Aging Coyotes Using Dental Characteristics

Michelle Maher

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Aging Coyotes Using Dental Characteristics

BY

Michelle Maher

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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IN THE GRADUATE SCHOOL, EASTERN ILLINOIS UNIVERSITY

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I HEREBY RECOMMEND THAT THIS THESIS BE ACCEPTED AS FULFILLING THIS PART OF THE GRADUATE DEGREE CITED ABOVE

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A Thesis Presented

By

Michelle Maher

Submitted to the Graduate School of Eastern Illinois University in partial fulfillment of the requirements of the degree of

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Department of Biological Sciences
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I would like to thank the Biological Sciences Graduate Program for my graduate assistantship and the Graduate School for my summer assistantship. I would also like to thank Dan Lloyd and Dave Gregory for collecting the teeth and the coyote hunters, trappers and fur buyers of Illinois for providing the Coyotes. In addition I would like to thank Bud Fisher for serving on my committee, Scott Meiners for being on my committee and for helping with the analysis and Tom Nelson for being on my committee, helping me develop a new project when my previous one fell through and for being willing to measure a few teeth. Lastly, I would like to thank Rebecca, Greg and Sara for measuring and aging a few teeth even though they knew what I went through.
The accepted methods of age determination in the coyote (Canis latrans) are either highly subjective and unquantifiable or expensive and require the extraction of the canine tooth. Since neither of these methods are ideal, their limitations have impeded research on this species. Therefore, it was my objective to (1) develop and test the accuracy and precision of a descriptive key based on tooth wear patterns on the lower canine tooth, (2) develop and test the reliability of multiple regression models for aging coyotes using measurements from extracted teeth, and (3) suggest criteria for improving the consistency of results using these techniques.

From a sample of 996 teeth collected from coyotes that had been previously aged by counting cementum annuli, a subsample of 303 teeth were carefully examined for characteristic tooth wear patterns. These characteristics were used to develop an illustrated tooth wear key that could be used to assign coyotes to 1 of 7 age classes: 0.5, 1.5, 2.5, 3.5, 4.5, 5.5, and ≥ 6.5 years. Using the illustrated key, I estimated the age of a subset of 203 of these teeth. I correctly aged 138 of the 203 (68%) teeth and of the remaining 65 teeth 58 (89%) were aged within one year. My estimated ages were highly correlated to the assigned ages (r = 0.882). Four other readers using the key and composite estimated the age of 20 teeth. The four readers had a mean coefficient of variation (CV) of 27.9, ranging from 10.8-35.6. The most accurate reader aged 16 of 20 (80%) teeth correctly and the least accurate 10 of 20 (50%). Older individuals tended to be underaged.
The second age determination technique came from multiple regression models. Multiple regression models were developed based on a series of 12 measurements taken from the 303 teeth. The measurements taken were: total tooth length, minimum root length, maximum root length, maximum root width, maximum root thickness and crown width, crown thickness, maximum crown width, maximum crown thickness, anterior crown length, posterior crown length and pulp width. No single measurement could be used to determine age or sex because of overlap in the ranges of measurements. However, there were significant differences ($p \leq 0.001$) between measurements for the sexes, except for pulp width ($p = 0.689$). Therefore, 3 multiple regression models were developed: one for males, one for females and one for both sexes combined. All were significant predictors of age ($p \leq 0.001$). The male model was the least accurate and the least precise. These models cannot be used on living coyotes without extracting the canine because each model required at least 2 root measurements. To investigate the precision of measuring teeth, 5 people measured 11 of the 12 measurements (excluding pulp width) on 20 teeth. The measurements of posterior crown length and maximum crown width were the least precise with CVs of 8.6 and 8.8. As expected, total tooth length was the easiest to measure with a CV of 1.5. Because there is some overlap in age-classes using either of these techniques (tooth wear or multiple regression), they probably are not as accurate as ages determined from cementum annuli aging which is usually cited as the most accurate method. But, they can be an alternative when either the tooth cannot be extracted from living coyotes or when time and expense are concerns.
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INTRODUCTION

Coyotes (Canis latrans) are important throughout much of the U.S. as a game and nuisance species and because they are the top carnivores in many terrestrial communities. Accordingly, coyote population management is a high priority for state and wildlife agencies. Critical information needed to develop biologically sound and effective wildlife management programs often includes the age-structure of a target population. Currently, the techniques for aging coyotes are either unreliable, costly, or require injuring the animal. These limitations impede research and management of this species. Thus cost-effective, accurate and non-invasive methods of aging are needed.

An ideal method of aging species would allow biologists to objectively assign individuals to a series of age-classes based on characteristics that have little to no overlap (Dimmick and Pelton 1994). However, this ideal is rarely attained and current techniques have limitations. Most aging techniques for coyotes are based on dental characteristics (Voigt and Berg 1999). One such method was developed by Gier in 1957. Gier’s (1957) composite drawing of progressive tooth wear on individuals from 1-8 years of age is still the standard used to age living coyotes. However, since there are no measurements to accompany this drawing, application of this method is subjective and relies heavily on the experience of the biologist aging the animal.

A more common technique aging coyotes involves counting cementum annuli. Coyotes are aged by extracting a canine tooth, which is sectioned and stained to highlight dark bands of cementum that are deposited annually. Although the technique is difficult, biologists generally agree it is the most accurate method of aging coyotes and other mammals (Linhart and Knowlton 1967, Thomas 1977, Tumlison and McDaniel 1984,
Landon et al. 1998, Gipson et al. 2000). However, this method also has limitations. Annuli are often faint and dark lines sometimes split or converge making counts subjective and imprecise (Nellis et al. 1978). Furthermore, the technique is expensive and requires extraction of a canine tooth. Since this tooth is important for intimidation displays, fighting and predation, extraction of a canine from a living animal may influence its future social status, fitness and survival (Van Valkenburgh and Ruff 1987, Gittleman and Van Valkenburgh 1997).

Increased concerns for animal welfare have prompted biologists to seek non-invasive aging techniques which are practical and reliable for use on living animals (Gipson et al. 2000). Although the cementum annuli technique continues to be commonly used for aging canids, the extraction of canines from animals that rely so heavily on these teeth for survival is undesirable. Even when aging is conducted on harvested carcasses and the removal of the tooth is not a welfare issue; it would be beneficial to have a faster and more cost-effective alternative to cementum annuli counts.

Therefore, it was my purpose to develop and test the efficacy and reliability of 2 less expensive and invasive methods for aging coyotes based on characteristics of the canine tooth. My objectives were to: (1) develop and test the reliability of multiple regression models for aging coyotes using measurements from extracted teeth, (2) develop and test the accuracy and precision of a descriptive key based on tooth wear patterns on the lower canine tooth, and (3) suggest criteria for improving the consistency of results using these techniques.
Dentition and Tooth Replacement in Coyotes

Coyotes exhibit diphydont dentition, meaning that temporary milk teeth erupt first and are replaced later by permanent teeth. Milk teeth erupt at approximately 2 weeks of age and are replaced by permanent teeth about 6 months later (Gier 1957). The eruption of the permanent canine teeth occurs between the ages of 4 and 5 months (Linhart and Knowlton 1967, Nellis 1978). At 9 months, the root canal closes (Linhart and Knowlton 1967). The pulp cavity closes rapidly during the animal’s first winter and continues to decrease in width with each subsequent year (Linhart and Knowlton 1967). Due to the predictability of timing, all of these teeth characteristics have been used to determine the age of individual coyotes <1 years old.

Coyote teeth are composed of 4 major components: enamel, dentine, pulp and cementum. Enamel, which is the outermost layer, contributes to the strength and longevity of the tooth (Sicher 1962). The enamel only covers the exposed tooth down to the gum line. Even though this is the hardest calcified tissue in mammals, it is still worn away with age. With enough wear, the enamel eventually will erode exposing the dentine layer beneath (Peyer 1968). Dentine, which comprises the majority of the tooth, continues to deposit with age, decreasing the size of the pulp cavity at the center of the tooth (Linhart and Knowlton 1967). Nerves and blood vessels run through the pulp cavity, but its primary function is the production of dentine (Sicher 1962). The final component of the tooth is the cementum which covers the root. Cementum, like dentine, is deposited rapidly during the summer and slowly during the winter producing annular
growth rings (Peyer 1968; Sicher 1962). These growth rings, referred to as annuli, are useful in age determination in many groups of mammals.

**Age Determination Techniques**

Coyotes that are < 5 months old can be quickly and unobtrusively identified by the presence of milk teeth. Whereas, older juveniles (< 1 year) can be distinguished from adults by the presence of an open root canal in an extracted canine tooth (Linhart and Knowlton 1967). A common method of separating juveniles from adults is to extract a canine and x-ray it. The width of the pulp cavity can be measured on the radiograph of the tooth using calipers (Tumlinson and McDaniel 1984, Landon et al. 1998, Knowlton and Whittemore 2001). Several studies have shown that the ratio of pulp width to total tooth width can be used to reliably distinguish juveniles from adults (Grue and Jensen 1976, Kuehn and Berg 1981, Jean et al. 1986, Knowlton and Whittemore 2001). Pulp width has been used to accurately age wolves (Canis lupus) up to 7 years (Landon et al. 1998). However this technique cannot be used to age adult coyotes because of overlap in the ratios among adult age-classes (Knowlton and Whittemore 2001).

Adult coyotes are usually aged by counting cementum annuli in the roots of the canine or premolar teeth, the canine being the preferred of the 2 for its clarity (Dimmick and Pelton 1994). Individuals are aged by extracting the tooth and decalcifying the root. Then, the root is sectioned longitudinally and stained to produce visible dark bands of cementum annuli. Anyone with proper training, tools and chemicals can conduct these counts, but commercial laboratories (e.g. Matson’s Laboratory, Milltown, MT) are usually paid to age teeth. This method is the most common and trusted for aging coyotes and other canids. Nellis et al. (1978) correctly aged 6 of 7 known-age coyotes using this
Allen (1973) found 100% agreement between cementum annuli and known-ages in red foxes (*Vulpes vulpes*). Gipson et al. (2000) reported that the precision found with cementum annuli in gray wolves was greater than with any other aging technique. They reported that while younger wolves were accurately aged, older wolves were under-aged using annuli (Gipson et al. 2000).

Ages based on cementum annuli are sometimes inaccurate. Annuli can be difficult to count when they are faint, split or converge. Consequently, counts may differ between extracted teeth from the same individual and the clarity of the lines (and accuracy of the counts) may vary among geographic regions (Roberts 1978).

When animals are to be released for study the non-invasive method for aging is usually based on tooth wear. Gier (1957) published a composite drawing of the progressive tooth wear in coyotes for individuals from 1 through 8 years of age. The drawing shows progressive wear as a series of lines on a frontal view of the canines and incisors. This method is not quantifiable and broad overlap in age-classes limits its utility (Landon et al. 1998). However, Gipson et al. (2000) prepared a similar drawing showing wear in 2-year increments for gray wolves and reported that aging wolves using tooth wear produced an accuracy of 83%.

Grau et al. (1970) attempted to develop a quick and inexpensive way to separate raccoons (*Procyon lotor*) into 5 age-classes based on a series of 5 measurements on the canine tooth. They found the technique to be inaccurate due to overlap in measurements among age groups (Grau et al. 1970). To my knowledge this technique has not been attempted on coyotes. Because the body size of coyotes generally increases from the southwestern to the northeastern U.S., there is some concern that geographic variation in
the size of teeth may limit the utility of tooth measurements for aging. However, I am not aware of any research data to support the validity of this concern.

**METHODS**

The coyotes used in this study were harvested by hunters and trappers throughout Illinois from December 1995 to February 1996 and from December 1996 to March 1997. The sex and skinned body weight were recorded for each coyote and the lower mandible was removed and soaked in a water bath at $80^\circ$C for 3 days. Both lower canines were extracted, cleaned and labeled with India ink. Canines were collected because it is the tooth of choice for aging coyotes (Roberts 1978, Dimmick and Pelton 1994).

One tooth from each pair was x-rayed using a Picker 3000 radiograph. The other tooth was placed in a paper envelope and stored frozen. Canines from juveniles were distinguished by the presence of a large pulp cavity in radiographs (Kuehn and Berg 1981). Teeth with narrow pulp cavities were categorized as being from adults. The latter were sent to Matson's Laboratory where age was estimated by staining and counting cementum annuli. For this study, juveniles were approximately 0.5 years old. Adults were separated into 6 additional age-classes: 1.5, 2.5, 3.5, 4.5, 5.5 and $\geq 6.5$ years. Individuals older than 5.5 were grouped into the oldest age-class because they comprised only 3% of the sample. Teeth from 996 coyotes were aged in this manner. None of the coyotes used in this study were true known-age individuals. Therefore, the assigned ages used throughout were estimates based on pulp width for juveniles and counts of cementum annuli for the older age-classes.

From this large sample of teeth, I measured a subsample of 303 canines to investigate whether some measurement or combination of measurements could provide a
quick, inexpensive way of estimating the age of individual coyotes. This subsample was
selected in a stratified-random manner. Approximately 80 teeth were randomly selected
from coyotes in each of the 0.5, 1.5, and 2.5 age-classes. Because of the small number of
older individuals, all 63 coyotes in the 3.5, 4.5, 5.5 and ≥ 6.5 age-classes were included.
Any teeth that were broken or damaged were discarded and only teeth that had received
an “A” rating from Matson’s were used. An “A” rating signifies the expert reader at
Matson’s was certain of the assigned age for individuals up to 7 years old or certain to
within ± 1 year for older individuals.

The first measurements taken on each tooth were those used by Grau et al. (1970)
to age raccoons (Fig. 1). These included: total tooth length (TOTL), minimum root
length (MNRL), maximum root length (MXRL), maximum root width (MXRW), and
maximum root thickness (MXRT). In addition, I measured crown width (CW) and crown
thickness (CT) of each tooth half way down the crown. Maximum crown width
(MXCW) and maximum crown thickness (MXCT) were taken at the crown ridge. The
anterior crown length (ANCL) and posterior crown length (PSCL) were taken from the
tip of the crown to the ridge of the crown (Fig. 1). All width and thickness measurements
were taken at the same points on the tooth just rotated 90°. Finally, I measured the
maximum pulp width (PW) of each tooth on radiographs. All measurements were taken
to the nearest 0.1mm using digital calipers.

The tooth measurements were log transformed and then used to create multiple
regression models using the software package SPSS (SPSS Inc. Chicago, IL: Version
10.1) with assigned age as the dependent variable and individual tooth measurements as
the independent variables. Separate models were created for males, females and both
sexes combined. For all models, forward selection was used with a significance criteria of p<0.05. Two-sample t-tests were used to determine whether the sexes differed in individual tooth measurements. One-way ANOVA was used to determine if there were differences in variables among the 7 age-classes. The Bonferroni post hoc test was used to identify differences among means when these occurred.

A subset of 20 randomly selected teeth (2-3 from each age-class) was measured by 5 readers to test the precision of these variables. These readers were enlisted to take the 11 measurements for each tooth. Each reader was instructed to use the tooth measurement composite drawings to aid in measuring teeth correctly (Fig. 1).

Coefficient of variation values (CV = standard deviation/ mean) (Campana et al. 1995) were calculated to determine the precision of the 5 readers’ measurements by calculating the CV for each tooth and then averaging to get the CV for each individual variable.

To determine whether wear patterns could be used to age coyotes, I carefully examined the subsample of 303 teeth looking for characteristic signs of age and wear, such as the buildup of tartar on the tooth and flattening of the tip and/or ridges on each tooth. Based on these inspections, I developed a key describing the typical appearance of canines in each age-class (Fig. 2). To supplement the key, I also made composite drawings (Fig. 3) and digital photographs (Fig. 4) showing typical wear patterns associated with each age.

To evaluate the accuracy and precision of aging based on the key, I used the key to age a random sample of 203 teeth. In addition, the 20 teeth used for the tooth measurements were also used by 4 of the same readers to estimate age. Three of the four readers were inexperienced in tooth wear aging. The other reader has experience aging
other mammals based on tooth wear. All readers were given a brief lesson on how to use the illustrated key, and then asked to independently age each of the 20 teeth. The CV was calculated for each reader and age bias graphs were developed to evaluate the relative accuracy and precision of each reader’s age estimates (Campana et al. 1995). Pearson correlations were calculated to compare the 4 readers’ estimated ages to the assigned ages and to compare my estimated ages to assigned ages for the larger sample of 203 coyotes.

RESULTS

Tooth Measurements

No single measurement could be used to separate coyotes into the 7 age-classes. I found no differences in total tooth length, crown width, maximum root length, minimum root length or maximum root width among classes (Table 2). However, there were differences in measurements among some of the age-classes. For example, maximum root thickness differed between the 0.5 year olds and the 1.5 and 2.5 classes, but not for any of the other ages (Table 2). Similarly, crown measurements (anterior and posterior crown lengths) were larger for younger coyotes (≤ 2.5) compared to older ones (> 2.5), but I did not find differences among classes within these broader age groups (Table 2). Crown thickness differed among the younger age-classeses, but not among the older age groups (Table 2). Pulp width was wider in 0.5 year olds than in the older classes, but did not differ among older classes. Although means sometimes differed among classes, there was usually overlap in the ranges of the measurements among age-classes (Table 2).

Therefore, because of the overlap it would not be possible to establish distinct size ranges
for any measurement that would allow biologist to categorize a coyote into a particular age-class.

Some of the variables measured by the 5 readers lacked precision, which suggests that they were difficult to measure reliably. Measurements of posterior crown length and maximum crown width were the least precise with CV values of 8.6 and 8.8. There were 3 measurements with intermediate levels of precision. Both crown width and crown thickness had CVs of 5.7 and maximum root thickness was 5.4. All other measurements had high levels of precision < 5.0. These include: anterior crown length (4.3), minimum root length (4.1), maximum crown thickness (4.0), maximum root width (2.5) and maximum root length (2.0). Total tooth length had the greatest amount of precision with a CV of 1.5.

T-tests showed that there were significant differences between the sexes on all tooth measurements except pulp width (Table 3). Measurements were generally larger for males than females. However, there was too much overlap between males and females to distinguish the sex of individuals based on tooth measurements (Table 3; Fig 4).

Since single measurements were not sufficient to separate individuals into biologically significant age-classes, I developed multiple regression models to investigate whether some combination of these measurements could accomplish this. Models were developed for males, females and both sexes combined. Each model was a significant predictor of age (p < 0.01). The model for both sexes combined was based on 6 tooth measurements. The following equation depicts these independent variables in-order of significance and their coefficients:
Age = -1.588 - 4.458(log PW) + 10.355(log MXRW) - 6.752(log PSCL) + 5.197(log MXCT) - 4.505(log ANCL) + 3.222(log MNRL)

This model had an $r^2 = 0.79$ ($F = 184.23; \text{df } = 6, 303$). The estimated ages and assigned ages correlated strongly (Fig. 5; Table 4). The first variable entered into the model was the pulp width (PW) which had a negative relationship with age (i.e. pulp width decreases with age). The second variable entered into the model was maximum root width (MXRW) which increases with age, as does maximum crown thickness (MXCT) and minimum root length (MNRL). The third and fifth variables entered in the model are posterior crown length (PSCL) and anterior crown length (ANCL) which both decrease with age, presumably as the crown wears down.

The regression model developed for female coyotes showed the best fit between predicted and assigned ages. The regression equation for females also used 6 measurements:

\[
\text{Age} = -7.104 - 4.193 \text{(log PW)} + 9.033 \text{(log MXRW)} - 7.918 \text{(log ANCL)} - 5.173 \text{(log PSCL)} + 8.186 \text{(log TOTL)} + 5.177 \text{(log MXCT)}
\]

This model had an $r^2 = 0.83$ ($F = 108.12; \text{df } = 6, 141$). The estimated and assigned ages correlated strongly for this model (Fig. 6; Table 4). Again, pulp width was the first variable entered in the model, followed by maximum root width. Anterior and posterior crown lengths were the third and fourth variables in the model and both decreased with age. Total tooth length (TOTL) and maximum crown thickness were the final variable entered in the model; both increased with age.
The model for males was the least successful at predicting age from tooth measurements. This model produced an $r^2 = 0.77$ ($F = 128.23$; df = 4, 159). The regression equation was:

$$Age = 3.467 - 4.596(\log PW) - 10.711(\log PSCL) + 9.707(\log MXRW) + 5.468(\log CT).$$

There was also a strong correlation between estimated and assigned ages with the model for males (Fig. 7; Table 4). As with the other models, pulp width was the first variable enter in the model. Posterior crown length decreased with age and maximum root width increased with age in males. Crown thickness also was positively related to age in male coyotes.

Of the 12 measurements that were recorded for each canine tooth, 8 were used in one or more of the regression models. Crown width, maximum crown width, maximum root length and maximum root thickness were not used in any model. There were 3 root measurements included in one or more models, therefore these models could not be used on a living animal without extracting the tooth. All models had at least one variable with low precision (posterior crown length). For the model with both sexes combined and the female model, the other 5 variables had medium to high precision.

**Tooth Wear**

Characteristic wear patterns were evident on the lower canine tooth as coyotes aged. Coyotes that were 0.5 years old had white canines with no tartar and the tooth was pointed with no wear. The ridge on the posterior lingual surface of the tooth was sharp.
and well defined (Table 1; Fig 2, 3). Yearlings showed a build-up of tartar, a slight rounding at the tip and wear at the distal end of the posterior ridge.

By 2.5 years of age, the posterior surface near the tip was worn to a small, flat oval and the medial section of the ridge was less distinct. As coyotes aged further, wear on the posterior surface extended farther down the tooth from the tip and the ridge was no longer visible. The tip of the tooth was flat or angled anteriorly in coyotes that were ≥4.5 years old. Coyotes in the 5.5 year and older classes had crowns that were noticeably shorter due to wear. Enamel on the posterior surface near the tip was worn away exposing dentine and nicks in the enamel were often visible on other areas of the crown.

Using these characteristics, I correctly aged 138 of 203 (68%) teeth (Fig. 8). In addition I aged 58 of the remaining 65 teeth within 1 year of the assigned age. Coyotes in the 3.5 and 4.5 age-classes were the most difficult to age accurately. There was a high correlation between estimated age and assigned age using this method ($r = 0.882; p < 0.001$).

Of the 4 independent readers that aged a subsample of 20 teeth, the most accurate was reader 3 who correctly aged 16 of 20 (80%) teeth using the key and was within 1 year on the other 4 teeth. This reader was also the most precise with a low coefficient of variation of 10.8 (Fig. 9, Table 5). In contrast, reader 2 was the least accurate, aging 10 of 20 (50%) coyotes correctly. However of the 10 coyotes that were aged incorrectly, 9 were within in 1 year of the assigned age. Readers 1 and 2 were the least precise; each had relatively high CVs of 35.6 (Fig 9, Table 5). The correlation between estimated age and assigned age was high for each reader with $r$ values ranging from 0.73 to 0.93 (Table 5). All 4 readers were most successful aging coyotes in the 0.5 and 1.5 age-classes, but
most tended to under-age individuals in the oldest age-class (Fig 10). The coefficient of variation for all readers combined was 27.9.

DISCUSSION

Effective methods of aging coyotes are necessary to understand and manage coyote populations (Linhart and Knowlton 1967, Jean et al. 1986). Accurate ages are important when determining the sex-age composition of a population, measuring age-specific natality and mortality rates, or investigating aspects of coyote predation and depredation (Gipson et al. 2000). Currently researchers rely on either counts of cementum annuli or tooth wear for aging coyotes. The former is thought to be the most accurate method, but it is costly, time-consuming, and requires extraction of a tooth. Further, estimating the number of annuli in some teeth can be highly subjective, particularly for older aged individuals (Nellis et al. 1978). Consequently, this technique has several drawbacks. Most notably, it is not suitable for aging individuals that are to be released back into a population and it may not meet specifications established by animal care and use committees (Gipson et al. 2000).

Bowen (1982) compared the accuracy of aging coyotes using a tooth wear chart developed by Gier (1957) versus cementum annuli and found that tooth wear provided reliable ages only for pups and yearlings. Gipson et al. (2000) compared the 2 techniques for aging gray wolves and reported that cementum annuli provided more precise estimates, but tooth wear was more applicable for field studies. Clearly tooth wear has potential for aging coyotes, but refinement of Gier's (1957) aging chart is necessary if individuals >1.5 years old are to be aged accurately and with precision.
Aging Based on Tooth Measurements

My first objective was to determine whether coyotes could be aged inexpensively and quickly by measuring an extracted lower canine. I hoped to find a measurement or combination of measurements that would provide an inexpensive alternative to cementum annuli for accurately aging coyotes into annual age-classes through 6.5 years old. My results suggest that there is no single canine measurement that can be used to determine age because of overlap. Individuals that were 3.5 year olds tended to be classified into one category or the other depending upon the measurement. Tooth wear in coyotes became particularly evident at 3.5 years of age, which is about the same age (3-4 years) that wear becomes apparent in gray wolves (Gipson et al. 2000).

Pulp width proved to be the only measurement that could be used to distinguish one age-class from the rest with virtually no overlap. The 0.5 year olds could be distinguished from all other ages based on their large pulp cavity. This supports what has been found in coyotes and in gray foxes (Knowlton and Whittemore 2001, Tumlison and McDaniel 1984).

Based on my sample of teeth, it is clear that coyotes show sexual dimorphism in canine morphology. Every external tooth measurement differed between the sexes. But, because there was overlap in measurements between the sexes, sex determination based solely on tooth size would be impractical. Sexual dimorphism in the size of canine teeth has been found in a number of Carnivores (Grau et al. 1970, Johnson et al. 1981, Gittleman 1997). The length of canines differs between males and females in raccoons
and bobcats, but similar to this study, there is too much overlap in bobcats to be useful for determination of sex (Grau et al. 1970, Johnson et al. 1981).

Because canines differ in size between the sexes and no single measurement could be used to place coyotes into age categories, I developed separate regression models for determining the ages of males and females. These models were highly correlated with the ages assigned using cementum annuli. The model for females had the best fit between estimated age from tooth measurements and assigned age from cementum annuli ($r^2 = 0.83$). Individuals in the age groups from 0.5 to 4.5 and $\geq 6.5$ years old were typically predicted within $\pm 1$ year, but the 5.5 year olds had a span of $\pm 2$ years. The model developed for the males also produced a good fit ($r^2 = 0.77$). The model that combined both sexes ($r^2 = 0.79$) was successful at predicting age from canine measurements. This model tended to underage coyotes over 3.5 years and was most accurate in assigning individuals in the 0.5, 2.5 and 3.5 year age-classes. Yearlings were frequently aged incorrectly as 2.5 years old with the model for males. The models were most successful at classifying coyotes in the 0.5 to 3.5 age-classes. Since the vast majority of coyotes in most populations fall into this age range, most researchers would need the greatest accuracy aging these individuals (Gier 1957).

The most important independent variable in each model was pulp width, which is particularly useful for identifying 0.5 year olds. This is consistent with prior studies that have reported that radiographs or cross sections of teeth can be used to separate juveniles from adults (Grue and Jensen 1976, Kuehn and Berg 1981, Knowlton and Whittemore 2001). It is not surprising that anterior and posterior crown length also were important variables that were negatively correlated with age. As the canine wears the average length
and thickness of the crown decreases 10-15% between 2.5 and 5.5 years of age and this trend probably continues with age. Gipson et al. (2000) noted that crown length was reduced 30-50% in wolves that were 10-12 years old. The crowns of canines in wolves ≥13 years old had declined by ≥ 50% in length and ≥ 30% in width (Gipson et al. 2000).

If researchers use tooth measurements to age coyotes, it is important to be careful while taking some measurements. Whereas I found that even inexperienced readers could measure total tooth length, maximum root length, minimum root length, maximum root width, maximum crown thickness, and anterior crown length with a high level of precision, posterior crown length and maximum crown width were much more difficult to measure precisely.

Aging Based on Tooth Wear

My second objective was to develop and test a descriptive key for assigning coyotes to annual age-classes based on tooth wear that could be used on living coyotes. Illustrated graphs and keys have been used frequently to help wildlife managers and researchers age species (Dimmick and Pelton 1994, Harshyne et al. 1998). To date, the only aging chart that is available for coyotes is Gier’s (1957) drawing that shows progressive wear as a series of lines on a frontal view of the canines and incisors. Although this illustration has been widely reproduced and used by coyote biologists, there are several significant limitations to it use. First, aging a coyote by comparing the wear on an individual’s teeth to the lines on the drawing can be highly subjective. Second, the age-classes illustrated overlap broadly, limiting its utility (Landon et al. 1998). But in spite of these limitations, Linhart and Knowlton (1967) found that there
was a good correlation between ages assigned using this aging chart and counts of cementum annuli. Other important advantages are that the technique is quick, cheap and can be conducted in the field without extracting teeth. Gipson et al. (2000) produced a similar illustration for aging gray wolves, but added a written key to aid biologists.

I found that coyotes in Illinois do have characteristic patterns of tooth wear that correlate well with ages assigned using cementum annuli. Use of these wear patterns to estimate age provides a viable alternative to the use of cementum annuli, particularly when it is not desirable to remove the tooth or when limited budgets preclude the more expensive technique. Inexperienced readers were generally able to estimate age accurately. Collectively, readers correctly aged 50-80% of all coyotes and were within ±1 year on most others. Consequently, there was a high correlation between estimated ages based on wear and those from cementum annuli ($r^2 = 0.88; p<0.01$). Bowen (1982) reported that 17 of 30 (57%) coyotes were assigned to the same age using Gier's (1957) chart and cementum annuli counts. Linhart and Knowlton (1967) also found a high correlation between annuli counts and relative tooth wear using all of the teeth in a series of cleaned coyote skulls.

Readers using my key had the greatest difficulty aging coyotes that were 3.5 years olds. Whereas the mean age assigned to coyotes in the other age-classes was within 0.5 years of the assigned age, this was the only age that had a span of at least 1 year. As with tooth measurements, the amount of wear on canines that is visible during the third year is transitional between younger classes with little wear and older classes with noticeable wear. Therefore, there appears to be a tendency to under-age or over-age 3.5 year old coyotes. Since we were able only to examine one canine from each individual (the second
was submitted for cementum annuli counts), we may have been able to age individuals in this class more accurately if we could have examined both teeth. Individual animals have a tendency to chew predominantly on one side or the other, so wear may be uneven on the 2 canines. Taking both teeth into consideration when aging may improve accuracy using the key. Except for the overlap between 2.5 and 3.5 year olds, we found that it was relatively easy to distinguish the other age-classes.

It is important to note however, that I aged coyotes into annual age-classes only through 6.5 years of age, whereas laboratories that use cementum annuli typically age individuals up to 13 years (Linhart and Knowlton 1967). While aging old coyotes accurately may be necessary on occasion, the majority individuals in most populations occur in the 3 youngest age-classes. For example, Gier (1957) reported that approximately 90% of the coyotes in Kansas were less than 3 years old and few individuals lived past their sixth year. Similarly, Lloyd (1998) reported that 89% of the 996 coyotes that he examined in Illinois were ≤ 2.5 years old and 97% were ≤ 5.5 years old. Based on his data, only 2.5% of Illinois coyotes would be categorized into my oldest (≥ 6.5 years) age-class. Therefore, it does not seem to be necessary to extend the key to cover older classes.

The experience of the reader likely affects his/her precision in aging. The most experienced reader in my study was the most precise, producing the lowest CV value. CV values were relatively low for all readers, suggesting that even inexperienced readers can age coyotes with reasonably good precision using the illustrated key. Precision was lowest for the 2.5 and 3.5 year age-classes. Our precision was similar to that of a series of 4 readers who used an illustrated key to estimate the ages of wolves (Gipson et al
Our CV values ranged from 10.8-35.6, whereas theirs ranged from 19.5-26.7 (Gipson et al. 2000). I did not have known-age coyotes in my sample and could not evaluate the accuracy or precision of the ages assigned to my coyotes by the commercial aging service. However, Gipson et al. (2000) reported that this company was more precise (CV value = 14) than his readers at aging wolves.

In summary, both techniques that I evaluated for aging coyotes appear to provide practical alternatives to cementum annuli for aging coyotes. Anesthetized coyotes in the field can be aged up to 6.5 years old using the illustrated key, a dental mirror and a flashlight. My results suggest that 50-80% of these individuals will be aged correctly and the rest within ± 1 year of actual age. When a lower canine can be removed from a living coyote or harvested carcass, a series of tooth measurements can be used in conjunction with my regression equations to age coyotes. Regardless of which method is used, it may be beneficial to have 2 readers estimate the age of each individual and come to a consensus before assigning an age. In addition, age estimates may be more accurate if readers examine and/or measure both lower canines to estimate age. Researchers engaged in large-scale population studies, where accurate aging is important, could age all individuals using tooth wear, then submit a smaller subsample of teeth to a commercial laboratory for aging by cementum annuli. This subsample then could be used to monitor the accuracy of ages assigned to the larger sample. Although, I could not gauge the accuracy of my techniques on a sample of known-age coyotes, both methods produced results that were comparable to estimates using cementum annuli, both were quicker and cheaper than the latter method, and aging based on tooth wear has the additional advantage of being non-invasive.
LITERATURE CITED


Gier, H. T. 1957. Coyotes in Kansas. Agriculture Experiment Station, Kansas State University, Manhattan, Kansas, USA.


Table 1. Key for aging coyotes based on tooth wear.

1. If there is no wear on the posterior tip of the crown and it is rounded, it is either 0.5 or 1.5.
   - if the tooth is white, pointed and has a prominent ridge it is 0.5.
   - if the tooth is slightly rounded and there is some wear on the distal portion of the ridge, it is 1.5.

2. If there is some wear on the posterior tip of the crown, it is $\geq 1.5$.
   - if there is less than 2.5 mm of wear only at the tip on one side and the ridge is still distinct, it is 1.5.
   - if there is more than 2.5 mm wear only at the tip but it is smooth on one side or across the tooth and the ridge is still noticeable, it is 2.5.

3. If there is more than 3mm of wear on the posterior crown and it is no longer localized at the tip. There is some wear down the back of the tooth but the point is still rounded and the ridge is not as distinct it is either 3.5 or 4.5.
   - if the wear descends the posterior crown and it is starting to appear straight and flattened and it is still a large tooth, it is 3.5.
   - if the wear continues to descend the posterior crown and is starting to move anteriorly; the crown point is angled anteriorly; there are a few small nicks on the anterior distal portion of the crown but the tooth is still large, it is 4.5.

4. If the crown point is angled anteriorly and there is a noticeable amount of wear on the anterior portion of the crown or the point is flattened and smooth with anterior nicks, it is $\geq 5.5$.
   - if the tooth is still somewhat large with only a few nicks it is 5.5.
   - if the tooth is noticeable smaller with several small nicks or a few large ones, it is older than $\geq 6.5$ years.
Table 2. Means, standard deviations and ranges determined from a one-way ANOVA for tooth measurements from coyotes. Means followed by different letters significantly different at an α=0.05. Standard deviations are in parentheses. Ranges are shown beneath the means and standard deviations.

<table>
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<th>Age-class</th>
<th>0.5</th>
<th>1.5</th>
<th>2.5</th>
<th>3.5</th>
<th>4.5</th>
<th>5.5</th>
<th>&gt;6.5</th>
</tr>
</thead>
<tbody>
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<td>38.3 (2.1)</td>
<td>37.3 (2.5)</td>
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<td>37.2 (2.9)</td>
<td>37.7 (2.2)</td>
</tr>
<tr>
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<td>32.7-42.1</td>
<td>33.9-42.1</td>
<td>33.1-41.1</td>
<td>31.5-41.7</td>
<td>32.8-40.8</td>
<td>34.1-41.5</td>
</tr>
<tr>
<td>Anterior</td>
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<td>12.1abc (1.0)</td>
<td>12.5ab (1.2)</td>
<td>11.5c (1.4)</td>
<td>10.7c (1.4)</td>
<td>10.8c (1.4)</td>
<td>10.4c (2.0)</td>
</tr>
<tr>
<td>Length</td>
<td>13.7a (1.5)</td>
<td>14.1ab (1.3)</td>
<td>14.3ab (1.3)</td>
<td>12.9abc (1.4)</td>
<td>12.4c (1.4)</td>
<td>12.2c (1.5)</td>
<td>11.8c (1.8)</td>
</tr>
<tr>
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<td>11.1-17.4</td>
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<td>5.8 (0.5)</td>
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<td>4.9-6.3</td>
<td>4.7-6.2</td>
</tr>
<tr>
<td>Max</td>
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<td>8.8a (1.1)</td>
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<td>Crown</td>
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<td>6.7-10.8</td>
<td>7.2-9.3</td>
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<td>5.9-9.0</td>
</tr>
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<td>4.3ab (0.4)</td>
<td>4.4ab (0.4)</td>
<td>4.5b (0.4)</td>
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Table 2. continued

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<th>4.5</th>
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<th>&gt;6.5</th>
</tr>
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<td>5.8b (0.5)</td>
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<td>5.8ab (0.4)</td>
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<td>6.0b (0.3)</td>
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<td>4.6-6.9</td>
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<td>23.6-34.4</td>
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</tr>
<tr>
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<td>16.1-24.9</td>
<td>17.7-23.1</td>
<td>14.4-23.8</td>
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<td>Max</td>
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Table 3. Means, standard deviations and t and p-values for 2-tailed t-tests for significant
difference between male and female coyote measurements. The ranges are in parentheses
under the means.

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<th>Measurement</th>
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<th>Female</th>
<th>t-value</th>
<th>p-value</th>
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<td></td>
<td>X</td>
<td>SD</td>
<td>X</td>
<td>SD</td>
</tr>
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<td>1.8</td>
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</tr>
<tr>
<td></td>
<td>(35.3-42.1)</td>
<td></td>
<td>(31.4-40.8)</td>
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</tr>
<tr>
<td>Anterior Crown Length</td>
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<td>1.2</td>
<td>11.4</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>(8.7-15.2)</td>
<td></td>
<td>(8.0-14.2)</td>
<td></td>
</tr>
<tr>
<td>Posterior Crown Length</td>
<td>14.3</td>
<td>1.4</td>
<td>12.9</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>(10.5-17.7)</td>
<td></td>
<td>(10.1-16.2)</td>
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<tr>
<td>Crown Width</td>
<td>5.9</td>
<td>0.4</td>
<td>5.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>(4.7-6.9)</td>
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<td>(4.7-6.4)</td>
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<tr>
<td>Max Crown Width</td>
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<td>0.9</td>
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<td></td>
<td>(7.2-11.4)</td>
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<td>(5.9-10.8)</td>
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<tr>
<td>Crown Thickness</td>
<td>4.5</td>
<td>0.4</td>
<td>4.1</td>
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<td></td>
<td>(3.9-5.6)</td>
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<tr>
<td>Max Root Length</td>
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<td>27.6</td>
<td>1.9</td>
</tr>
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<td>(23.5-31.9)</td>
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</tr>
<tr>
<td>Min Root Length</td>
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<td>19.3</td>
<td>1.6</td>
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<td>(0.4-7.1)</td>
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</table>
Table 4. The independent r-squares for each variable that was included in the 3 multiple regression equations for both sexes combined, females and for males.

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<th>Measurement</th>
<th>Both Sexes Combined</th>
<th>Female</th>
<th>Male</th>
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<td>Max Root Width</td>
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<td>Posterior Crown Length</td>
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<tr>
<td>Crown Thickness</td>
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<td>-</td>
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Table 5. Simple linear regression analysis of estimated age and assigned age for the 4 readers.

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<tr>
<th>Reader</th>
<th>$r^2$</th>
<th>Intercept ($\alpha$)</th>
<th>Slope ($\beta$)</th>
<th>P-value</th>
<th>$Ho: \alpha=0$</th>
<th>$Ho: \beta=0$</th>
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<tr>
<td>Reader 1</td>
<td>0.82</td>
<td>0.31</td>
<td>0.93</td>
<td>0.31</td>
<td>&lt;0.001</td>
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<td>Reader 2</td>
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<td>0.34</td>
<td>0.90</td>
<td>0.39</td>
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<tr>
<td>Reader 3</td>
<td>0.93</td>
<td>0.00</td>
<td>1.00</td>
<td>*</td>
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<tr>
<td>Reader 4</td>
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<td>0.14</td>
<td>0.94</td>
<td>0.61</td>
<td>&lt;0.001</td>
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Fig. 1. Composite drawing showing tooth measurements for posterior and lingual views of the lower canine in coyotes.
Fig. 2. Tooth drawings showing typical wear on the lingual and posterior surfaces for coyotes in ages-classes 0.5 to ≥6.5. Arrow on the lingual view identifies crown ridge. Arrow on posterior view identifies posterior ridge.
Fig. 3. Pictures of tooth wear on the lingual and posterior surfaces for ages 0.5-6.5 years old. Circles highlight areas of wear.
Fig 4. Assigned age (based on annuli counts) and maximum root thickness for male and female coyotes. Females are the dark circles, males the clear diamonds.
Fig. 5. Age bias graph for assigned age versus model predicted age for coyotes of both sexes combined (n = 303; $r^2 = 0.79$). The solid line is the 1:1 equivalence line. The triangles are mean predicted age and the bars represent 95% confidence intervals for each mean.
Fig. 6. Age bias graph for assigned age (based on annuli counts) versus model predicted age for female coyotes (n=141; r=0.90). The solid line is the 1:1 equivalence line. The triangles are mean predicted age and the bars represent 95% confidence intervals for each mean.
Fig. 7. Age bias graph for assigned age (based on annuli counts) versus model predicted age for male coyotes (n=159; r=0.877). The solid line is the 1:1 equivalence line. The triangles are mean predicted age and the bars represent 95% confidence intervals for each mean.
Fig. 8. Age bias graph for assigned age (based on annuli counts) versus estimate age (based on tooth wear) for the subset of 203 lower canine teeth from coyotes (n=203; r=0.882). The solid line is the 1:1 equivalence line. The triangles are mean predicted age and the bars represent 95% confidence intervals for each mean.
Fig 9. Age bias graphs for assigned age (based on annuli counts) and estimated age (based on tooth wear) by the 4 independent readers and their coefficient of variation values. The solid line is the 1:1 equivalence line. The triangles are mean predicted age and the bars represent 95% confidence intervals for each mean.
Fig 10. Age bias graph of assigned (based on annuli counts) age versus mean estimated age (based on tooth wear) for all readers combined (CV=27.9). The solid line is the 1:1 equivalence line. The triangles are mean predicted age and the bars represent 95% confidence intervals for each mean.