The Use of Helical Computed Tomography (Helical CT) in the Identification of the Manufacturing Techniques of Pre-Columbian and Contemporary Rubber Balls

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Abstract
This paper will analyze the advantages of studying rubber objects by using Helical Computed Tomography. Our first step will be to discuss the techniques employed for manufacturing rubber balls in Pre-Columbian times, using 16th century historical sources and contemporary ethnographic studies. Our conclusions will be compared to the results obtained by using Helical CT for studying archaeological and ethnographic rubber balls.

We will also refer to the utilization of the Surface Shading Reconstruction as a method for rendering a three-dimensional extemal image of the archaeological materials we examined. Both techniques are very interesting, given their non-destructive nature, their capability to create three-dimensional images of the objects under study, and to observe the interior of the objects without dissecting them.

Keywords: Tomography, Rubber balls, Templo Mayor, Manufacturing

Introduction
The finding of rubber artifacts can be counted among the most rare occurrences in Mesoamerican archaeology. The number of objects recovered to this date is quite small, particularly if we consider that rubber-producing abounded in almost all the tropical zones of Mexico and Central America, and that Pre-Columbian societies used this polymer in many ways, as is demonstrated by historical sources and indigenous codices.

The contradiction between the archaeological data and the biological and historical information can be easily explained: rubber is a biological material that is extremely vulnerable to a wide array of deteriorating agents. Some of these are oxygen, ozone, light, heat, metals, acids, strong bases, oils, fats, and microorganisms. Their isolated, or joint, action rapidly affects the molecular structures of rubber, characterized by their weak chemical bonds.

The few archaeological rubber artifacts presently known come from three Pre-Columbian sites that are very distant from each other, in space and time: El Manati, in Veracruz, Chichen Itza, in Yucatan, and Tenochtitlan, in the Federal District. These sites have in common waterlogged or completely submerged archaeological contexts. In those conditions, temperature remains stable and the percentage of free and dissolved oxygen is reduced significantly, thus delaying oxidation processes. Other beneficial factors that characterize these environments are their low levels of light or their total darkness, their temperatures close to 10° Celsius, their neutral pH and the absence of metals (Filloy Nadal 1993).

Given the scarcity of rubber artifacts, and their enormous importance for the religious life of Mesoamerican societies, we shall review in this paper the recent discovery of 12 rubber balls in the Centro Histórico of Mexico City. Our main purpose, however, is to bring to light the analysis techniques used in the study of these biological materials, and, particularly, Helical Computed Tomography.

The finding

The rubber balls were found inside the Eagle House, one of the main religious buildings in the Sacred Precinct of Tenochtitlan. In 1980, the exploration of the eastern wing of the Eagle House brought to light three rooms built during the reign of Motecuhzoma Ilhuicamina. Each room is decorated with polychrome benches, large ceramic braziers, mural paintings and an altar. In 1992 we made several excavations below these altars with the aim of unearthing offerings S, T and U, which had been previously detected thanks to the presence of long fissures in the stucco floors. Years later, in 1997, offering X was discovered and excavated in the entrance to the northern wing of the building.

When we exhumed the four offerings we observed that their respective gifts had completely different degrees of preservation. This fact was extremely surprising, since these offerings contained almost identical biological objects and artifacts, which were obtained or made in the same places, and were quite likely buried on the same day, during the ceremonies to consecrate the building.

The remarkable differences in the deterioration of each offering were the result of the combination of two interesting natural phenomena: on the one hand, the peculiar way in which the Eagle House has been sinking and, on the other, the seasonal fluctuations of the water table. There is enough evidence to assert that the building started sinking early on, perhaps even in the 15th century. From the beginning the northern end of the building sank faster than the southern end. Because of that, Offering S –the most northerly of them all– sank deeper and was completely submerged in water. The presence of water with a neutral pH, a constant temperature of 16° Celsius 24 hours a day, scarce oxygen and total darkness characterized this context. Offerings U and X were placed in an intermediate position. In this zone the constant fluctuation of the water table pushed sediments inside the caches, so that the gifts ended up inserted in clay matrices, that were sometimes humid and sometimes waterlogged. The pH was neutral, the temperature was stable and oxygen was present in small quantities. In contrast, Offering T -the southernmost of them all- remained for centuries in an elevated place, where humidity was not significant and the percentage of oxygen was very high.

The differing combination of these phenomena accounts for the fact that the biological materials in Offering S are the best preserved, those in Offerings U and X are more damaged, and those in Offering T are very deteriorated or have almost vanished (López Luján 1998; López Luján *et al.* 1996).

The rubber balls

The collection of rubber balls from the Eagle House consists of 10 complete pieces and 2 incomplete ones. Even though their morphology has changed through the years, it is evident that these objects were originally spherical. Their diameters range from 6 to 8 centimeters, and their weight from 91 to 212 grams. All the balls have a peculiar ridge with straight walls and a curved bottom that resemble a human mouth.

Some of the physical characteristics of these rubber balls derive from the kind of context in which they remained buried. The balls in Offering s –found in a completely submerged context– have darker surfaces, ranging from grayish brown to black, and their surfaces are very irregular, flexible and have a large number of cavities. In contrast, the balls in Offerings U and X –found in waterlogged environments– have light brown, smooth, rigid and cracked walls with few cavities (López Luján 1998; Filloy Nadal and Canseco 1996).

These balls had a strictly ritual function. In fact, in Pre-Columbian times the production of rubber artifacts centered to a great extent on the creation of religious objects. Prominent among them were the divine images known as *ulteteo,* the balls for the game *ulamaliztli;* and the balls used in offerings, such as the ones found in the Eagle House, known as *ultelolotli.* Compared with the balls used for playing, the offering balls were always smaller and with less regular walls. They had three distinct destinies: they were burnt in bonfires or braziers; or they were thrown into springs, cenotes or sacred lakes; or else, they were buried in caches, as in the Eagle House.

Offering balls are represented in Mesoamerican codices inside temples, on top of altars, braziers or firewood bundles, in front of divine images, and on the extended hands of characters depicted in the act of oblation. As in the balls from offerings S, U, and X, most of the balls depicted in the codices are spheres with a ridge in their upper part, where one, two or three feathers were inserted (Filloy Nadal 1993).

The archaeometrical analyses

After the extraordinary finding in the Eagle House, we decided to carry out a systematic series of archaeometrical analyses, given the scarce bibliographical information about archaeological rubber. Obviously, the fact that we were dealing with unique cultural works limited our liberty to take samples and therefore reduced the scope of our study. Our first step was to use Fourier's Infrared Modified Spectroscopy (FTIR) to determine that the sole raw material used in the production of these objects was cis poly-isoprene or natural rubber (Filloy Nadal and Canseco 1996; Filloy Nadal 1996). Although there are many rubber- producing plants endemic to Mesoamerica, *olquahuitl* or *Castilloa elastica* was the most widespread, and thus the one most frequently used by Pre-Columbian cultures. Therefore we surmise that the balls from the Eagle House were made with latex culled from that species and that they could have been bought, already manufactured, at the Tlatelolco market, as Sahagun states, or received as tribute from the Oaxaca province of Tochtepec, as registered in the *Codex Mendoza.*

Later, the utilization of Differential Scanning Colorimetry (DSC), of Thermo-Gravimetric Analysis (TGA), and of Gel Permeation Chromatography (GPC) allowed us to evaluate the transformations in the physical and chemical properties of the rubber, resulting from the deterioration processes it underwent, and also to establish that such changes were directly related to the characteristics of their respective archaeological contexts (Filloy Nadal and Canseco 1996; Filloy Nadal 1996).

Helical Computed Tomography

Our next step was to define the technique used for manufacturing the balls. Thanks to 16th century historical sources, and to several contemporary ethnographical studies, we knew that there were two different techniques. Both began with the making of an incision in the bark of the rubber-producing plant to cull the latex. The viscous liquid thus collected was then boiled to separate the rubber itself from the other components of the latex. According to the historical descriptions of Fernandez de Oviedo, Martir de Angleria and Cervantes de Salazar, the long threads of the resulting elastic material were simply kneaded together until they were shaped into a ball, which was then left to dry. On the other hand, ethnographies of the Lancandon Maya, the Tarahumara, and the *mestizos* of Sinaloa describe a more complex technique in which the balls are shaped by rolling the threads of rubber into a circle in a concentric fashion. Each layer is smoothed with the fingers, hit against a flat surface and pinched with a thorn or a nail to prevent the formation of air bags inside (Oliver Vega 1992). This operation is repeated until the ball reaches the desired size. In this regard, it is interesting to point out that Floyd Lounsbury (1973) discovered that the Maya glyph for rubber in the *Madrid Codex* is a spiral that reminds us of the rolled rubber threads of the Lacandon.

Taking into account this difference between the historical and the ethnographic descriptions, we tried to determine if the Mexica used the kneading or the rolling procedure. Therefore we sought an *imagenology* technique that would allow us to observe the interior of the archaeological balls without having to dissect, and thus destroy, them. That is why we used the Helical CT.

As is well known, the basic principles of tomography lie in radiology, a non-destructive technique that has been employed successfully since the 1930's to analyze archaeological objects. *Grosso modo,* in a radiography a beam of X-rays is projected through a cultural object with the aim of obtaining an image of its internal structure on a photographic plate. This image reflects the different densities of the materials that constitute the object, reflected in the different rates of absorption of the radiation. Unfortunately, radiography has important limitations, there is no way to obtain three-dimensional images and to modify the plate once it has been exposed to the X-rays (Hours 1980).

Fortunately, Helical CT has managed to overcome both limitations efficiently. This new technique projects simultaneous and massive doses of X-rays on all the surfaces of the cultural object. This allows us to see of its internal structure, creating a three-dimensional figure with information about relative depths. Since the information is digitalized and saved to a computer file, the image can be modified and filtered to increase or decrease its visual contrasts.

Our study was carried out at facilities of CT-Scanner de México, a private institution that has one of the most modern tomographers in the country, a Pro-Speed machine from General Electric. We took axial sections, 1 to 3 millimeters wide, of the totality of each rubber ball. This allowed us to generate many three-dimensional images of the balls' interior. The equipment also allowed us to calculate the tomographic density of the most conspicuous internal structures of each ball, using Hounsfield units. Finally, thanks to the Surface Shading Reconstruction of the tomographer we obtained a three-dimensional reconstruction of the external image of each ball.

The corpus of our analysis consisted of three of the archaeological balls discovered in the Eagle House and of two modern balls used for playing, from the ethnographic collection of the Museo Nacional de Antropología. The largest comes from Sinaloa, and has a diameter of 17 centimeters; the other one was acquired in the Mixtec region and has a diameter of 10 centimeters.

Results

Our first step was to obtain the tomographies of the two ethnographic balls. We confirmed that the Mixtec ball was made using the rolling technique. We observed a spherical core, s centimeters wide, made with strings of a very dense material. This could be a skein of yarn or cloth that was later surrounded with nine layers of natural rubber. In contrast the *ulama* ball from Sinaloa has an amorphous internal structure with some air bags, produced by the kneading technique. The presence of an external rim in the sphere's equator indicates that, once kneaded, the Sinaloa ball was introduced in a hot spherical mold to achieve its very regular finish. Interestingly, we found inside this ball a 8.5-centimeter long needle.

Our second step was to obtain the tomograms of the three archaeological balls that were best preserved. We selected one from Offering U and two from offering S. In the latter we chose one ball found at the bottom of the cache and another that was floating in the water table because we wanted to explain their different densities in relation to water.

In the three cases, we could appreciate a clearly defined core, around which there are several spiral layers of rubber. As if this was not enough, in one of the balls we could clearly see the end of one of the rubber threads. This proves beyond any doubt that, just like the Mixtec game ball, the Mexica balls were made by rolling rubber threads around a more homogeneous core. Interestingly, between the layers of rubber we detected small particles with a greater brightness and density. We assume that they are dust particles that stuck to the surface of the balls during the manufacturing process, as each layer was struck and smoothed over a flat surface.

The tomograms also revealed that the ridges in the balls were made after they were finished, since the threads of rubber are interrupted abruptly by them, and do not follow their edges. The surface of the cut, and the flexibility of the material involved suggest that the ridges were carved using instruments with very sharp straight edges, perhaps made of obsidian.

On the other hand, in the ridge of one of the balls we detected a material with a significantly lower density than rubber. We think that it could be some kind of adhesive, applied to affix the feathers that were inserted in the balls.

Finally, we should point out that the ball that was floating on the water table differed from the rest because of the low density of its rubber and the presence of numerous cavities.

Conclusion

To conclude, we are convinced that Helical CT is a useful technique for making physical analyses of archaeological biological materials.

Some of its best features are its non-destructive nature; the possibility of seeing the interior of the objects without dissecting them, the ability to generate three-dimensional images of the surfaces, and its efficiency in calculating the relative density of the different internal structures.

Resumen

Este artículo analiza las ventajas de estudiar objetos de hule utilizando tomografías helicoidales. Primero se discutirán las técnicas empleadas para la manufactura de pelotas de hule en épocas precolombinas, usando fuentes históricas del siglo XVI y estudios entográficos contemporáneos. Compararemos nuestra conclusión con los resultados que se obtengan usando la TC Helicoidal para el estudio de pelotas de hule. También nos referiremos a la reconstrucción con sombreado de superficie como un método para interpretar una imagen externa tridimensional de los materiales arqueológicos que hemos examinado. Ambas técnicas son interesantes debido a su naturaleza no destructiva, a su capacidad de crear imágenes tridimensionales de los objetos estudiados y a que se puede observar en el interior de los objetos sin tener que maltratarlos.

Palabras clave: Tomografía, pelotas de hule, Templo Mayor, Manufactura

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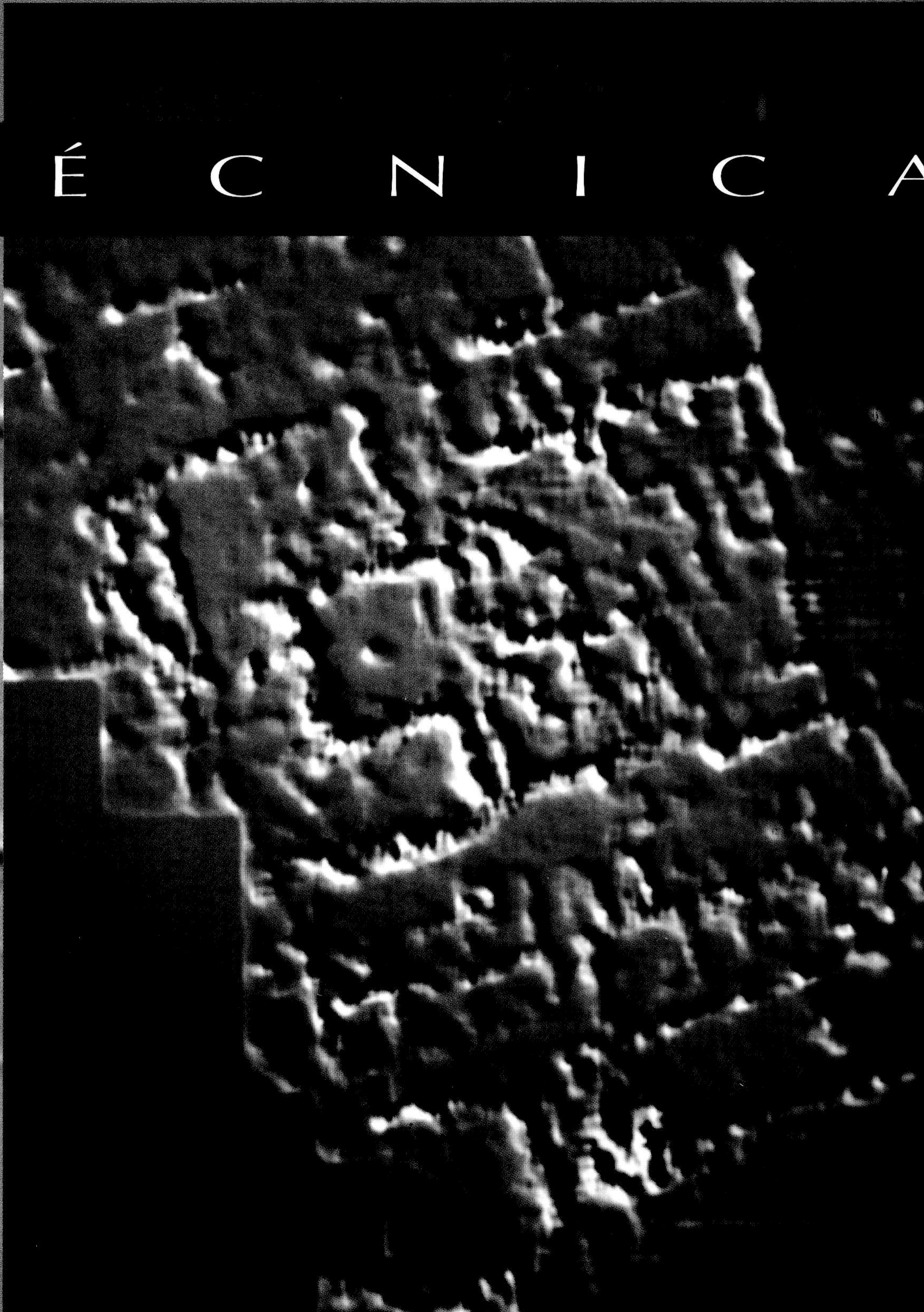

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