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TECHNICAL NOTE

Caroline M. Wilkinson,[1] *Ph.D. and Sophie A. Mautner,*[1] *B.Sc.*

Measurement of Eyeball Protrusion and Its Application in Facial Reconstruction

ABSTRACT: The estimation of eyeball protrusion from the bony orbit has traditionally relied upon Wolff's theory (1976) that the cornea will be tangental to a line taken from the superior to the inferior orbital margin. This study tested this theory by taking measurements from MRI cranial images of 78 eyes of white adult subjects. Orbital depth had a significant negative linear correlation with eyeball protrusion, and protrusion of the eyeball was determined by the following standard: eyeball protrusion = 18.3 − (0.4 x orbit depth). Current eyeball position determination was shown to be as much as 3.9 mm too deep in the socket, and a practical application of this result to facial reconstruction is discussed.

KEYWORDS: forensic science, facial reconstruction, orbit, eye

Facial reconstruction is the building of the face of an individual onto the skull, and has been used as an investigative tool in the forensic identification of skeletal remains (1–4). This procedure has been exercised for over a century and the three main techniques (two-dimensional, three-dimensional, and computer-generated) share the common principle of relating the skeletal structure to the overlying soft tissue. Such a relationship was first suggested by Galen, (c. 129–199), the Roman physician, who stated "As poles to tents and walls to houses, so are bones to all living creatures, for other features naturally take their form from them and change with them" (3). The ultimate aim of facial reconstruction is to recreate an in vivo countenance of an individual that sufficiently resembles the deceased person to allow recognition. Many forensic investigations world-wide have used facial reconstruction to produce recognition and identification. The American method as practiced by Gatliffe (1) claims a 65% success rate and the British method as used by Neave (3) and Wilkinson (5) claims a 75% success rate. There has, however, been much criticism of the accuracy of facial reconstruction. In 1922, Stadmuller (6) carried out several accuracy studies and concluded that a reconstruction provides only an approximation of a basic head type. More recently, Hagland and Reay (7) carried out an experiment to evaluate facial reconstruction techniques in identification of the Green River serial murder victims, and concluded that "although resemblance to the deceased is desired, this goal is rarely achieved . . . and unrealistic expectations among both the public and the investigators have been created." Stephan and Henneberg (8) carried out a study of the accuracy of several methods of facial reconstruction, and their results suggested that facial reconstruction does not produce a good likeness to an individual and would be detrimental to any forensic identification case.

Many other studies have shown facial reconstruction in a more positive light. Wilder (9) was a great proponent of the facial reconstruction procedure and stated that the method is so simple that it can be readily performed by anyone who follows the directions and the very first attempt cannot help being at least moderately successful. However, he did warn that any weakness lay in the opportunity for imagination on the part of the investigator at such features as the lips, the soft parts of the nose, and the set of the eyes. In 1970, Snow et al. (10) carried out an appraisal of the method and expressed guarded optimism that a reconstruction may produce a face bearing a fundamental resemblance to the individual. Gerasimov (11) attributed failure in the facial reconstruction technique to the "carelessness [of sculptors who] do not pay great attention to the correlation between the shape of the skull and the thickness of the soft parts." In 1940, he carried out a blind mass control experiment using 12 cadavers from a mortuary in Moscow Medical Institute, and claimed that all 12 heads established a similarity with police photographs of the deceased. Neave (3) carried out a blind study of the reconstruction of a skull copied from the CT data of a live volunteer. The reconstruction was sufficiently similar to the individual for Neave to recognize him in a room full of people.

There has been substantial research into quantifying the relationship between the skeletal structure of the skull and the overlying soft tissues of the face, with the express purpose of facilitating facial reconstruction. Gerasimov (11) was convinced that there was a clear correlation between the relief of the skull and the surface of the soft stratum. He stated that this can be seen in the asymmetry of the skull, which shows itself in the asymmetry of the face. He suggested that asymmetry is a basic element of individuality and that since the asymmetry is natural, any reconstruction of the soft tissues will define the character of this asymmetry and secure simi-

[1] University of Manchester, Unit of Art in Medicine, 3.239 Stopford Building, Oxford Road, Manchester, M13 9PT, United Kingdom.
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larity to the actual face. Broca (12) is widely considered to be the first researcher to study the congruences between the structure of the skull and the overlying soft tissues that define appearance. He found great individual variation in soft tissue thickness from one person to the next and noted that the features of the face appeared to be based on the individual skull. Krogman and Iscan (13) stated that "the skull is the matrix of the living head; it is the bony core of the fleshy head and face in life." Gerasimov claimed that the main error when carrying out a facial reconstruction was to view the separate details of the face as something independent or isolated from the general composition of the face (11). He suggested that the facial form should be recreated using observations on the correlation between muscle attachments on the skull and the degree of size and configuration of the separate parts of the skull. The caricaturist Drucker (14) stated "We all have the same features, it's the spaces between them, their proportions and relationships to one another that distinguish one face from another."

The majority of facial anthropology research has concentrated on the relationship between the bony skull and the mouth and nose (15,16). There has been little scientific study into other facial features and one neglected area is the relationship between the eyeball and the orbit. The eyes are a vital part of the final face, and their position clarifies the correct proportions of the middle third of the face. Whitnall (1911) published initial studies of the orbits with the first known description of the malar tubercle and Stewart further studied the position of the palpebral ligaments at the inner canthus on the Terry Collection of skulls at the Smithsonian Institution (17). Angel placed the inner canthus 2 mm lateral to the lacrimal crest and at their middle, while the outer canthus was placed 3–4 mm medial to the malar tubercle (18). Fedosyutkin and Nainys (12) found that the length of the eye fissure was 60–80% of the width of the orbit. When the malar tubercle was absent (in 15% of skulls), they suggested placing the outer canthus 8.5 mm below the frontozygomatic suture in males and 9.5 mm below in females. However, all these studies, with the exception of Stewart, did not produce rigorous scientific data to substantiate these claims.

Currently the eyeball is positioned in the orbit by placing the cornea approximately tangent to a line drawn from superior to inferior margins of the orbit (19). Wolff stated that "a straight line placed against the superior and inferior orbital margins will just touch or just miss the front of the cornea" (20). Fedosyutkin and Nainys disagreed and proposed that "protrusion of the eyeballs from the orbit is established based on the depth of the orbital cavity, vertical inclination of the orbit and thickness and degree of overhang of its upper rim" (12). Some clinical studies have attempted to determine eyeball position, using medical imaging data, but the formulae suggested is not easily applied to skeletal material (21,22). There have been many ocular morphometry studies using MRI and CT scans, but these studies did not determine eyeball position (23,24). Many sources mention placing the eyes in the sockets "at the proper depth," but few explain how this is calculated and the decision appears to be left to the discretion of the forensic artist (25–27). Some research has been carried out into eyeball size. Wolff (20) stated that the anteroposterior eyeball diameter is 24 mm in adults, with the mean male diameter of 24.6 mm and a mean female diameter of 23.9 mm. Tian et al. (23) used MRI to study orbital structures and found that the mean eyeball diameter was 25.5 mm, with no differences related to sex. Other studies are in agreement with Wolff (28,29), who also found no differences related to racial origin. Gerasimov (30) discovered that Negroid skulls had the smallest orbits, Caucasoid skulls had medium-sized orbits and Mongoloid skulls had the largest orbits. But he found that the size of the eyes was not correlated to the diameter of the orbits and that Caucasoid skulls had the largest eyes, Negroid skulls had medium-sized eyes and Mongoloid skulls had the smallest eyes. However, Gerasimov did not publish his measurements and there are no recorded standards for eyeball size differences between ethnic groups. Most of the existing data appears to be taken from a Caucasoid population.

This study aimed to test the validity of these methods of eyeball placement in an adult white population. MRI was chosen in order to provide clear images of a structure containing both soft tissue and bone with good contrast (31). Hydrogen is abundant in fat and water, so MRI has better soft tissue resolution than CT and, due to MRI's high inherent contrast resolution, the clarity of the edges between tissue and bone allow measurements. MRI also produces images in optical sections and has multi-planar capabilities, which make it useful for this type of study.

Many studies (32,33) suggest that the appearance of the eye will change in relation to age, but these changes appear to be related to the amount of soft tissue surrounding the eye and the width and slope of the eye fissure. The orbital volume, eyeball size, and eyeball position has been shown to be relatively consistent throughout adulthood (21,34). However, disease, dehydration and fatigue can

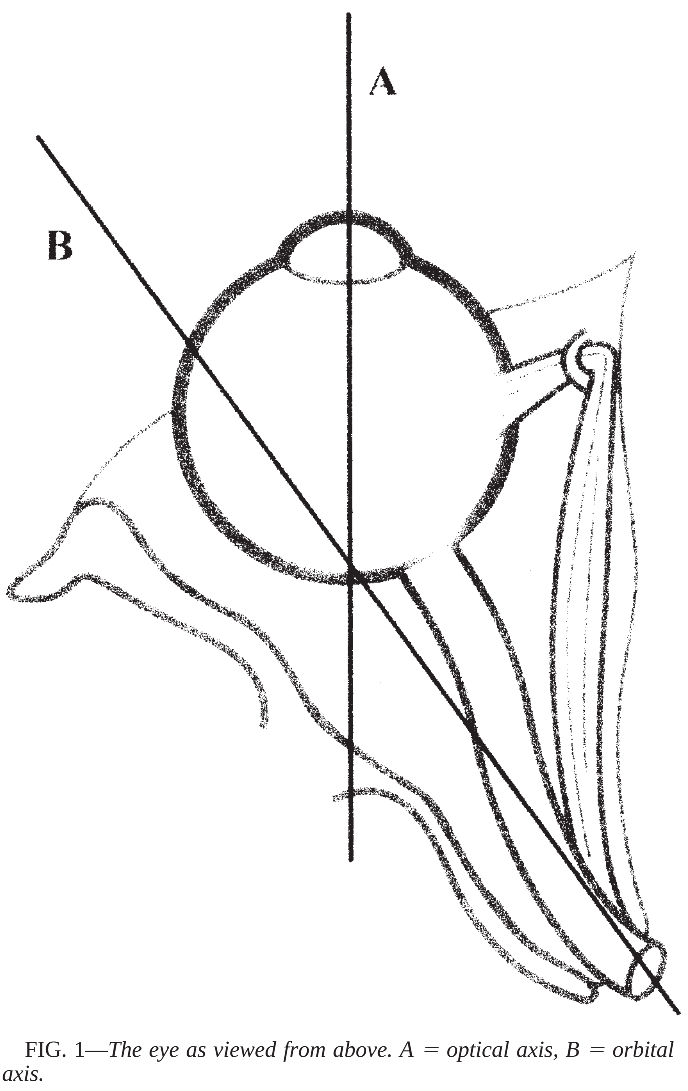

FIG. 1—*The eye as viewed from above. A = optical axis, B = orbital axis.*

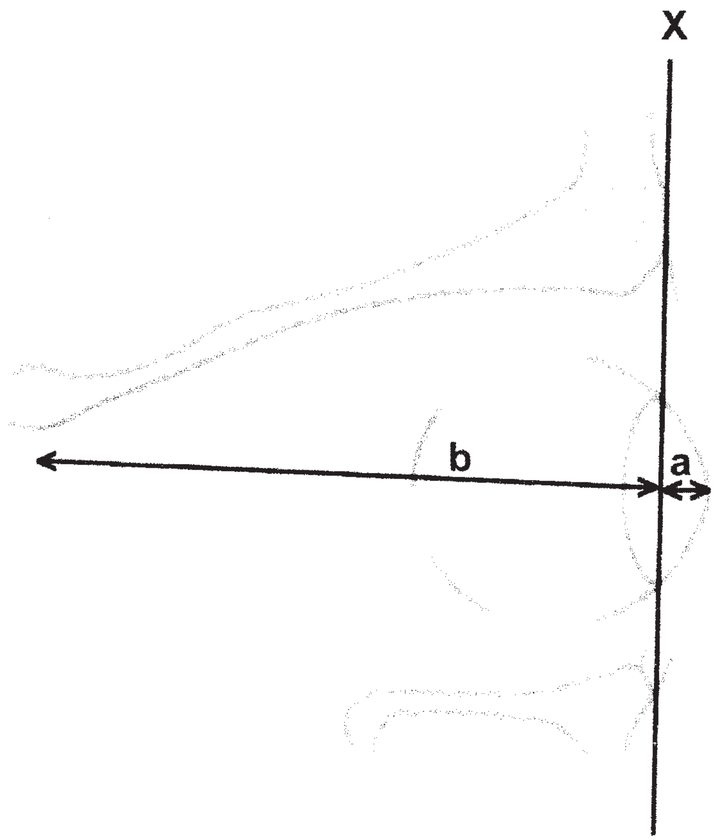

FIG. 2—*The eye as viewed in lateral view. X = tangential line from mid-supraorbital to mid-infraorbital points. a = eyeball protrusion, b = orbital depth.*

all affect the "apparent" eyeball position. Clearly the many facial changes associated with development and growth will affect the appearance of the eyes. Eyeball volume, orbital volume, ocular muscle volume, intercanthal distance and interpupillary distances have all been shown to alter in relation to age throughout childhood (21,31,35). Therefore this study was limited to adults and the use of only a single elderly age group was not considered to be significant. The aims of this research were to study the relationship between the depth of the orbit and the protrusion of the eyeball, and evaluate the possible applications of this study for use in forensic facial reconstruction.

Method

The heads of 39 white adult patients (11 males and 28 females) were scanned using a Philips NT Gyroscan Powertrak 6000 MRI scanner, as part of a study carried out in 1999 by Professor Alan Jackson (School of Biological Sciences, University of Manchester) on Elderly Depression. The subjects ranged in age from 60 to 90 years old and the scans were taken as series of 1.5 mm (T1 volume) "slices." The images were then imported into the Philips Sun workstation running a UNIX operating system with Philips EasyVision software, so that measurements could be taken. The image was manipulated in the sagittal plane to show the full depth of the orbit from the apex where the optic nerve exits the orbit to the cornea. This is called multi-planar reconstruction and was carried out due to the 20°–25° angle between the optical axis and the axis of the bony orbit (see Fig. 1). This reconstruction gives a slightly curved plane along which the full measurement of orbit depth can be taken. Two measurements were taken from each orbit (left and right) on the sagittal plane with an accuracy to 0.1 mm. A tangental line (X) was taken from the mid-supraorbital point to the mid-infraorbital point. The two soft tissue measurements were taken from the mid-point of line X. The first: (a) was taken from X to the outer edge of the cornea (eyeball protrusion), and the second (b) was taken from X to the apex of the orbit (orbit depth) (see Fig. 2).

The statistical package SPSS was used to carry out analysis of the results. Correlation was used to discover whether orbital depth bears any relationship to eyeball protrusion. If the correlation was statistically significant, regression was then carried out to determine whether one could be used to predict the other.

Results

There was no significant difference between left and right eye results or between male and female groups (see Table 1). These results showed that Wolff, among others, was incorrect in stating that a straight edge placed against the superior and inferior orbital margins will just touch or just miss the front of the cornea (14). Not a single measurement for eyeball protrusion (a) showed a negative figure (indicating that the cornea was deeper than line X) (see Table 1). The range was from 0 to 9.4 mm, with a mean of 3.8 mm (±0.1 mm), showing that the eyeball touched or protruded past the line X in every case.

Statistical analysis between eyeball protrusion: (a) and orbit depth, (b) showed the R value to be -0.646 ($p < 0.001$). There was significant negative correlation between eyeball protrusion and orbit depth (see Fig. 3). As orbit depth increased, eyeball protrusion decreased, and eyeball protrusion can be calculated using the following formula:

$$\text{eyeball protrusion} = 18.3 - (0.4 \times \text{orbit depth})$$

It would be difficult to find the optical axis and the sagittal orbit depth on a dry skull, since this relies on the position of the eyeball relative to the socket. If this research is to be of use, it was essential to find a practical way to position the eyeball in the socket. Therefore, it was determined that the eyeball can be positioned in the orbit so that a tangent taken from the superior to the inferior orbital margins touches the iris, rather than the cornea, assuming that the cornea is approximately 3.8 mm beyond the iris (20). This gives a more realistic shape to the orbital area than the previous method, since using Wolff's technique resulted in the eyes being placed too deeply, giving the appearance of smaller eyes.

TABLE 1—*Ocular morphometry results.*

	Eyeball Protrusion	Orbit Depth	Eyeball Diam
Total ($n = 39$)			
Mean (mm)	3.8	36.32	23.28
SD	2.48	4.01	1.66
Male ($n = 11$)			
Mean (mm)	3.82	36.32	23.21
SD	2.43	3.98	1.76
Female ($n = 28$)			
Mean (mm)	3.75	36.32	23.42
SD	2.65	4.16	1.41
T-test—sex (p value)	0.914	0.994	0.612

It is essential, at this stage, to mention that the appearance of the eyes in the face is not solely based on their protrusion. The appearance of the eyes depends greatly on the tissue around them, including "the shape of the eyelids, their folds, the size and shape of the eye opening, the form of the eyelashes, and so forth" (18). Fedosyutkin and Nainys point out that a well-developed brow ridge and bridge of nose intensify the impression of deep-set eyes because of the shadow cast in the socket area (12). There are also factors that change the appearance of the eyes continually, such as fat, age and dehydration. Age causes "marked alterations in the face" and although the actual position of the eyeball in the socket does not appear to change over time, the superficial fascia around the orbit does (18). As connective tissue becomes less elastic with increased age, the skin around the eyes tends to "droop." There is also a noted loss of muscle mass in aging accompanied by a tendency for fat to be laid down around and within the muscles (36). This has a cumulative effect, leading to an impression of deeper set and lower placed eyes.

It seems that Wolff, and many others, were not as accurate in their method of determining eyeball protrusion as Fedosyutkin and Nainys, who claimed that eyeball protrusion can be determined from the depth of the orbital cavity, vertical inclination of the orbit and the thickness and degree of overhang at the superior orbital margin (12). The orbital inclination and superior orbital margin pattern have not been examined in this study, but it is clear that much greater emphasis should be placed on the depth of the orbital cavity than has been considered by many before. It would also be interesting to analyze the relationship between the eyeball protrusion and the orbital inclination, superior orbital margin pattern and the inter-relationships between these factors. There is obviously a great deal more work to be done to investigate the role of the orbit

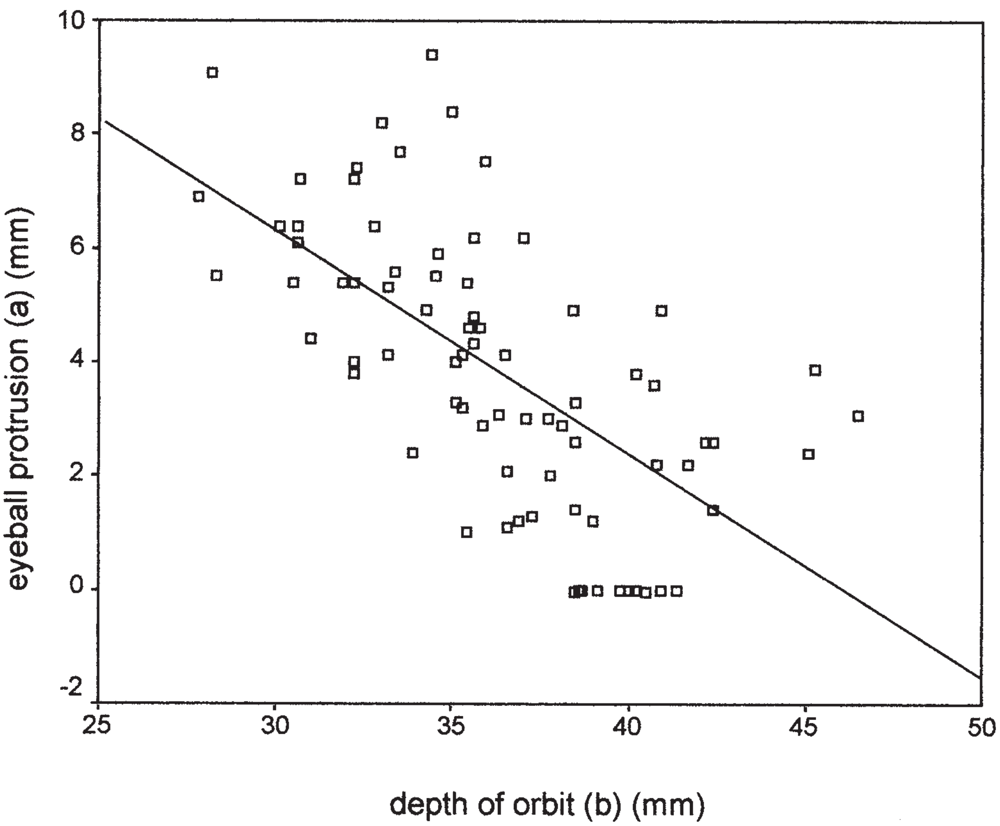

FIG. 3—*Graph showing eyeball protrusion in relation to orbit depth.*

in facial reconstruction. This research has drawn some interesting conclusions about the accuracy of the current method of determining eyeball protrusion. It is clear that, although these results were statistically significant, further research is necessary. As Gatcliff (1) states, "the outcome [of facial reconstruction] is uncertain in every case," but this research and similar studies may limit that uncertainty as far as possible by creating scientific standards. Any increase in the amount of facial detail that can be extrapolated from the bony skull will increase the degree of accuracy of the facial reconstruction, and, hopefully, increase the success rate of forensic identification investigations.

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Additional information and reprint requests:
Caroline M. Wilkinson, Ph.D.
Unit Manager/Medical Artist
Unit of Art in Medicine
Faculty of Medicine, Dentistry, Nursing and Pharmacy
3.239 Stopford Building
Oxford Road
University of Manchester
M13 9PT
United Kingdom