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FEATURE ARTICLE

Virtual Anthropology (VA): A Call for *Glasnost* in Paleoanthropology

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The adventurous scientist, with a hat protecting him from the fierce sun as he travels from one remote place to another, hunting for fossils of our ancestors, has been a part of the romantic imagination associated with anthropological research in the 20th Century. This picture of the paleoanthropologist still retains a grain of truth. Indeed, many new sites were discovered under troublesome conditions in the recent past and have added substantial information about our origins. But on another front, probably less sensational but no less important, are contributions stemming from the analysis of the already discovered fossils. With the latter, a rapid evolution in anthropologic research took place concurrently with advances in computer technology. After ambitious activities by a handful of researchers in some specialized laboratories, a methodologic inventory evolved to extract critical information about fossilized specimens, most of it preserved in the largely inaccessible interior as unrevealed anatomic structures. Many methodologies have become established but, for various reasons, access to both the actual and the digitized fossils is still limited. It is time for more transparency, for a *glasnost* in paleoanthropology. Herein are presented some answers to the question of how a high-tech approach to anthropology can be integrated into a predominantly conservative field of research, and what are the main challenges for development in the future. *Anat Rec (New Anat) 265:193–201, 2001.* © 2001 Wiley-Liss, Inc.

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VIRTUAL ANTHROPOLOGY

Virtual anthropology (VA), computer-assisted anthropology, or however else one may call it, is designed to allow investigations of three-dimensional morphologic structures by means of digital data-sets of fossil and modern hominoids within a computational environment. Three-dimensional (3D) data are acquired by different computer-necessitating processes, depending on the needs of the analysis at hand. For surface measurements, a laser scan can record the complete surface. Laser scans can be regarded as an appropriate tool for paleoanthropological tasks (Aiello et al., 1998). If one is focusing on landmark or contour data, simple digitizers based on magnetic field-dependent systems or mechanical systems can fulfill a reliable and time-saving task.

More expensive in every sense is the acquisition of volume data, but once it has been recorded, it provides more flexibility for many kinds of further analysis because the real object has been converted into a virtual one throughout the volume. The exact copy of the original object is limited only by the spatial resolution of the scanning device. Medical diagnostic radiology is most often used for volume recording. This idea is not recent; only 7 years after W. Roentgen presented the details of the discovery of x-rays, two-dimensional radiographs were used to study the fossilized Krapina Neanderthals (Gorjanovic-Kramberger, 1902). But the extension into the third dimension dramatically enhanced the possibilities of qualitative and quantitative analysis of morphology. Computed tomography (CT), also based on x-ray technology and developed in the early 1970s, was applied to fossil studies in the 1980s by Conroy and Vannier (1984), Wind (1984), and Zonneveld and Wind (1985). CT is especially useful when studying fossil skeletal remains, because the fossilized material delivers excellent signals. The resulting output of a CT scanner is a 3D data matrix, consisting of small information units, called voxels (cf. pixels in 2D). Dedicated software can visualize the virtual object on the computer screen and allows for manipulations like scaling, magnifying, rotating, cutting, moving, measuring, or photographing.

A related kind of data, but acquired with a different method based on pulses of radiofrequency, is produced by magnetic resonance imaging (MRI). In contrast to CT, this technique is sensitive to spin orientation of hydrogen nuclei and, thus, best ap-

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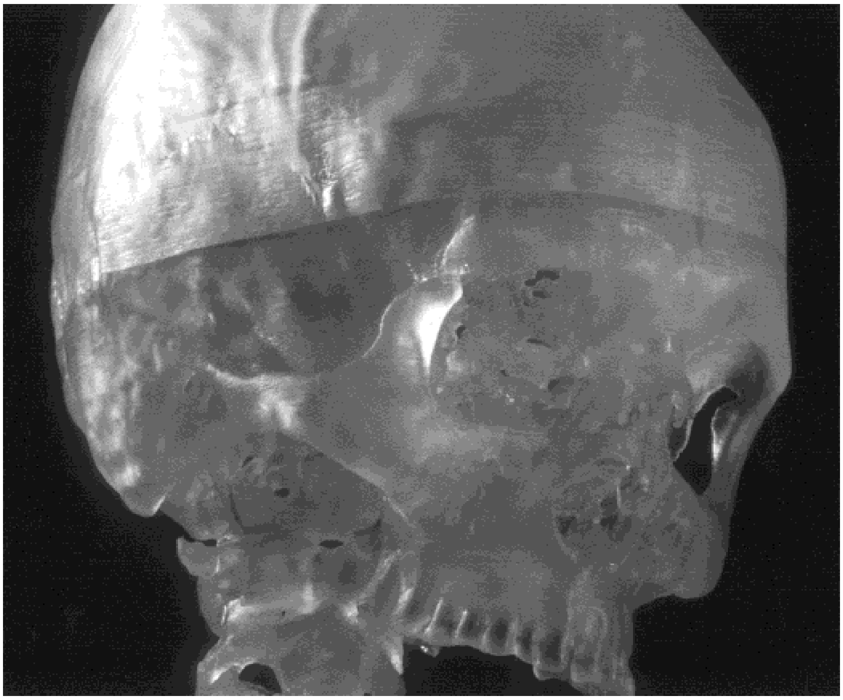

Figure 1. Stereolithographic model of the cranium of the Tyrolean Iceman, reconstructed in two parts (calotte removable). All structural details are manufactured from the polymer with a resolution of 0.15 mm. Through the translucent material, the *Sulci ateriosi* on the inner surface of the right parietal bone are visible. Note the fracture at the right fronto-zygomatic suture.

plicable to specimens in vivo. Mineralized bone delivers no (or only weak) signals but soft tissue, such as the brain or other organ tissue, is well defined. Morphologic investigations can also profit considerably from these methodologies when ontogeny is analyzed, suggesting to the investigator mechanisms for evolutionary changes. Comparative studies with primates and recent humans play a key role in this context (Semendeferi et al., 1997). The technical details of diagnostic radiology have been reviewed many times (Vannier and Conroy, 1989). Recently, a very readable elementary technical introduction from the paleoanthropologist's point of view was published by Spoor et al. (2000), suggesting the use of radiology in this field.

Most important for anthropological and clinical use are the striking advantages that can be seen when comparing VA with traditional methods of analysis:

- the accessibility of all, including hidden, structures (e.g., endocranium, sinuses, tooth roots, medullary cavity of long bones, etc.)
- the permanent availability of the virtual objects
- the controllable accuracy and reproducibility of measurements
- the possibility to obtain information for advanced methods of morphometric analysis
- the possibility to share data (specimens) easily by using electronic media

INNOVATIVE RESULTS IN THE PAST

The need for CT data in anthropological studies arose occasionally, but not with a highly increasing rate, as one would expect as soon as computer and CT technology became widespread and available. Some scholars (e.g., White, 2000) question the necessity of high-tech approaches to anthropological research, claiming that expensive equipment and new techniques generate big grant funds but do not provide substantial results. Perhaps the biological validity of the newly obtained results is inadequately assessed by such conventionally trained anthropologists, because of the multitude of the novel methods and procedures that have to be used.

The Tyrolean Iceman and Stereolithography

To understand the potential of these high-tech methods, a brief review of substantial results that have been achieved with them is essential. For example, one can begin the story with the Tyrolean Iceman (Seidler et al., 1992), arguably one of the world's most spectacular archeological finds of the past decade. The related research activities promoted new techniques and an intensive collaboration between radiologists and anthropologists that was later successfully transferred to evolutionary studies. The 5,300-year-old mummy is not of exceptional interest for a paleoanthropologist, nor was putting the first man on the moon a meaningful effort in itself. What do these two projects have in common? These projects, which were strongly driven by the public visibility, benefited from the development of methods needed to realize them. In the case of the flight to the moon, certainly the development of computer technology, cybernetics, specialized tools for application in weightlessness, and many more, was facilitated.

Measurements on virtual objects are valid and reliable enough to be used in lieu of measurements on the original; all the more so because they can also be taken of physically inaccessible structures.

In the case of the Iceman, advanced technology, usually used in medicine and technical design, was applied. Through it, a 3D hardcopy of the inaccessible skull of the precious mummy (Fig. 1) could be produced to examine its anatomy. This was the first time worldwide that a "stereolithographic model" was used for anthropological investigations (zur Nedden et al., 1994). The model was solely based on the CT data of a rapidly un-

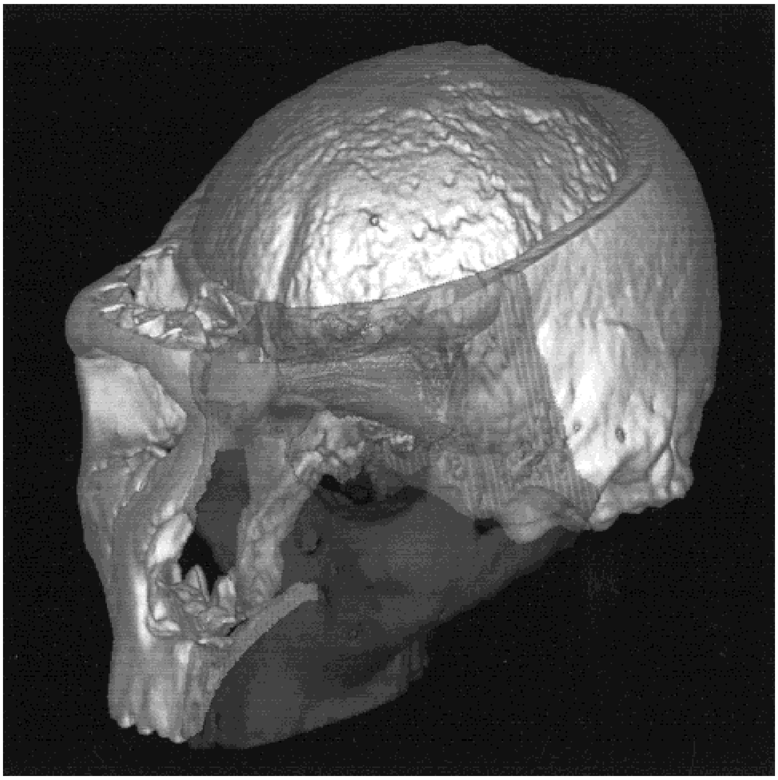

Figure 2. Three-dimensional reconstruction of computed tomographic data of the cranium of Petralona (*Homo heidelbergensis*, ~200 kya, Greece). The cranium was electronically separated into three parts; for this view, the calotte has been removed, and the left facial part was made translucent. The extraordinarily pneumatized frontal sinus is clearly visible. The image also shows the electronically produced virtual endocast and how it fits into the cranial cavity.

dertaken scan of the frozen mummy, which could, in contrast to dried mummified bodies that are more commonly CT scanned (Lewin et al., 1990; Pickering et al., 1990; Melcher et al., 1997), only leave the refrigerator environment for at most 30 min. The noninvasive approach allowed subsequent morphologic investigations leading, among other things, to the conclusion that the Iceman was indeed of local origin and not a translocated fake item from some other place, such as Egypt.

Endocranial Morphology

The translucent stereolithographic models also turned out to be helpful for studies concerning endocranial morphology in evolutionary studies. CT-scanned fossils could be re-created physically. The stereolithographic apparatus needed consists of a laser beam that cures a photosensitive liquid resin polymer layer by layer, thus constructing all the internal features, including the cranial cavity, sinuses, nerve canals, etc. These are visible inside the translucent material and are even accessible if the specimen is replicated in several disassembleable parts. There is a good reason for this expensive procedure: because a representation on a computer screen is still two-dimensional and the third dimension an optical illusion, it is quite often necessary to have a tangible model to understand the spatial relationships of structures. This is the major purpose of such models. Of course, conventional casts of fossil specimens can also be used for morphologic comparison and do contain some information about texture, but they do not provide information about internal features. It follows that the stereolithographic models are excellent visual aids.

Some *Homo heidelbergensis* specimens are known for their extraordinarily pneumatized skulls. Although studies had been undertaken with radiographs and even with 2D CT data (Le Floch-Prigent and Moschidou-Polizois, 1991), the true extent could only be realized when stereolithographic models and 3D reconstructions of CT data (Fig. 2) were available. Moreover, the brain is certainly one of the key differences between humans and other primates, but unfortunately, its development and the endocranial morphology in general is still poorly understood. The published data suggest that skulls resemble each other externally, yet this does not necessarily mean that they resemble each other internally. In studying this morphology by using virtual fossils and stereolithographic models, some insights were provided that contributed to the hotly debated discourse regarding the origins of Neanderthals and modern humans (Seidler et al., 1997).

Another brain-related research question is that of cranial capacity, which in addition to the structural characteristics of the brain, can be an important item of taxonomic classification. Estimating this volume is relatively easy if a skull is almost intact, but the task is more susceptible to observer errors in the case of fragmented skulls. Virtual endocasts (Fig. 2) of the braincase have been produced electronically in a highly reproducible way and helped to visualize and measure the cranial capacity of *Australopithecus africanus* specimens or archaic *Homo* with a minimal error (Conroy et al., 1998, 2000; Falk et al., 2000). Another intriguing application in a paleontological specimen shows that CT scanning can also help to study natural endocasts, in this case of a carnivorous dinosaur (Rogers, 1999).

In the next decade, perhaps the most challenging task for virtual anthropology will be the reconstruction of fragmented fossils and the reversal of deformations.

Sinus Morphology

Basically, every cavity, whether accessible on the original specimen or not, can be extracted and treated as a separate object. Shape and size analysis of sinuses are just one other example for this technique (Koppe et al., 1999; Rae and Koppe, 2000). An excellent contribution to morphologically important traits distinguishing species came from the examination of the labyrinth in the temporal bone. Spoor et al. (1994) had shown that the relative size of the semicircular canals are very similar in *H. sapiens* and *H. erectus*, whereas australopithecines show great-ape–like proportions. Furthermore, some intermediate evolutionary stages, attributed to *H. habilis*, could be distinguished by this trait. Moreover, labyrinth morphology was used to identify specimens after the discovery that Neanderthals have derived features of the inner ear morphology (Hublin et al., 1996).

SPECIMEN REASSEMBLY: PROBLEMS AND LIMITATIONS

Generally, fossils have many undesirable properties, stymieing the ambitious researcher. Partial destruction is a consequence of taphonomic processes during the specimen's progress from the biosphere to the lithosphere. Once discovered, the goal of paleoanthropologists is that the finds should begin their return to a condition that can offer reliable clues to the morphology of the assigned species, whatever it happened to be. But fossils are not only frequently fragmented, they can also be highly interspersed with sediments. Often, fossils need to undergo a series of analytic procedures, all of which are prone to subjective influences.

Some specialists have achieved remarkable results in reconstructing specimens electronically (Kalvin et al., 1995; Zollikofer et al., 1995). But the reassembly of fragmented fossils, physically and/or electronically, is a very delicate problem, involving considerable knowledge about the fossil record and competence in technological issues. The physical reconstructions rarely meet the conventional scientific expectation of reproducibility of experiments and are, therefore, often hotly contested. The simple mechanical removal of encrustations inherently has the same disadvantage. It has to be noticed that both the physical reconstruction and the physical preparation of a real specimen tend to have the taste of a "final" intervention, tainted with the disadvantage that later corrections based on a deeper knowledge are, literally, too late.

The electronic preparation of CT data is in fact a highly sophisticated but helpful and, in contrast to physical methods, a reversible process that can be also applied to internal structures. This insight led, for example, to a representation of the anterior cranial fossa and paranasal sinuses of the mid-Pleistocene specimen of Steinheim (Prossinger et al, 1998), more than 60 years after its discovery. This approach also offers a second benefit: Preparators sometimes use artificial material to complete a partly fragmented skull. Occasionally, it is difficult for investigators to distinguish (painted) plaster from fossilized bone primarily because one fears scratching the specimen surface. The different gray values in CT scans often reveal a clear answer, as demonstrated in the case of the Neanderthal specimen of Le Moustier I (Thompson and Illerhaus, 1998); it had, by the way, an unbelievably turbulent history and is the ultimate monument to the blunders that had been made in the physical preparation and reconstruction of a fossil specimen, including the destruction and loss of parts (Thompson and Illerhaus, 1998).

How can morphologic diversity be studied on a large scale if access to fossil specimens is restricted by time, distance, or the benevolence of curators?

VA IN NOVEL RESEARCH

The previous examples point out the potential of VA for meaningful morphologic analysis when using procedures that are similar to those applied in traditional anthropology. But, VA also allows for study programs that are completely novel.

Digital 3D data per se are a source of information for morphometric analysis, no matter if they were acquired with CT scans, MRI scans, mechanical surface measuring devices, or by laser scanning. Landmark coordinates, linear and angle measurements, surface areas, and volumes represent quantitative data that validate and document the evolutionary changes of species with hard numbers and permit statistical analysis of form and shape by methods of usual biometry (Sokal and Rohlf, 1995) or the methods of geometric morphometrics (Bookstein et al., 1985; Bookstein, 1991; O'Higgins and Jones, 1998). The possibility of probing every hidden structure rapidly increases the amount of data generated. For example, a very interesting result only became evident by the recent morphometric analysis of mid-Pleistocene and modern hominids: The forms of the inner and outer aspects of the human frontal bone (Fig. 3) are determined by completely independent factors (Bookstein et al., 1999). The morphometric analysis also indicated that an unexpected stability in anterior brain morphology was evident during the time when modern human cognitive capacities emerged (Bookstein et al., 1999).

The accuracy and reproducibility of the measurements conducted on virtual objects has been well described (Hildebolt et al., 1990; Richtsmeier et al., 1995; Feng et al., 1996; Weber et al., 1998). By paying attention to several influencing factors, it can be concluded that measurements on virtual objects are valid and reliable enough to be used in lieu of distance and volume measurements on the original; all the more so because they can also be taken of physically inaccessible structures.

Because so many data points are available with 3D-digitizing methods, completely different approaches to morphologic analysis become feasible. For example, bone thickness is an interesting feature of human evolution, yet most studies fall short of offering adequate information about the structural details of a cranium, because usually only a few measurements are taken. With CT scans, thickness maps of bones can be drawn

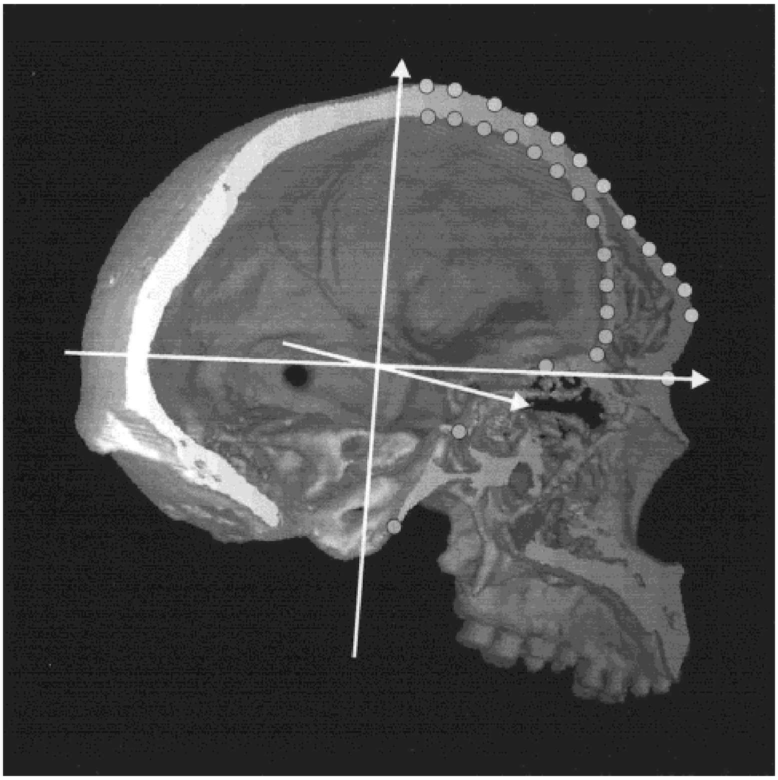

Figure 3. Median-sagittal section of the three-dimensional reconstruction of the cranium of Kabwe (*Homo heidelbergensis,* Zambia), showing endocranial morphology and selected endocranial and exocranial landmarks and semilandmarks for comparative morphometric analysis (Bookstein et al., printed with permission from the publisher).

(Zollikofer et al., 1998). By using semiautomatic algorithms, topographical maps based on several thousand thickness measurements are obtained along the surface of a single cranial bone (Fig. 4). The evaluation of these maps shows that not necessarily the mean or maximum thickness but the pattern of thickness distribution differs between species (Weber et al., 2000). In another example, the laser scan-based analysis of congruency of joints was used to test whether a fossil tibia (OH35) and talus (OH8) could be assumed to originate from the same individual. In this case, the assumption of congruence was rejected, based on the 3D characteristics of the articular surfaces (Wood et al., 1998).

As mentioned before, from the paleoanthropologist's point of view the 3D imaging methods are valuable not only for the study of individual fossils. Ontogenetic studies provide comparable data for detecting evolutionary constraints, like allometry and heterochrony. Therefore, MRI is also important for ontogenetic analysis with respect to phylogeny because it provides detailed visualization of soft tissue such as brain tissue (Falk et al., 1991; Semendeferi et al., 1997; Rilling and Insel, 1999, Semendeferi and Damasio, 2000), cerebrospinal fluid, or blood vessels (Tokumaru et al., 1999). The latter study is, by the way, an example for the possible combination of MRI scans with CT scans of the same individual. For a further understanding of the relationship of skeletal elements with soft tissues (above all with the brain itself), the constraints of development need clarification, e.g., the emergence of the basicranial flexion (Ross and Henneberg, 1995) or the shortening of the sphenoid (Lieberman, 1998; Spoor et al., 1999). Virtual anthropology, based on diagnostic radiology, certainly contributes significantly to solve this question.

TRENDS FOR THE NEXT DECADE

With this undoubtedly incomplete list of biologically meaningful research by using virtual anthropology, now let us turn to the future prospects. As shown above, anthropological research profits substantially from VA in that it enables views into the interior of structures as well as ensures highly reproducible quantitative measurements and easily controllable manipulations. No doubt, an essential part of studies will have to be carried out not on the real object, but in a computer lab, by using various kinds of digital data. Nonetheless, some particular questions will remain the prerogative of a predominantly classical research approach. And, for the creative interaction with the specimen, for the genesis of new ideas, and for a more comprehensive picture of the fossil record, the original specimens will retain their immense importance. All paleoanthropologists are well advised to take every opportunity to study actual specimens. We should keep in mind that, although we have acquired a plethora of new VA tools, their application to fossil material will be no panacea to guarantee meaningful results; interpretation is still the paramount obligation of a responsible scientist.

In the next decade, perhaps the most challenging task for VA will be the advanced reconstruction of fragmented fossils and the reversal of deformations. Missing features on one side of a skull can be re-created by mirroring the preserved feature, or crania can be completed (at least as a first approximation) with pieces from other specimens. In most cases, there may be a unique solution (which is unattainable) for their reassembly. Instead, there are various proposals by scientists as to how a reassembled specimen should look, if it is considered to be in a certain taxon. Fortunately, electronically assembled fossils can easily be disposed by transferring them to the trash of the computer desktop, and a new model can be inexpensively made—a major advantage over conventional methods.

So far, all reassembling experiments rely more on the "morphological eye" of the scientists than on reliable and reproducible empirical standards (i.e., parameterized skull models). Herein lies one of the most important future directions for VA. For an understandable reassembly of a specimen as well as for the creation of a "composite-specimen," statistical

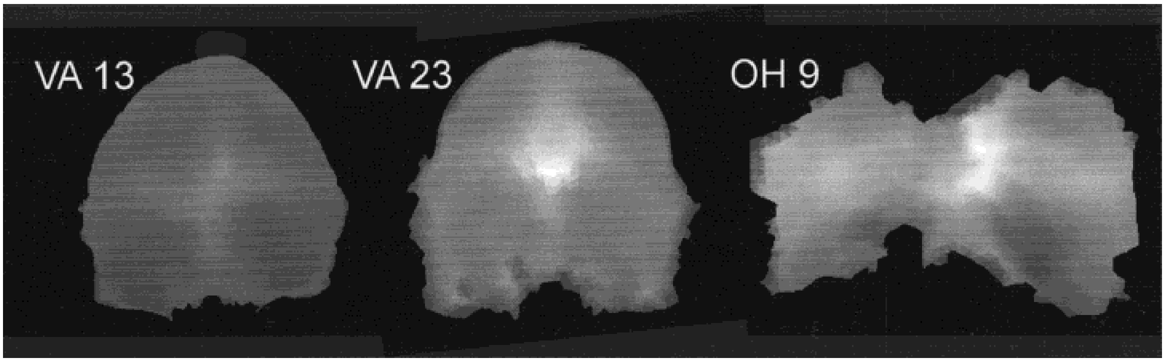

Figure 4. Topographical thickness maps of the occipital bone of two *Homo sapiens* specimens (VA 13, VA 23) and of a *Homo ergaster/erectus* specimen from Tanzania (OH 9). The maps are based on the computation of more than 1,000 thicknesses on each bone; thin bone regions are dark gray, thick bone regions are white. The figure shows the great variation of bone thickness among *Homo sapiens* and the fact that maxima of bone thickness in *Homo sapiens* are no less than in *Homo ergaster/erectus* (white center). For the characterization of specimens, it seems to be more promising to analyze the distribution of thickness over the entire bone than to compare single thickness measurements.

information on the distribution of homologous landmarks, ridge curves, and other surface properties is indispensable. One possible approach is to model biological objects mathematically, with the properties mentioned in Lestrel (1989) and Richtsmeier et al. (1992). If the parameterized average model's of skulls of different species are known, it will then be possible to reconstruct missing parts with a certain specifiable degree of reliability or to find justifiable intermediate stages in a line of skull development by means of warping (Weber and Neumaier, 2001). Moreover, all the manipulations on the computer are more precise and also reproducible—handiwork cannot match these standards. It is true that a preconception about the type of organism to reconstruct is needed, but in contrast to a traditional approach, this method is 100% reproducible and supplies quantitative data about the fitting of pieces and variability.

Even more sophisticated is the possible correction for plastic deformations of the bone if there is clear evidence of the force fields. But there are rarely clues and it is necessary to know the taphonomic history of a fossil when reconstructing different pressures to different parts of the bone for different periods. There is not, and there may never be, a satisfactory solution to this vexing problem. However, assuming some simple approximation prerequisites such as symmetry and semblance with other, non- (or less) deformed specimens, the technical possibility of compensating for deformations exists: (1) either by breaking the skull into parts and reassembling them (Braun et al., 1999), or (2) by general sizing or skewing of a part until symmetry of the skull is attained (Ponce de Leon and Zollikofer, 1999).

Perhaps a more advanced procedure for future application would be to compute a mathematical representation of the skull surface by using reverse engineering techniques (Eck and Hoppe, 1996; Bajaj et al., 1997), where the surface is modeled usually with NURBS (Non Uniform Rational B-Splines; de Boor, 1978; Farin, 1990). The latter are defined by control points that allow for manipulations to correct deformations in a highly reproducible and controllable manner according to the inverse deformation function, if it is known. Conversely, the effect of a deformation can be demonstrated by executing these algorithms on an initially intact individual.

The new kind of data and the new tools of VA are not meant to displace traditional methods, rather, they complement them.

All these results can be illustrative, although their scientific value might be disputable. This is also true for soft-tissue reconstructions based on models (Zollikofer and Ponce de Leon, 1999). Since *Jurassic Park*, it has become commonplace to expect a true color, fully textured, soft-tissued and, whenever possible, animated representation of a fossil specimen. In an article about human evolution in a popular magazine, one can be sure to see the hairy individuals displayed. This is not reprehensible, as long as readers are aware that they are presented with a considerable deal of speculation.

Another main direction to be anticipated is the increase in resolution, by using micro-CT (Thompson and Illerhaus, 1998). Current medical scanners allow isometric voxels of 0.5 mm^3 at best, which results in an approximately 200 MB data file for a skull. With micro-CT, a spatial resolution of 5 μm^3 becomes possible. For the anthropologically acceptable resolution of 0.1 mm in all dimensions, this means that the amount of data to load into the computer memory is around 25 GB. Such high-resolution CT scans enlarge the spectrum of possible investigations. The scientist can decide, after having explored the 3D surface properties of the cranial vault, for example, to measure the volume of the hypothalamic pit and determine the radii of the semicircular canals, or to study dental enamel thickness (Spoor et al., 1993) and perikymata structures of the teeth. Currently, micro-CT is also the tool for medical applications in osteoporosis research, because it allows one to look beyond simple bone density measurements (Borah et al., 2001). The data allow researchers to predict mechanical properties. The suggested method for

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CD-ROM Edition - Fossil Hominids

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Dieter zur NEDDEN
Wolfgang RECHEIS

The Skull of
BODO

Figure 5. The cover of the world's first CD-ROM with digital three-dimensional data of a fossil hominid (Bodo, ~600 kya, Ethiopia) for general access (http://www.anthropology.at/bodo/bodo.html). It contains data in different formats, as well as pictures of the actual and the virtual specimen, and brief summaries of publications dealing with paleoanthropological aspects of Bodo.

studying trabecular structures in patients is also a very promising one for the study of the direction of principal strains in fossilized bones to investigate behavioral patterns of hominids (Macchiarelli et al., 1999). The computational costs are, however, enormous. At the moment, only a few financially very well-off institutes with adequately trained personnel can afford to make micro-CT scans and to analyze the resulting data.

For those who wish to enter the world of virtual anthropology, however, there is good news: adequately powerful desktop computers that can handle the data files are now available (and affordable), and software developers often program in a Windows NT or Linux environment. Soon, I expect many institutes dealing with paleoanthropological questions to adopt the new tools and use them.

GLASNOST FOR PALEOANTHROPOLOGY

New hominoid fossils are discovered nearly every month and many long-known fossils are waiting to be reanalyzed by using the new approaches described here. The third dimension is now included in quantitative morphologic studies. At the same time, the chronology (or fourth dimension) of paleoanthropology is becoming clearer, in part due to more sophisticated excavating and dating methods. Human evolution is more and more in evidence, because the spatial and chronological aspects are becoming more precise and clear.

I think it is time to implement a quasidemocratic process for paleoanthropology. It has become increasingly obvious that knowledge about diversity is a telltale concept for the assessment of specimens and constructing phylogenetic trees (Tattersall, 2000). But how can morphologic diversity be studied on a large scale if access to fossil specimens is restricted by time, distance, or the benevolence of curators? Of course, the latter have the responsibility to protect their treasures and are alarmed by the ever-increasing number of applications for access. For some key fossils, conventional distance measurements are taken for the umpteenth time, thereby risking micro-destruction due to coming in contact with sharp instruments. Such inadequacies should be, and can be, easily avoided.

Hominoid fossils are the heritage of all mankind. The digital 3D data of all fossils should be freely accessible for global use, at least to those scientists with a clear plan for a research project involving comparable specimens. Of course, interests of the collectors should be protected to ensure the primacy of first publication of their findings, but only within a limited time span (perhaps 5 years). The idea of making fossils available in the form of pictures, drawings, casts, and measurements after a limited time is certainly not new (e.g., Conroy, 1998b). But pictures and drawings are two-dimensional, measurements often need clarification because of some ambiguous definitions of landmarks, and casts are physical objects of varying quality that have to be stored physically in places where they might not be accessible all the time.

Therefore, I suggest that, additionally, each specimen should be digitized with appropriate methods (be it laser surface scanning, CT scanning, micro-CT, etc.), and that these data should be accessible in a joint archive by means of the Internet or on some storage medium (e.g., CD-ROM). Such a globally accessible archive would introduce transparency of activities and access. This opening of the electronic archives, this *glasnost*, would enable many more comparative analyses of morphology, because the nearly complete fossil record would be at everyone's disposal.

Clearly, the progress in analyzing diversity would be enormous. For instance, new important traits, especially internal features, have been discovered (as described above) and others undoubtedly will be. Moreover, the results of published studies would become directly verifiable within minimal time. There would be an added additional bonus of having digital 3D data available: everyone has the opportunity to produce his/her own hard copy—a stereolithographic or a fast-deposit model—of the complete specimen, including the internal structures. This modeling is not restricted to the whole specimen; one can isolate or enlarge a detail and model it separately.

At our institute, we made a beginning in this proposed direction by publishing the first CD-ROM (Fig. 5) with 3D data of a fossil cranium, the Bodo specimen (Seidler et al., 1999). Another fragment of a large-scale archive project also exists: the INDABA project, wherein the 3D data of East and South African specimens are exchanged between the members from Tanzania, South Africa, United States, Germany, France, and Austria. Certainly, similar rudimentary cooperations exist between other labs. Of course, unresolved issues remain (data standardization, financing, administration), but paleoanthropologists should think about the feasibility of collecting as much information as possible about hominoid fossils for a common worldwide database (digital record of FOssil HOminoids–drFOHO), comparable to what the genetic scientists are doing in the Human Genome Project (Genome International Sequencing Consortium, 2001; Venter et al., 2001). Beside the drFOHO, one should not forget the modern hominoids that are also of great value for comparative anatomy. Again, several small archives containing 3D data exist (e.g., Shapiro and Richtsmeier, 1997) awaiting their integration into another globally accessible archive of modern hominoids (digital record of MOdern HOminoids–drMOHO).

The new kind of data and the new tools of VA are not meant to displace traditional methods—rather, they complement them. The romanticism associated with the fascination of discovery of fossils in the field will remain. Nevertheless, the paleoanthropologist walking with eyes fixed to the ground in the sunlight now has a respectable partner, who is to be found active in the computer lab gazing upon a phosphorescent screen.

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