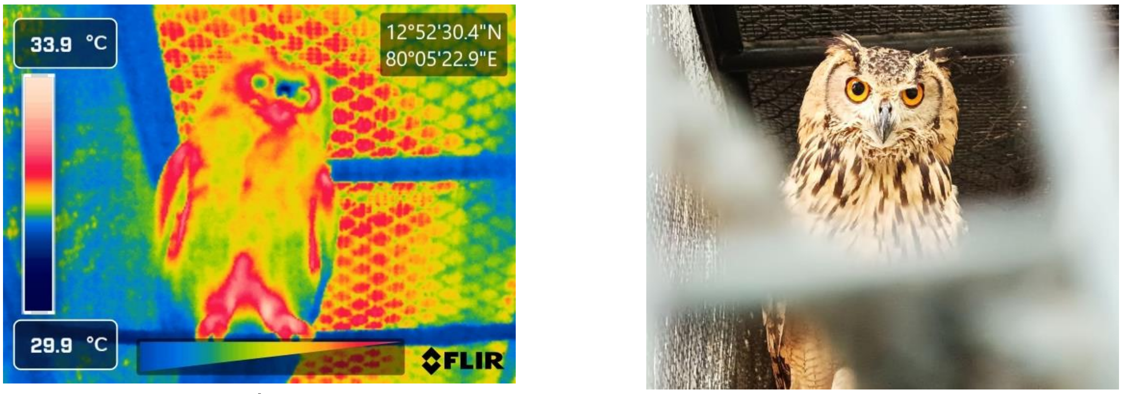


Figure 53. Thermograms of spotted deer where they have (A & B) and do not have (C & D) velvet covering their antlers.

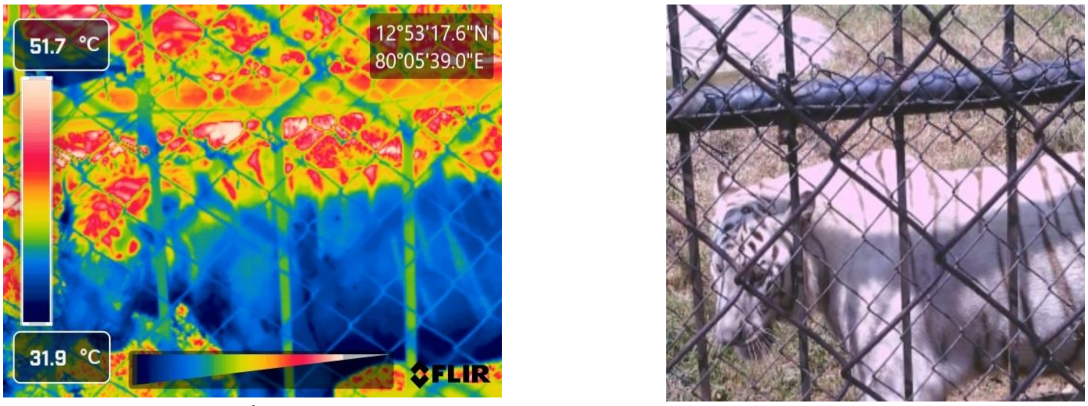
- Thermograms recorded of an Indian eagle-owl (*Bubo bengalensis*) at AAZP showed that the body was well insulated and did not exhibit much outward radiation except for the face and beak, feet and underwings - regions that are sparsely feathered and hence lacked insulation (Fig. 54). Apart from their role in flight and aerodynamics, feathers are well known for their ability to act as highly effective insulators, which is crucial in regulating the body temperature in birds. Their varied shapes, ability to layer and adjust positions, water resistance, and regular moulting to replace old/damaged feathers contribute to their insulating properties (Veghte & Herreid, 1965; Terrill & Shultz, 2023).



A B

Figure 54. Thermogram of Indian eagle-owl showing the effect of feathers on insulation.

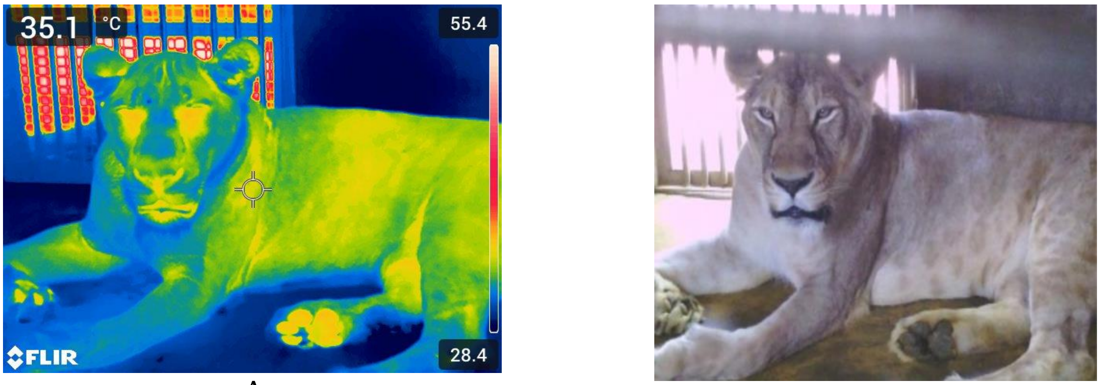
- Thermograms of a white Bengal tiger at AAZP, recorded on a hot sunny day, showed patterned radiation on its back and face, mainly emitting from the black stripes of the animal. The white portion of the skin looked relatively cooler, almost 4°C lower, than the black stripes (Fig. 55). The effect of body colour on the thermoregulation of animals is varied and complex (Stuart-Fox 2017). This subject has been studied in similarly patterned animals like zebras (Hilsberg-Merz, 2008), which showed significant differences in the surface temperature between the black and white stripes.



A B

Figure 55. Thermogram of white Bengal tiger showing the effect of coat colour of surface temperature.

Similarly, thermograms recorded of a resting Asiatic lion (*P. leo leo*) in its enclosure at AAZP were captured on a hot, sunny day. The paw pads, darker in colour than the coat, exhibited more radiation than the paws by a difference of more than 2.5°C, evidencing the effect that colour has on surface temperature (Fig. 56).

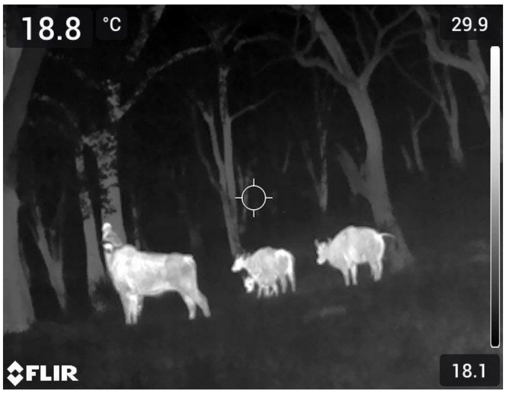


A B

Figure 56. Thermogram of Asiatic lion showing increased radiation from its paw pads.

- As mentioned in "Wild Elephant Encounters," IRT has helped visualise and identify elephants in dark and sub-optimally lit circumstances. Figure 57 illustrates some other instances where other wild animals were encountered.

Since IRT does not require a light source and only detects the radiation emitted from a body, mammals (hot-bodied) are very easily visualised in the dark against a relatively cold background. Even though these thermograms were recorded from a vehicle moving at moderate speed, the team could confidently identify the presence of an animal from long distances due to its heat signature. IRT was also helpful in visualising animals hidden amidst fog and mist (Fig. 58), as the underlying working principle remains the same in this situation too.



A

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C

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Figure 57. Thermograms of free ranging animals recorded during late nights; A - Indian gaur, B - Sambar deer, C - Herd of spotted deer and D - Elephant.

Figure 58. Thermal camera showing a herd of spotted deer resting amidst heavy fog, image captured in Topslip, ATR.

CONCLUSION

As a non-invasive technology that does not cause discomfort and stress to the subject and is easy to employ in the field, infrared thermography has proved very useful in monitoring wildlife such as captive elephants under human care. Like any pets or livestock, these captive elephants also require routine care and regular upkeep. However, unlike pets or livestock, which can be transported at will, restrained comfortably, and examined easily by veterinarians, giant 'semi-wild' elephants cannot be examined instantly and require multiple hands to coax the animal into cooperating with examination and treatment. In addition to routine tests such as blood, serum, urine, and stool analyses, which are relatively easy to conduct, more complex and invasive procedures like endoscopy, ultrasonography, and radiography cannot be conducted casually. Both the animal's cooperation and the procurement of the necessary instruments pose particular challenges.

In these situations, infrared thermography is very useful. Being a portable instrument that delivers real-time results, thermal cameras continue to find more applications in the veterinary field. Animals can be observed from a distance, eliminating the need for immobilisation or restraint. Although the results may seem only surface level, these thermograms can be interpreted with appropriate training and knowledge to arrive at a preliminary diagnosis, like a blood test, and plan the next course of action. Apart from being portable and delivering instantaneous visual imaging, the data captured can be stored and analysed in further detail, facilitating documentation and preservation of medical data.

Implementing infrared thermography in the field requires attention to certain aspects. The instrument does require some basic training, as the thermographer must be aware of the instrument's capacity to choose the appropriate settings to record the best-suited thermogram. If the thermographer wishes to employ the thermal camera for diagnostic purposes, they must be knowledgeable of the animal's anatomy and physiology to make accurate diagnoses. Additionally, the thermographer must be aware of the surroundings and environmental conditions the animal resides in, as these factors can also influence the thermograms. However, one important aspect is the need for regular and continuous documentation of any biological process identified and recorded by infrared thermography. These processes, whether physiological or pathological, have their own timelines and must be tracked from start to finish. Infrared thermography cannot be considered a one-time procedure, and instead needs to conducted regularly to achieve significant results.

In conclusion, the application of infrared thermography has proven to be an effective diagnostic tool in captive elephant management. It requires fewer prerequisites compared to other diagnostic equipment and can be handled with ease without encumbering the elephant. The instantaneous relay of results can serve as a primary diagnosis on which further decisions can be made. Coupled with its uses in monitoring and surveillance, infrared thermography can prove helpful in the hands of the staff of elephant camps and Reserved Forests, aiding in the better management and conservation of elephants, both captive and wild.

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TABLES

Table 1. Name, age and sex of the elephants housed at Kozhikamuthi and Varagaliyar camps in Anamalai Tiger Reserve (ATR) that were involved in the study

Sl. No.	Name of the Elephant	Age (years)	Sex
1.	Abinaya	19	Female
2.	Andal	63	Female
3.	Ashok	14	Male
4.	Barani	40	Male
5.	Chinnathambi	27	Male
6.	Deivanai	15	Female
7.	Devi	20	Female
8.	Durga	29	Female
9.	Kaleem	60	Male
10.	Kapildev	42	Male
11.	Mariappan	34	Male
12.	Muthu	23	Male
13.	Narasimman	19	Male
14.	Paari	44	Male
15.	Rajavarthan	26	Male
16.	Ramu	55	Male
17.	Sanjeev	10	Male
18.	Saravanan	18	Male
19.	Selvi	64	Female
20.	Sivagami	74	Female
21.	Surya	51	Male
22.	Suyambu	27	Male
23.	Tamizhan	20	Male
24.	Urigan	15	Male

Table 2. Name, age and sex of the elephants housed at Theppakadu and Abhyaranyam camps in Mudumalai Tiger Reserve (MTR) that were involved in the study

Sl. No.	Name of the Elephant	Age (years)	Sex
1.	Anna	65	Male
2.	Bhama	75	Female
3.	Bommi	3	Female
4.	Cherambadi Shankar	37	Male
5.	Cheran	37	Male
6.	Ganesh	54	Male
7.	Giri	14	Male
8.	Indhar	72	Male
9.	Jambu	37	Male
10.	Kamatchi	64	Female
11.	Krishna	12	Male
12.	Masini	16	Female
13.	Mudumalai	60	Male
14.	Raghu	6	Male
15.	Santhosh	53	Male
16.	Shankar	54	Male
17.	Sujay	52	Male
18.	Senthilvadivu	52	Female
19.	Udhayan	25	Male

Table 3. Name, age and sex of the elephants housed at Elephant Rehabilitation Centre (ERC), Tiruchirapalli that were involved in the study

Sl. No.	Name of the Elephant	Age (years)	Sex
1.	Gomathi	70	Female
2.	Indhu	39	Female
3.	Indira	62	Female
4.	Jainy	60	Female
5.	Jayanthi	26	Female
6.	Kirathi	64	Female
7.	Malachi	38	Female
8.	Rupali	23	Female
9.	Santhiya	48	Female
10.	Sumathi	57	Female
11.	Sundari	67	Female

Table 4. Surface temperatures of elephants housed at ATR and MTR with mean and standard deviation

Elephants		Head Surface Temperature (°C)	Ear Surface Temperature (°C)	Torso Surface Temperature (°C)	Forelimb Surface Temperature (°C)	Hindlimb Surface Temperature (°C)
A1	Males	29.55	29.3	28.3	28.95	28.2
A2		27.95	25.45	27	26.2	25.9
A3		27.95	23.6	27.3	29.3	28.6
A4		33.1	31.9	33.06	31.1	31.3
A5		28.75	26.3	28	28.6	29.1
A6		25.3	22.4	24.7	24.7	24.85
A7		29.2	29.2	28.43	26.95	27.03
A8		25.6	23.4	24.8	25.4	24.9
A9		25.85	22.5	25.2	24.9	24.7
A10		29.25	28.4	28.65	27.8	27.4
A11		31.9	32.1	32.62	31.3	30.7
A12		25.95	22.8	25.23	25	24.4
A13		29.9	26.2	29.26	30.1	29.8
A14		27.05	26.3	27.15	28.5	27.5
A15		24.7	22.4	25.2	23.4	23.3
A16		31.5	28.7	32	31.4	31.2
A17		33.65	33.3	33.5	33	33.2
A18		27.1	23.5	25.8	26.5	26
A19		29.05	26.4	29.6	26.7	26.05
A20		25.65	22.1	25.65	26.5	25.92
A21		30.3	27.2	28.2	28.9	29.1
A22		26.2	22.6	25.84	26.4	25.7
A23		30.6	28.1	30.2	30.2	30.35
A24		28.95	27.1	27.87	26.9	25.5
A25		30.15	26	29.86	28.9	27.8
A26		25.15	22.05	24.53	24.8	24.4
A27	Females	30.7	26.9	29.33	30.1	29.75
A28		24.8	20.75	24.13	23.65	22.85
A29		29.25	26.65	28.65	29.7	30.05
A30		31.7	31.8	32.06	29.8	29.9
A31		33.2	32.2	33.7	33.3	33.3
A32		26.5	22.7	25.23	26.9	26.56
A33		26.85	23.9	28.1	25.5	25
A34		26.85	22.7	26.1	25.8	25
A35		28.8	25.6	28.4	28.75	28.8
Mean		28.54	26.07	28.1	27.88	27.54
Standard Deviation		2.54	3.44	2.75	2.56	2.73

A1 – Anna; A2 – Ashok; A3 – Barani; A4 – Cherambadi Shankar; A5 – Chinnathambi (A); A6 – Chinnathambi (B); A7 – Ganesh; A8 – Kapildev; A9 – Krishna; A10 – Mariappan; A11 – Muthu (A); A12 – Muthu (B); A13 – Narasimman; A14 – Paari; A15 – Raghu; A16 – Ramu; A17 – Sanjeev (A); A18 – Sanjeev (B); A19 – Saravanan; A20 – Surya; A21 – Suyambu (A); A22 – Suyambu (B); A23 – Tamizhan; A24 – Udhayan; A25 – Urigan (A); A26 – Urigan (B); A27 – Abinaya (A); A28 – Abinaya (B); A29 – Andal; A30 – Bommi; A31 – Deivanai (A); A32 – Deivanai (B); A33 – Durga (A); A34 – Durga (B); A35 – Selvi

A & B refer to thermograms recorded in the same elephant during different time periods

Table 5. Right and left eye temperatures of elephants with mean and standard deviation

Elephants	Right Eye Temperature (°C)	Left Eye Temperature (°C)
B1	32.0	31.3
B2	33.0	31.9
B3	32.8	31.6
B4	32.5	32.8
B5	32.4	32.5
B6	32.3	33.3
B7	32.7	33.1
B8	33.2	33.8
Mean	**32.61**	**32.53**
Standard Deviation	**0.39**	**0.87**

B1 – Kapildev; B2 – Muthu; B3 – Kaleem; B4 – Sanjeev; B5 – Urigan; B6 – Durga; B7 – Ashok; B8 – Abinaya

Table 6. Average surface temperatures (°C) of elephants housed at ATR and MTR classified according to different age groups.

Age groups	Head Surface Temperature	Ear Surface Temperature	Torso Surface Temperature	Forelimb Surface Temperature	Hindlimb Surface Temperature
1 to 6 years	28.2	27.1	28.63	26.6	26.6
7 to 15 years	28.69	25.96	28.1	28.06	27.73
16 to 25 years	28.98	26.29	28.53	27.99	27.43
26 to 50 years	27.93	25.34	27.45	27.45	27.13
51 years and above	28.99	26.93	28.57	28.71	28.53

Table 7. Temperatures of thermal windows in elephant Raghu before and after bath

Thermal Windows	Temperature Before Bath (°C)	Temperature After Bath (°C)	Difference in Temperature (°C)
1	26	26.2	0.2
2	26.3	28.2	1.9
3	25.4	25.7	0.3
4	24.2	23.8	-0.4
5	24.9	24.7	-0.2
6	25.6	25.6	0.0
7	25.7	25.7	0.0
8	26.2	26.0	-0.2
9	25.5	25.2	-0.3
10	25.5	25.1	-0.4
11	24.8	24.0	-0.8

Table 8. Temperatures of thermal windows in elephant Krishna before and after bath

Thermal Windows	Temperature Before Bath (°C)	Temperature After Bath (°C)	Difference in Temperature (°C)
1	26.6	26.8	0.2
2	26.4	28.0	1.6
3	27.0	28.2	1.2
4	25.9	25.8	-0.1
5	26.2	26.8	0.6
6	26.5	26.3	-0.2
7	25.9	26.7	0.8
8	25.6	26.5	0.9
9	26.3	26.3	0.0
10	26.3	26.4	0.1
11	26.3	26.6	0.3
12	25.8	26.2	0.4
13	26.3	26.5	0.2
14	26.8	26.7	-0.1
15	26.6	26.8	0.2
16	25.8	26.4	0.6
17	25.7	26.4	0.7

Table 9. Temperatures of thermal windows in elephant Udhayan before and after bath

Thermal Windows	Temperature Before Bath (°C)	Temperature After Bath (°C)	Difference in Temperature (°C)
1	27.3	27.6	0.3
2	26.3	27.5	1.2
3	26.7	27.8	1.1
4	26.4	27.1	0.7
5	27.2	27.8	0.6
6	26.5	25.9	-0.6
7	25.5	25.9	0.4
8	26.1	26.9	0.8
9	26.7	27.2	0.5
10	27.7	28.0	0.3
11	26.9	27.7	0.8
12	26.3	26.4	0.1
13	26.6	27.4	0.8
14	26.7	27.3	0.6
15	26.5	27.2	0.7
16	26.1	26.6	0.5
17	25.7	26.0	0.3
18	26.0	26.9	0.9
19	26.7	27.2	0.5
20	25.7	26.2	0.5

Table 10. Surface temperatures of elephants housed at ERC with mean and standard deviation

Elephants	Head Surface Temperature (°C)	Ear Surface Temperature (°C)	Torso Surface Temperature (°C)	Forelimb Surface Temperature (°C)	Hindlimb Surface Temperature (°C)
C1	31.3	28.7	30.65	30.9	29.9
C2	33.75	33.9	33.45	32.66	32.6
C3	30.45	31.1	31.35	30.7	30.8
C4	35	34.6	35.3	35.15	34.8
C5	31.25	28.8	30.25	31.9	31
C6	34.9	34.4	35.9	34.7	34.7
C7	30.25	30.1	29.6	30.75	30.5
C8	35.45	34.8	37.1	36	36.1
C9	31.3	29.6	31.55	30.9	31.1
C10	34.2	34.6	33.85	33.5	33.4
C11	31.25	28.1	31.05	30.05	29.5
C12	34.45	34.4	35	34.85	34.15
C13	30.6	29.4	30.5	31.25	30.6
C14	32.55	32.2	32.8	33.7	33.4
C15	28.4	27	28.4	28.2	28.2
C16	35.05	34	34.85	35.26	35
C17	29.8	29.4	29.46	28.1	27.5
C18	34.75	34.3	35.46	35.3	34.9
C19	28.9	28.8	29.66	29.4	29.65
C20	34.6	34.5	34.1	33.5	32.8
C21	27.35	26	27.52	27.65	28.26
C22	34.25	33.5	34.9	34.05	34.1
Mean	32.26	31.46	32.39	32.2	31.95
Standard Deviation	2.48	2.92	2.72	2.57	2.54

C1 – Gomathi (A); C2 – Gomathi (B); C3 – Indhu (A); C4 – Indhu (B); C5 – Indira (A); C6 – Indira (B); C7 – Jainy (A); C8 – Jainy (B); C9 – Jayanthi (A); C10 – Jayanthi (B); C11 – Kirathi (A); C12 – Kirathi (B); C13 – Malachi (A); C14 – Malachi (B); C15 – Rupali (A); C16 – Rupali (B); C17 – Santhiya (A); C18 – Santhiya (B); C19 – Sumathi (A); C20 – Sumathi (B); C19 – Sumathi (A); C20 – Sumathi; C21 – Sundari (A); C22 – Sundari (B)

A & B refer to thermograms recorded in the same elephant during different time periods

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