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Applications of imaging methodologies to paleoanthropology: Beneficial results relating to the preservation, management and development of collections

Applications des méthodes d'imagerie en paléoanthropologie : apports en termes de préservation, gestion et développement des collections

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ABSTRACT

The limited number of unearthed fossils and their accessibility are factors that hinder paleoanthropological studies. Original remains, but also osteological collections of extant specimens, have to be curated in optimal and adapted environments, and direct manipulation needs to be limited in order to preserve this irreplaceable patrimony. Imaging methodologies have recently provided ways for innovative advances in the preservation of these collections, as well as offering new perspectives to museographic displays and original scientific studies. Here, we describe recent examples of developments obtained from imaging methodologies and discuss methodological and ethical implications of these new "virtual" collections. Undeniably, "virtual anthropology" is an additional tool in our large set of analytical possibilities and for curators, with its specific constraints related to the particular nature of the analysed material. Finally, we suggest some possible guidelines for the optimisation of the preservation, management and development of collections while preserving their scientific exploitation.

RÉSUMÉ

Le nombre réduit de fossiles découverts et leur accessibilité sont deux facteurs limitants en paléoanthropologie. Les fossiles originaux et les collections ostéologiques de spécimens actuels doivent être conservés dans des environnements parfaitement adaptés et leur manipulation doit être restreinte pour préserver ce patrimoine irremplaçable. Les

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méthodes d'imagerie ont récemment permis des avancées innovantes pour la préservation de ces collections, mais ont aussi ouvert de nouvelles perspectives en termes de présentation muséographique et d'analyses scientifiques. Nous décrivons des exemples récents obtenus grâce aux méthodes d'imagerie et discutons des implications méthodologiques et éthiques de ces nouvelles collections « virtuelles ». Incontestablement, « l'anthropologie virtuelle » est un outil supplémentaire dans notre éventail de possibilités analytiques, mais aussi pour les conservateurs, avec des contraintes liées aux particularités du matériel étudié. Enfin, nous proposons des pistes pour l'optimisation de la préservation, la gestion et le développement des collections tout en favorisant leur exploitation scientifique.

1. Introduction

Numerous well-known limitations compose the everyday life of paleoanthropologists. The limited number of unearthed fossils and their accessibility are two factors that hinder studies of specimens' characteristics and comparative analyses. Moreover, specimens are disseminated all around the world and students and researchers working on restricted budgets may encounter difficulties to be involved in analyses including original specimens. Fossils are also fragile and their manipulation has to be restricted, which complicates their exhaustive observation, particularly of hidden internal structures. The role of curators is twofold: preserving unique fossil remains and osteological collections on the one hand, and facilitating their museographic and scientific valorisation on the other. This difficult conciliation can be conflict-provoking at times regarding paleoanthropological study requests.

Historically, the invention of new imaging methodologies has encouraged rapid applications to the study of fossil hominid remains. As an example, the discovery of X-rays by Roentgen dates back to 1895, and Gorjanović-Kramberger (1902) published the first study based on two-dimensional radiographs on the Krapina fossils (other early examples are Walkhoff, 1903 and Schoetensack, 1908). Computed-Tomography (CT) was developed in the early 1970s (e.g., Hounsfield, 1973, 1976) and its use in anthropological research began as early as in the next decade. Pioneer researchers (e.g., Jungers and Minns, 1979; Ruff and Leo, 1986; Tate and Cann, 1982; Wind, 1984; Zonneveld and Wind, 1985) were attracted by the opportunity to get access to the hidden structures of fossils, in spite of the technical limits of earlier equipment, at least compared to the current potentialities. Since then, this remarkable technological enhancement has produced numerous and diverse applications (e.g., see Spoor et al., 2000a, 2000b for a review of elementary concepts in applications of diagnostic radiology to paleoanthropology). CT has obviously been a tool for diagnosis of normal anatomy and pathology in medical sciences but it has also been applied to ancient human skeletal remains for researching taphonomic bone alteration and pathology, and for describing their morphology. This imaging methodology permits to register, preserve and share our cultural heritage and opens up new perspectives while giving access to previously unavailable internal morphological features (Figs. 1 and 2). It therefore considerably increases the range of available data for studying morphological variability and the evolution of fossil hominids. Some examples of applications in paleoanthropology include the study of the frontal sinuses and their relationship with the face (e.g., Prossinger, 2008; Seidler et al., 1997), the morphology of the maxilla and its pneumatisation (e.g., Maureille and Bar, 1999; Rae and Koppe, 2000; Zollikofer et al., 2008), the temporal bone pneumatisation (e.g., Balzeau and Radovčić, 2008), the bony labyrinth (e.g., Hublin et al., 1996; Spoor et al., 2003; Fig. 2a, b), the auditory capacities (e.g., Martínez et al., 2004), teeth (e.g., Conroy, 1988; Conroy et al., 1995), the cranial vault thickness and its internal composition (e.g., Balzeau 2006; Balzeau and Rougier, 2010; Weber and Kim, 1999), the endocranial morphology (e.g., Bruner and Manzi, 2008; Falk et al., 2005; Rosas et al., 2008), the mandibular corpus (e.g., Daegling, 1989; Zollikofer et al., 1998), some previously unavailable features to evaluate individual specimen's age (e.g., Coqueugniot et al., 2004) and pathological alterations (e.g., Bräuer et al., 2003; Gracia et al., 2009; Lukaszek et al., 2010). Moreover, this methodology allows the reconstitution and reconstruction of partial and/or deformed skulls (e.g., Suwa et al., 2009; Zollikofer, 2005), the virtual association of anatomical structures and of osteological chains to modelize biological mechanisms (e.g., Chapman et al., in press; Ponce de León et al., 2008; Fig. 2c, d, e), and prototypes can be obtained from the 3D reconstructions (e.g., Seidler et al., 1997; Zur Nedden et al., 1994; Fig. 1c). Applications to studies of the infra-cranial skeleton are less frequent and most have concerned the structural characteristics of long bones based on analyses of 2D sections (e.g., Ruff et al., 1999). Studies of enamel thickness and of the internal structure of teeth have recently benefited from rapid advances in micro-CT (μCT) (e.g., Bayle et al., 2010; Braga et al., 2010; Macchiarelli et al., 2006; Olejniczak et al., 2008; Skinner et al., 2008; Smith and Tafforeau, 2008). Finally, imaging methodologies are also becoming a common complementary tool for the description of fossil specimens at the time of their announcement (e.g., Berger et al., 2010).

Imaging methodologies have recently provided ways for innovative advances in the preservation of collections of fossil and osteological specimens as well as offered new perspectives to museographic displays and original scientific studies. Here, we present some examples of applications of imaging methodologies to "cultural heritage" and scientific purposes and we discuss the limits and constraints of this approach. We also describe recent examples of collaborative developments of shared databases obtained from imaging methodologies and we discuss methodological and ethical implications of

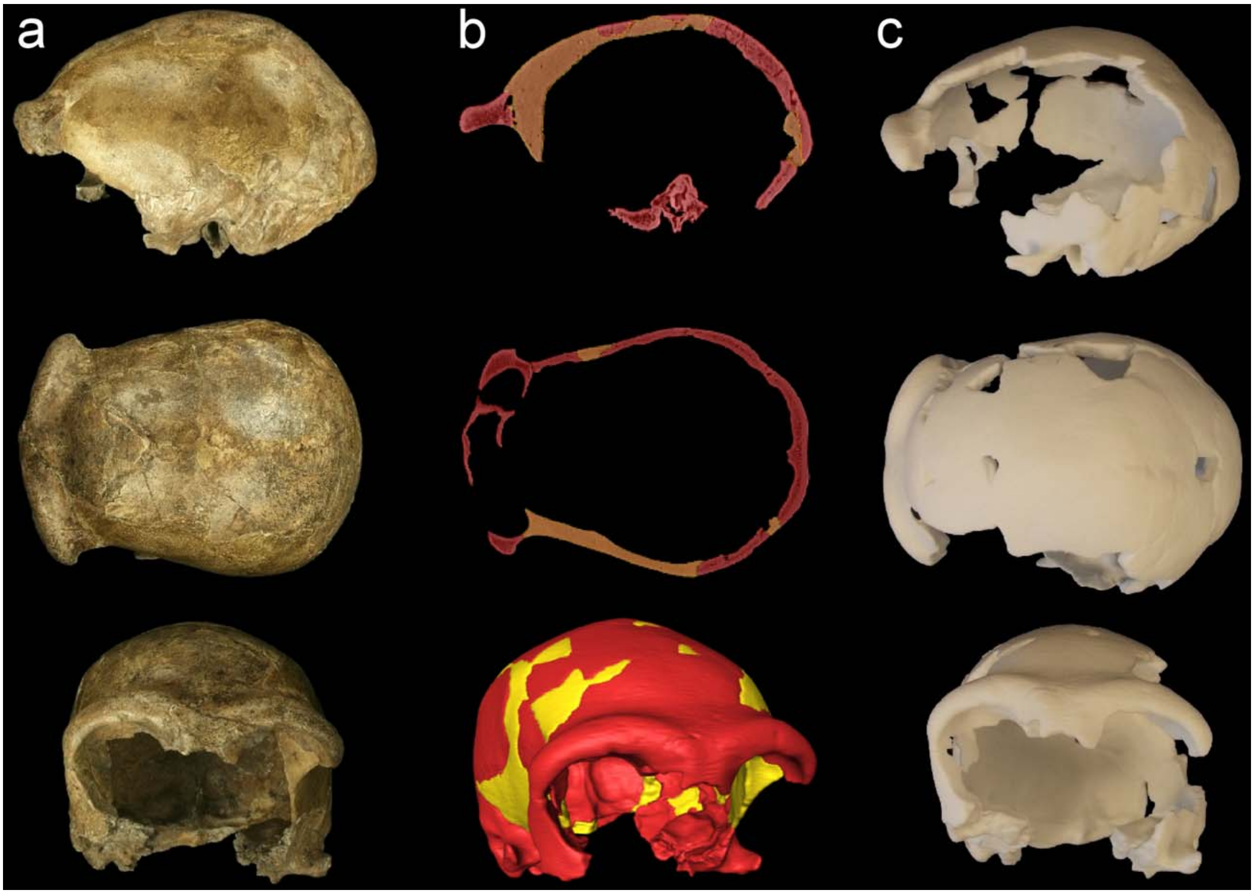

Fig. 1. The Spy 1 cranium; **a**: original specimen, from top to bottom: left lateral view, upper view and frontal view; **b**: CT images and 3D reconstruction; **c**: prototype obtained from the 3D reconstruction of the original specimen without all the non-osseous structures used to complete the specimen just after its discovery at the end of the 19th century (RBINS/TNT).

Fig. 1. Crâne Spy 1 ; **a** : spécimen original, de haut en bas : en vue latérale gauche, en vue supérieure et en vue antérieure ; **b** : coupes CT et reconstruction 3D ; **c** : prototype obtenu à partir de la reconstruction 3D du spécimen original, sans les matières artificielles utilisées pour reconstituer le spécimen juste après sa découverte à la fin du XIX^e siècle (RBINS/TNT).

these new "virtual" collections. Finally, we suggest some guidelines for the optimisation of the preservation, management and development of collections as well as their scientific exploitation.

2. General considerations about anthropological collections

Original fossil remains, as well as osteological collections of extant specimens, have to be kept in an optimal environment in terms of light, humidity and temperature, and manipulations have to be limited in order to preserve this patrimony. Fossil specimens are rare, fragile and evidently unique and irreplaceable. This is also true for osteological collections, which constitute the comparative samples of paleoanthropological studies, and which represent a valuable material for the analysis and interpretation of traits variability in recent and large samples. When considering, for instance, the great ape osteological material of the Royal Museum for Central Africa in Tervuren (Belgium), it even comes to mind that the biodiversity present in museums may in the future outgrow the natural biodiversity encountered in the field (Gilissen, 2009). Similarly, collections of anatomically modern humans housed in institutions around the world constitute a record of humankind in all its spatial and chronological aspects, which largest part remains to be studied.

Curators face a dilemma that lies in dealing with two antagonist missions: preserving unique fossil remains and osteological material on one hand, and facilitating their museologic and scientific development on the other, whereas the repetitive use of collections may at times endanger the preservation of their integrity (e.g., Culotta, 2005; Orschiedt, 2008; White and Toth, 1981). Moreover, museum collection management has entered a new era because of the increasing use of new methodologies. Geometric morphometrics and imaging facilities, among others, and the development of new tools (e.g., digitizers, surface or CT scanners, etc.) have indeed generated a growing demand for access to osteological collections. New analytical methods also provide useful information in various fields (e.g., dating, diet, growth, pathology, palaeogenetics...), but they require destructive sampling, i.e. definitive damage to collections

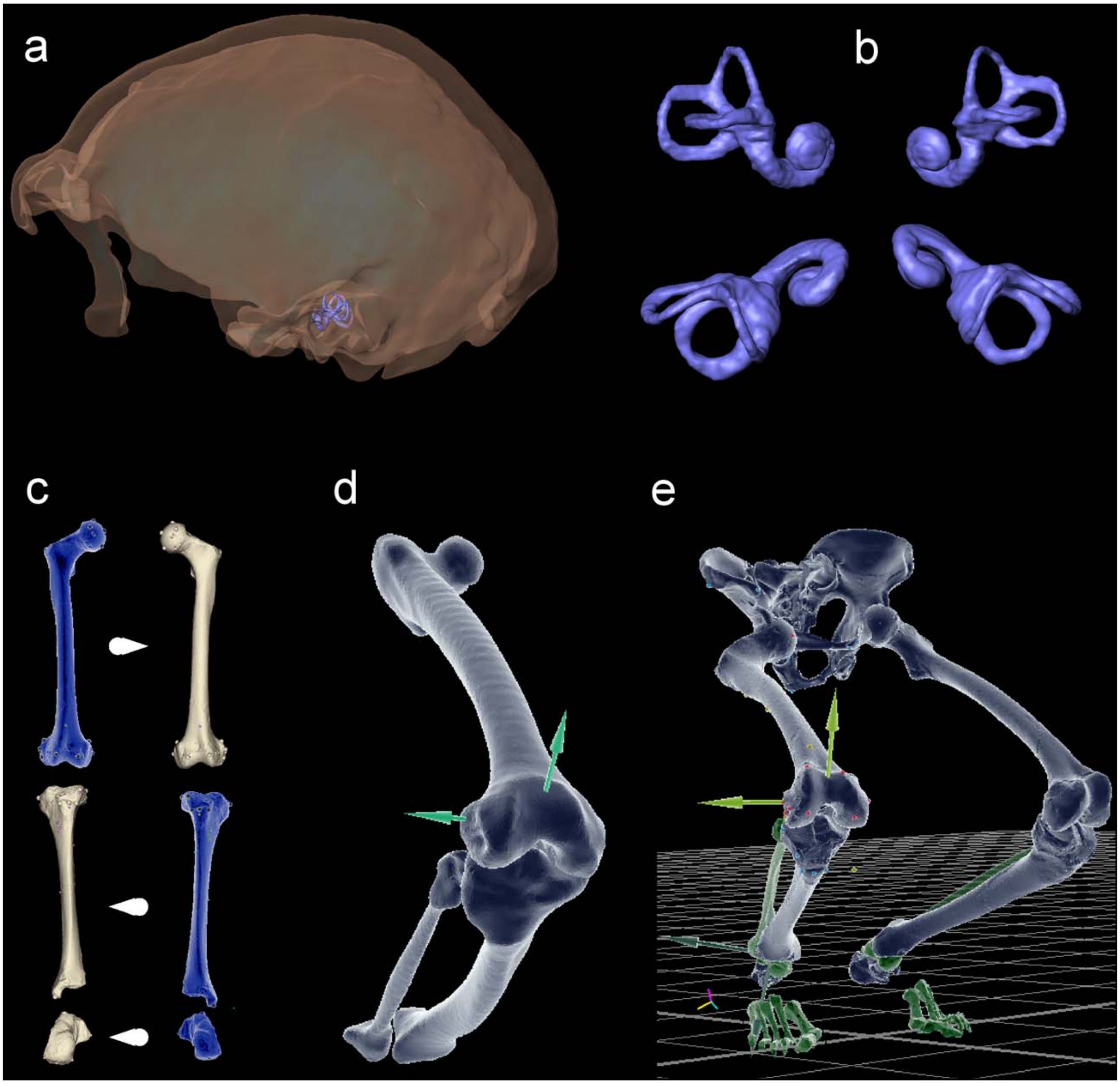

Fig. 2. Examples of scientific analyses based on the CT data of the Neandertal remains from Spy (Belgium). **a**: left lateral view of the Spy 1 cranium with its *in situ* left bony labyrinth; **b**: right and left bony labyrinths of Spy 1 in lateral and upper views (images L. Bouchneb, RBINS/TNT); **c**: virtual models of the femur, tibia and calcaneus of Spy II and mirroring of the missing bones; **d**: the Spy II femur, tibia and fibula during a squat movement; **e**: the Spy II skeleton during a squat movement (published with kind permission of T. Chapman, ULB; see also Chapman et al., 2010, this issue).

Fig. 2. Exemples d'analyses scientifiques à partir des données CT des vestiges néandertaliens de Spy (Belgique) ; **a** : vue latérale gauche du crâne Spy 1 et son labyrinthe osseux gauche représenté *in situ* ; **b** : labyrinthes osseux droit et gauche de Spy 1 en vues latérale et supérieure (images L. Bouchneb, RBINS/TNT) ; **c** : modèles virtuels des fémur, tibia et calcaneus de Spy II et symétrisation des ossements manquants ; **d** : fémur, tibia et fibula de Spy II durant un mouvement d'accroupissement ; **e** : squelette de Spy II pendant un mouvement d'accroupissement (publié avec l'aimable autorisation de T. Chapman, ULB ; se reporter à Chapman et al., 2010, ce volume).

(e.g., Hublin et al., 2008). Undoubtedly, the value of a collection depends on what the data collected from its specimens can contribute to the scientific accumulation of knowledge.

In this context, applications of imaging methodologies offer important new opportunities for the preservation and the development of collections. All the information concerning the dimensions and the morphology of specimens may be registered. Moreover, this pluridisciplinary approach allows "virtual" manipulations and modifications of specimens, which were not possible before. Based on imaging datasets, the different parts of an object may be individualised, moved, rotated, scaled, restored, deformed, completed... In this respect, imaging methodologies represent an important opportunity for anatomical studies. They allow the observation, description, and quantification of previously unavailable features and, at the same time, they offer new perspectives for the preservation of collections.

Imaging methodologies are reputed for their non-destructive nature. This is partly true as the technique itself does not require any invasive preparation of the specimens to be imaged. Nevertheless, it is necessary to manipulate the original objects to dispose them in the acquisition equipment and to take them back to their repository after the procedure. Any manipulation is risky, be it in the lab with portative CT equipment or when specimens have to travel to be scanned in a hospital, in another laboratory or at a synchrotron facility. Moreover, the effects of intensive (and repetitive) exposure of fossils and osteological specimens to X-rays have not been studied on a large scale yet (e.g., Horton et al., 2010).

For these reasons, the digitisation of collections should not be intensively repeated until major technical improvements are achieved and the role of curators is crucial in managing the preservation of collections, the digitisation of specimens and their study by the scientific community.

3. Specific constraints of "virtual anthropology"

2D CT datasets and 3D reconstructions, when correctly used, allow the observation and quantification of information similar to that obtained directly from original fossils. Moreover, "virtual" objects are permanently available for study. Classic descriptions, metric analyses and approaches in geometric morphometrics can be generated from this data, while preserving the original specimens.

Nevertheless, paleoanthropologists eager for novelty have to be aware that application of these methods to their field of research has limits. Some are directly inherent to the methodology itself. For example, in the case of heavily mineralised specimens, the settings of the acquisition procedure can be modified to avoid or limit imaging artefacts like overflow and beam hardening (Spoor and Zonneveld, 1994), but it is not always possible to obtain precise images with information about the fossil's internal structures with a CT scanner. Partial volume averaging and limits in spatial resolution (Spoor and Zonneveld, 1995) are two other important limitations of slice-based imaging methodologies. In relation to these two constraints, the accuracy and the reproducibility of measurements and of the definition of landmarks coordinates on both 2D and 3D data were tested and validated (e.g., Coleman and Colbert, 2007; Richtsmeier et al., 1995; Schoenemann et al., 2007). However, the influence of measurement error is rarely quantified and discussed in publications in the field of "virtual (paleo)anthropology" (or VA). Different sources of uncertainty are involved at each step of the complete procedure when imaging methodologies are exploited, from the acquisition of imaging datasets on the original specimen, through informatics treatments of the data, and to metric or landmark determination on the virtual 3D reconstruction.

At the time of data acquisition, it is imperative to restrict the field of acquisition to the anatomical structure to be studied (Badawi-Fayad et al., 2005). Moreover, slice thickness has to be of comparable size as, or smaller than, pixel size in order to optimise the definition of the dataset in 3D. Physical and technical limitations may prevent the acquisition of some objects because of their size; this is particularly true for industrial CT scanners that are devoted to very small objects. Moreover, high-resolution acquisitions implicate large datasets that cause difficulties for their storage and their informatics processing. Today, it is sometimes necessary to reduce the resolution of original datasets obtained from μ-CT scanners or Synchrotron facilities to be able to study them because of limitations in informatic calculation capacities. On another hand, it is important not to dramatically reduce the spatial resolution during 3D reconstruction when using smoothing, compression or reduction procedures. The objective is not to obtain a beautiful model but a precise one. Slice data are by nature an incomplete registration of the 3D morphology of the original specimen. Computer-calculation reconstructs the 3D model from "cubic" information (i.e. voxels; pixels are the slices components and slice thickness provides the 3rd coordinates). Global segmentation permits to easily and rapidly obtain a 3D reconstruction. However, this model does not necessarily have a definition corresponding to the original spatial resolution of the CT dataset and does not automatically reproduce exactly the morphology of the original specimen because of variations in density of the different elements composing the images. It would be interesting to test the variation and accuracy of models obtained with different automatic segmentation procedures, and using various algorithms and software. Furthermore, users may encounter difficulties in defining precise outlines with automatic procedures. It is necessary to use manual segmentation with as many different settings as necessary to accurately isolate the outlines of a structure, particularly when sediment or plaster are present, or when the different parts of a fossil are characterised by large variations of density. In previous studies, we used multiple threshold values as a function of the variation in the mineralisation of fossils' different components (bone, matrix, plaster...) to obtain 3D models. This was done for the endocranial cavity of the Mojokerto calvaria that is filled with sediment (Balzeau et al., 2005) and for virtually "cleaning" models of the Spy Neandertal crania (Balzeau et al., in press) of all the non-osseous structures that were used to complete the specimens just after their discovery at the end of the 19th century (Fig. 1).

Measurement error cannot be inferior to the resolution of the data used to quantify measurements of a specimen, but we have to be aware that the error can be very large depending on the different factors described above. Resolution of the original imaging dataset, estimations during 3D reconstruction, difficulties in determining the position of the landmarks on a virtual model are additional sources of error to more classic ones like repeatability of the determination of landmarks, quantification of the analysed traits and validity of the analytical protocol. We recently developed a specific protocol to quantify endocranial petalias using CT data (Balzeau and Gilissen, 2010; Balzeau et al., 2010). Datasets were obtained following the previous recommendations for acquisition and treatment procedures. Measurement error was defined as the variation of the traits used to quantify symmetry and which actually represent a small percentage of anatomical traits size. Measurement error was then tested on a large part of the analysed samples and at the various methodological steps by comparing different CT acquisitions, different 3D reconstructions and different landmark acquisitions for the same specimens. Measurement error was found to be small compared to the variation observed for the different analysed features and it was comparable to the definition of the CT datasets used to reconstruct 3D models of the endocranial cavities. This demonstrates the high potential of imaging methodologies for studying small size anatomical traits when used properly.

The highest available resolution is of course preferable for the acquisition of specimens, but it should be kept in mind that analytical protocols are not necessarily reliable and valid simply because high resolution datasets are recorded.

First, the classic uncertainty in the determination of anatomical landmarks has to be considered. It is very easy to visualise details of a structure on a 3D model thanks to magnification possibilities on computer screens, probably even easier than on original specimens. However, a type II or III landmark (e.g., Bookstein, 1991; O'Higgins, 2000) is obtained by construction on the virtual model and the user has to determine its location with the inherent imprecision of such a procedure. Similarly, the junction of sutures, in the case of type I landmarks, is not a point of infinitely small size that can be perfectly localised.

Second, any analytical protocol has to consider the particularities of imaging data, such as those described above, and particularly when dealing with 2D slices. A slice defined as passing through a particular structure or a number of anatomical landmarks does not have a real anatomical significance and will not be repetitive between individuals, even less between species. Moreover, a slice cuts structures in different oblique orientations depending on the orientation of the slice and of the structure that was imaged. This limitation is particularly significant when quantifying the thickness of a structure on 2D slices, such as cranial vault thickness (see Balzeau, 2006, 2007; Balzeau and Rougier, 2010 for examples of protocols overcoming this problem; see Spoor and Zonneveld, 1995 for a protocol to analyse semi-circular canals size; Fig. 2a).

Finally, other limitations of "virtual anthropology" are the restricted number of specimens concerned by the studies and the difficulties in getting access to imaging datasets. The small sizes of our samples have to be acknowledged when interpreting results in terms of individual characteristics and variation.

Studies of internal anatomical features with imaging methodologies should be built while keeping in mind all the aspects presented above about the different steps of VA. For this reason, it is important that anthropologists working with imaging data are aware of all the information concerning the data they study; this is particularly true for data that were passed on by another scientist, and for 3D models that were not reconstructed by the user himself (Kullmer, 2008). In this context, scientists need complementary knowledge and skills in anatomy, imaging methodologies and informatics as much software is necessary for the various applications in paleoanthropology.

4. Formats and supports

From a technical viewpoint, the great variability existing in raw data format is problematic. The Digital Imaging and Communication in Medicine (DICOM) format is a standard that was originally defined within the field of medical sciences to homogenise data obtained from CT scanning imaging equipment. However, variation remains between manufacturers and dedicated software is not able to open all DICOM format data. μ-CT devices produce radiographs that are turned into 2D slices after a reconstruction step. Classically, slices obtained from a μ-CT scanner are in TIFF format. Imaging datasets have the great advantage to be informatics data, hence easy to transport and to share, but they represent a large amount of data. In the near future, μ-CT scanners, and more probably synchrotron equipments, will certainly allow the acquisition of imaging data for complete skulls and large infra-cranial bones at a resolution of 50 μm or even less. Such a dataset would be meaningful in terms of the recording and preservation of a specimen at high resolution; however, it would require excessively large capacities of storage, and it would be extremely time consuming. In any case, possibilities of access to synchrotron facilities are currently so restricted that it is impossible to image more than one (or two) specimens at a time. Finally, the question of the long-term existence of data is problematic regarding both the storage of information and informatics formats. A policy for long-term management of "virtual" databases will be necessary and should be developed in museums in the same way as it exists for 'physical' collections.

5. Perspectives for "virtual" paleoanthropologists

In the future, progresses in data acquisition and informatics treatment will certainly facilitate applications of imaging methodologies to paleoanthropology and will allow studying additional anatomical features of fossil specimens. It will also certainly be possible to include more specimens in "virtual" analyses as data acquisition becomes easier and cheaper, at least if present practices for data management and sharing evolve in a positive and productive way. Potential developments will concern the analysis of minute traits thanks to higher resolution capacities of acquisition facilities and the study of highly mineralised specimens thanks to the higher ability of these equipments to discriminate fossilised structures. Other possibilities will concern the reconstruction of fragmented fossils and the reversal of post-mortem deformations (Gunz et al., 2009), and advanced morphometric approaches based on large amounts of landmarks, surface and volume data.

6. Perspectives for "virtual" curators

2D slices, CT derived or surface scanning 3D virtual reconstructions (e.g., Slizewski and Semal, 2009) and their derived prototypes are only partial images of the original objects, and their visualisation and analysis encounter specific constraints. Therefore, paleoanthropologists still have to study the original fossils to have a total understanding of the specimens. VA needs to be considered as an additional tool in our large set of analytical possibilities. For the institutions and museums represented by the curators, VA provides a "digital backup" of the specimens, it allows studies of taphonomic and/or curational processes and it provides useful information for the preservation and restoration of collections. For this reason, virtual models should be a part of the documentation associated to original collections in combination with pictures, drawings and metadata. This implicates the development of new expertise(s) related to the digitisation of original collections, not only for specific scientific questions but for a larger spectrum of applications.

7. Ownership of "virtual" data

The question of ownership of "virtual" data deserves some attention. The simplest case is when the curator of the actual specimen is also responsible for the virtual data. It may occur that a specimen is imaged by a scientist with his own equipment or at his request. In this case, the scientist may consider that the virtual data are his property or he may request a period of exclusivity. This strategy is unproductive for the curator of the original specimen as well as for the scientific community. We should distinguish the importance and paternity of ideas and those of the specimens we study. Two principal levels of study of specimens are concerned by the applications of imaging methodologies. On one side, paleoanthropologists accomplish the exhaustive study of specimens and of their anatomy, either completing the study of ancient discoveries using new methodologies or describing recently unearthed and yet unpublished fossils. On the other side, applications concern the variation of anatomical traits among large samples to test general anthropological hypotheses. It is reasonably rational to preserve some mystery and discretion around analytical protocols and hypotheses to be tested before the publication of a paper or the accomplishment of a Ph.D. thesis. It is also undoubtedly natural that the discoverers of specimens be guaranteed the best conditions by curators to achieve the exhaustive study of their discoveries. Nevertheless, we should dismiss the longstanding idea that fossils and "digital fossils" are the unique property of their inventor, of their curator or of a scientist. A detailed policy should be established in order to manage this problematics.

During our own experience as "virtual paleoanthropologists", we have had the opportunity to include specimens in our samples, which were unpublished or not yet fully published, because our work was not in conflict with the exhaustive studies of the fossils by their discoverers. The people in charge of these fossils gave us access to different sorts of data (CT, 3D model or landmark coordinates, depending on the protocol we used) for specific studies. In this context, we were able to analyse the variation of internal anatomical traits in hominins including large comparative series and important new specimens. In the same way, during the reassessment of the Spy collections by a pluridisciplinary team (Figs. 1 and 2), most of the 3D data sets produced were uploaded on the NESPOS and MARS databases and available to scientists on request.

8. Ethical issues

Ethical issues are a complex aspect of VA. Rules for the use of imaging data and of the resulting images should be the same as for original specimens. The current policies concerning imaging data of fossils and osteological collections are highly variable between institutions according to various factors. Means in terms of staff, available budgets and collections are the three main elements that have permitted institutions to enter the "VA world" more or less rapidly. Institutions with paleoanthropologists interested in imaging methodologies and with funding resources have had opportunities to image their own collections or to contact other institutions to scan their specimens. Therefore, the scientific perspectives of applying imaging methodologies to paleoanthropology have been favoured first, and aspects of preservation and management of collections became a matter of interest only more recently. No one could have imagined the development of VA in terms of methodological improvement, multiplication of applications, quality of the results and number of scientists involved in such a short period of time. As a result, we have inherited a situation in which the management and control of the new "virtual" collections is ruled by variably well-defined conventions between scientists and institutions. Some problems arose and it is probably time for global, mutual and collaborative discussions and brainstorming. Following are some examples of situations that may emerge with the expansion of VA; they are marginal at the most, but they illustrate how complex the current situation is and why it would be useful to agree on some solutions.

STL files generated from imaging datasets permit one to obtain physical replicas of original specimens that may easily be used for commercial purposes. This issue is difficult to control, and it demonstrates the necessity of well-defined conventions at the time of imaging acquisition and before potential dissemination of the data. In some cases, a given scientist who generates a "virtual collection" may think that since he is the source of the collection, he may be its owner. This is a crucial point, and this situation might occur because CT scans, which are basically data, can easily be confused with the actual collections. When such an amalgam occurs, museums lose their intellectual property. This might happen when CT scans are shared by two or more scientists without leaving a copy at the museum where the scanned specimens are deposited; the museum (and funding agencies which covered the costs of the CT scanning) might not be acknowledged in publications using the CT data and they might be replaced by the owner of the CT scans. The same problem might occur with all of the information derived from original CT data, such as 3D models, and images of 2D slices and of 3D models. 3D reconstructions may indeed be shared by scientists without referring to the curators of the original specimens, and images obtained from CT data are occasionally published without reference to the institutions where the specimens are housed.

Finally, allowing a period of exclusivity to scientists who generated CT scans of specimens is problematic. When researchers scan specimens in institutions other than those that house the fossil material or with their own acquisition instrument, if the issue of intellectual property of the scans is not properly addressed, repeated scanning may occur and data may be unavailable for long periods of time. This raises issues about costs, repeated transport, repeated use, and repeated radiations, which consequences are naturally harmful to collections. Again, the role of curators is essential in combining the optimal conditions for the preservation of original specimens and for their scientific and museologic exploitation.

9. Overview of "virtual" collections and of their policies

In this section, we want to present a few examples of anthropological "virtual" collections, which involve objectives in terms of both the preservation of collections and data sharing with the scientific community in prevision of new analyses. The earliest example of imaging datasets that were made widely available dates back to 1997 and concerns an osteological collection of extant modern humans (Shapiro and Richtsmeier, 1997). Data for fossil specimens have been made available to the scientific community starting in 1999 through the digital archives of fossil hominoids (Weber, 2001); CT scans of Kenyan fossil hominins are accessible through the National Museums of Kenya under individual license conditions. Another example is the Open Research Scan Archive (ORSA) database funded by the National Science Foundation and containing CT data of extant specimens (http://plum.museum.upenn.edu/~orsa/). The basic policy of this experience is to encourage data exchange, which may be problematic for those who do not have "virtual" collections, but also when considering problems relating to data property as discussed above.

CT data of the specimens housed at the Museum national d'histoire naturelle (France) are disseminated to researchers for specific scientific purposes with the interdiction of sharing the data with a third party. Further analyses are only allowed after a new request is submitted in order to avoid conflicts in case of concurrent scientific approaches by different teams or scientists. Recently, some of us described and quantified the internal cranial features of RG 9338, the type specimen of *Pan paniscus* housed in the Royal Museum for Central Africa, Tervuren, Belgium, and most importantly, we provided a complete landmark description together with a 3D model (http://www.metafro.be/primates/panpaniscustype) in order to allow other scientists to include this key specimen in their own research (Balzeau et al., 2009a, 2009b). The original CT dataset is also available to scientists on request.

The largest project of 2D and 3D datasets repository in paleoanthropology is the NESPOS Society database (http://www.nespos.org) developed in the framework of 'The Neanderthal Tools' (TNT 2004–2006, a combined RTD- and demonstration project of the 6th framework program of the EU; see Semal et al., 2004b; Weniger et al., 2007). This project represents a major step in terms of collaborative and sharing developments of a web-based database for imaging datasets of fossil hominins, as well as of specific tools for anthropological and paleontological studies (i.e. the Visicore suite). The database is divided between public and private spaces. Registered users may download data on their local computer in order to use specific applications. Nevertheless, they are requested to mention the NESPOS origin of the data in the references of the publications using them. For the private spaces, sharing of data is established after a request is submitted and an agreement is found with the curator of the data. The NESPOS database offers a centralised solution for hosting 3D datasets. Curators are relieved of the hardware and technical infrastructure needed for housing digital collections, and they benefit from a common searching and sharing platform related to Pleistocene people and places.

The Royal Belgian Institute of Natural Sciences (RBINS) also developed a web database based on OpenSource technologies (Plone/Zope), which houses and allows the sharing of the digital collections of the institute, including all metadata related to original fossils. The MARS project (Multimedia Archeological Research System; Semal et al., 2004a), funded by the Belgian Science policy, hosts all CT, μCT and surface scanning files of the RBINS anthropological Pleistocene collections. This includes the Neandertal specimens from Spy, La Naulette and Fond-de-Forêt (Semal et al., 2005), and the Late Stone Age human remains from Ishango (Democratic Republic of Congo). To access these collections, a request has to be submitted to the curator and a user profile is then created on the MARS system.

This approach allows institutions to manage their own databases as a Multimedia CMS related to their collections. The use of a common portal like NESPOS, or other collaborative systems, redirects users to the server of each institution with their specific access rules and policy.

10. Proposed guidelines for the benefit of collections

Through our various experiences, as scientists studying collections or dealing with particular anatomical traits, and/or as curators of fossil specimens and osteological collections, we have encountered the different difficulties discussed in this article about applications of imaging methodologies to paleoanthropology. This gave us the opportunity to think about possible guidelines for the preservation, management and development of collections while preserving their scientific exploitation.

10.1. It is the role of curators to guarantee optimal conditions for the preservation of original specimens

Whenever possible, specimens should be documented using photography, high-resolution molding or prototyping, and surface and (μ)-CT scanning. This record of specimens is crucial in the perspective of possible repatriations of osteological elements, when invasive sampling is considered (e.g., Semal et al., 2009), or in the case of the loan and/or the exhibition of specimens, which are as many situations when the integrity of fossils may be threatened. Moreover, existing CT scans, surface data and 3D models should be made available at the request of visitors in order to limit manipulations of the original specimens for all the data acquisition that may be done as accurately on the "virtual" objects as on the originals. Finally, curators have to facilitate and to manage the scientific exploitation of the specimens in their care and of the corresponding "virtual" datasets.

10.2. Imaging data obtained from specimens should remain the property of the institutions where the specimens are housed

A distinction should be made between raw data (original CT data, radiographs, TIFF files in the case of micro-CT data, photographs and surface views), which constitute a digital record of the specimens and are part of the collections, and segmented or reconstructed data (3D models produced from the various imaging methodologies, labels and segmented areas on slice-based data), which result from data processing and represent the work generated by the scientist him/herself. Nonetheless, any information derived from the original CT data, such as 3D models or images of 2D slices or of 3D models, should not be shared without referring to the curators of the original specimens.

Institutions and museums represented by the curators of fossil and/or osteological collections being also responsible for the management of the corresponding "virtual" raw data allows major benefits for the preservation and the exploitation of collections. Curators may grant several scientists or teams simultaneous access to the imaging datasets of specimens housed in their institution when it permits the achievement of complementary analyses and does not impede ongoing studies. When testing similar approaches or hypotheses, scientists should discuss potential conflicts of interest and redundancy of their analyses, and curators have to arbitrate in the best interest of the collection they are in charge of.

Finally, any scientific publication using fossil and/or osteological collections should systematically acknowledge the institutions which supplied the imaging datasets and where specimens are housed.

11. Conclusions

In the near future, one of the major tasks concerning applications of imaging methodologies to paleoanthropology will be to conciliate the interests of the institutions and museums represented by the curators, who are in charge of the preservation and management of fossil and osteological collections, and of paleoanthropologists, who study the specimens. Imaging methodologies have provided ways for innovative advances in the preservation of collections as well as offered new perspectives for original scientific studies, which are sometimes conflicting. Ongoing and future developments of imaging methodologies, through the optimisation of acquisition equipments and of dedicated software, will certainly expand the possibilities of "virtual anthropology". Methodological aspects of this pluridisciplinary approach should not be dismissed either. Scientists should be concerned with the optimal adaptations of acquisition and treatment protocols to the specific constraints of paleoanthropological remains and with the improvement of the repeatability and validity of their analytical procedures. Curators and scientists may find a common interest in developing a pedagogical approach for the public that they have more or less abandoned so far. Beautiful, colour images published in popular journals and flashy animations presented in congresses are now the rule, but we may also use the newly available opportunities for more advanced museographic displays. Finally, we hope that collaborative studies based on large samples of imaging datasets will be possible soon. This would provide more robust results and would certainly be beneficial for the preservation and the exploitation of collections. Fossils and osteological specimens compose the foundation of our research, and we should do all we can to preserve this heritage.

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