Evaluating and identifying pearls and their nuclei by using optical coherence tomography

Myeong Jin Ju,1 Sang Jin Lee,1 Eun Jung Min,1 Yuri Kim,2 Hae Yeon Kim,3 and Byeong Ha Lee1,2,*

1Department of Information and Communications, 261 Cheonmad-gwagiro, Buk-gu, Gwanju 500-712, Korea
2Graduate Program of Medical System Engineering,GIST, 261 Cheonmad-gwagiro, Buk-gu, Gwanju 500-712, Korea
3Korea Pearl Laboratory, 141-1 Bongik-dong, Jongno-gu, Seoul 110-390, Korea
*leehb@gist.ac.kr

Abstract: Optical coherence tomography (OCT) has been utilized to evaluate pearls including their nuclei noninvasively. By visualizing the internal structure of a pearl, we could measure the thickness of its nacre layer, observe the fine sub-structure of the nacre, and inspect the nucleus through the nacre. The system also allowed us to classify pearls into beaded- and non-beaded ones; usually, the saltwater ones have nuclei even though there are beaded freshwater pearls and non-beaded saltwater pearls. Any cracks, crevices, or blemishes not only in the nacre but in the nucleus of a pearl could be clearly visualized. The OCT system was based on a 20 kHz swept-source of a 1.31 µm central wavelength and an 110 nm full-width-at-half-maximum (FWHM) bandwidth. To get the 2-D images all around the circumference of a pearl, the pearl was rotated by a motorized rotating stage. And to achieve 3-D volume images, galvano-scans were made along two axes. Of all things, the OCT allowed us to check the use of a forbidden nucleus, usually made of a Giant Clam shell thus fragile, without hurting the pearl. With this modality, we believe, it would be possible evaluating pearls both in qualitative and quantitative. Comparison with the images taken with an optical microscope and X-ray radiograph gives the refractive index of pearl as about 1.53 in average.

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OCIS codes: (120.3180) Interferometry; (110.0110) Imaging systems; (110.2960) Image analysis; (110.4500) Optical coherence tomography; (110.6880) Three-dimensional image acquisition; (160.4890) Organic materials.

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#126529 - $15.00 USD Received 5 Apr 2010; revised 24 May 2010; accepted 3 Jun 2010; published 8 Jun 2010
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1. Introduction

A pearl holds a unique position amongst gems by reason of its natural beauty which needs no enhancement at the hands of a lapidary. It is also distinguished from others by the fact; its origin is a living organism such as an oyster or mollusk [1]. In general, gemologists perform the grading of pearls with the shape (balance), luster, and thickness of nacre. Since the nuclei made from Giant Clam shells have been introduced, however, identification of the pearl nucleus becomes a main factor for pearl evaluation also [2]. The usage of the Giant Clam shell as nuclei for pearls is under controversial.

Due to the development of jewelry processing technology, even for a professional appraiser, pearl evaluation becomes more difficult. Therefore, several implements for gauging the pearl’s quality have been invented. An electron microscope and a spectrophotometer are representative examples; they are very effective and accurate in measuring the luster and the surface in detail. When it comes to the internal structure inspection, however, any apparatus and method has not been proven yet in terms of efficiency even though there are several equipments and avenues. Furthermore, there is no way to verify the kind and quality of nucleus already inserted into the pearl so far.

For measuring the nacre thickness and verifying the type of nucleus, inspecting the inner structure of the pearl is very valuable [3,4]. The pearl cultured for a long period has a thick nacre layer as well as a balanced shape. The pearl nucleus, implanted into the gonad of a marine mollusk or the pearl sac of a freshwater mussel, is categorized into two types; a typical freshwater shell nucleus and a Giant Clam nucleus. However, with the pearls having the Giant Clam nuclei, the inclinations to shatter easily and to deform irregularly were shown [2], which increases the importance of identifying the nucleus of an already cultured pearl.

A conventional X-ray radiograph and an electron microscope are currently used for checking the presence of the nucleus and analyzing the nacreous laminated pattern [1,5,6]. However, since the X-ray radiography is making an image by accumulating the layer images from the top to the bottom of the pearl, distorted and obscure images are inevitably involved. Likewise, the electron microscope has a serious drawback; the pearl under inspection should be cut off. Consequently, the pearl will lose its value as jewelry after the measurement.

Recently, to overcome these drawbacks, optical coherence tomography (OCT) has been introduced [7]. OCT is a well known technique for creating noninvasive but high resolution images of biological microstructures [8]. OCT has several advantages for nacre thickness measurements. Firstly, it can reveal the internal structural of a pearl with a high resolution. Secondly, its high acquisition speed, easy operation and simple image interpretation guarantee high measurement efficiency. Further, the operation procedure is noninvasive, nondestructive, innocuous, and applicable to all sorts of pearls. However, even with OCT, inspecting the sorts of nucleus of a cultured pearl has never been performed yet even though it becomes a critical factor for grading pearls.

In this article, we graft a motorized rotating stage onto a conventional swept source OCT system (SS-OCT) for analyzing the all around internal structure of a pearl. With this system,
we could observe the accumulation pattern of the nacreous layer and the flaws made inside of a pearl, and also identify the nucleus through the nacreous layer.

2. System description

Figure 1 shows the schematic of the proposed system based on SS-OCT. The system comprises of a wavelength-swept source, a Mach-Zehnder interferometer, a data acquisition (DAQ) electronics, and a sample scanning stage. The light source is a ready-to-ship scanning light source (HSL-2000, Ver. 1.0, Santec). It has a scanning rate of 20 kHz, light output duty cycle of 65%, -3dB single-path coherence length of 10 mm, central wavelength of 1.31 µm, and full-width-at-half-maximum (FWHM) bandwidth of 110 nm. The theoretical depth resolution that the source can give is 6.9 µm in air.

![Fig. 1. Schematic of the system. SS: frequency swept laser source, PC: in-line polarization controller, C: circulator, L1-2: collimation lens, RM: reference mirror, OL: objective lens, RS: motorized rotation stage, BPD: balanced photo-detector.](image)

The input light is coupled to a 5:95 single mode fiber coupler; 5% of it is directed to the reference arm and the other 95% to the sample arm. In the sample arm, the lateral scanning on a sample is made in two ways. The first one is using a motorized rotating stage (PRM1 Z7E: Thorlabs, Inc.). The sample is fixed onto the rotating stage and rotated with the stage. The second way is that the sample is fixed but the incident beam is scanned by a one- or two-axis galvanometer scanner. In this case, a scanning lens (LSM03, Thorlabs, Inc.) of a 36 mm effective focal length is used. The reference and sample beams are directed to a 50/50 fiber coupler, reflected, and make interference with each other. The interference signal is detected by a dual balanced photo-detector (Model 1817, New Focus, Inc.) and band-pass filtered from 1.5 MHz to 40 MHz. The balanced photo current, i.e. the spectral interference signal, is converted into voltage and directed to a DAQ board (National Instruments NI-6156, 100 MS/s). The detected signal is rescaled into the wave number domain by using the rescaling parameters determined by a simple calibration method [9]. This signal is Blackman windowed, zero-filled, and digitally inverse Fourier transformed to yield a single A-scan signal having 4096 data points. These experiment procedures are controlled and performed by a LabVIEW program. The experimental axial resolution was measured to be ~12 µm and the sensitivity was over 100 dB.

3. Performance & result

Nacre quality is the most important factor in pearl identification [3,4]. The bead material used to create the nucleus has historically been from freshwater mussel shells found mostly in the Tennessee River and in the Mississippi River Basin, i.e., Three-ridge pearly mussel, Ebony shell, Wash-boad pearly mussel, Pig-toe pearly mussel, Monkey-face pearly mussel, and
Mayple-leaf pearly mussel [10]. Because the available stock of natural shells has been dropped significantly as increasing the popularity of cultured pearls, researches on alternative nucleus material have been actively made. Recently, Giant Clam shells become now used to a large extent. However, according to the checklist of CITES (Convention on International Trade in Endangered Species), Giant Clams (Tridacna gigas) are protected against over-exploitation through international trade [11]. And also the Giant Clams are listed as vulnerable by the IUCN (International Union for Conservation of Nature) because of extensive collecting for food, aquaculture and aquarium trade [12]. In addition to these, the bead of the Giant Clam shell is known as having fragile disposition; the pearls having this bead are much more prone to cracking during the drilling process [13]. Therefore, the identification of the nuclei of already cultured pearls becomes the most vital factor for prohibiting non-proper nuclei production and grading pearls.

3.1. Inspection of the internal structure of a pearl

A pearl is formed when a small irritant or parasite penetrates and lodges in the mantle tissue of a mollusk. In response, a substance called nacre is secreted, and the creation of a pearl begins. Nacre is a combination of crystalline and organic substances. The nacre builds up in layers, as it surrounds the irritant to protect the mollusk, and after a few years, this build up of nacre forms the pearl. Since nearly all pearls are currently cultured, many researches and methods for culturing the pearls are in progress [14–16]. The cultured pearls are categorized into saltwater pearls and freshwater ones. The saltwater pearls are usually produced by saltwater mollusks in saline environment. Recently, beaded freshwater and non-beaded saltwater pearls have been introduced on the market also. Thus, categorizing cultured pearls only with the presence of nuclei becomes more and more difficult. When it comes to the population, however, the saltwater cultured pearls tend to be more round than the freshwater ones since the saltwater pearls are universally bead nucleated. On the other hand, the great majority of freshwater pearls is not bead-nucleated; thus is not as round as the saltwater pearl. In this article, we try to confirm the presence of the nucleus and also inspect the internal structure of the pearl with OCT.

Figure 2 shows the OCT images of a bead-nucleated saltwater pearl (a) and a non bead-nucleated freshwater pearl (b), respectively. The data was taken while rotating the pearl along its center position with the rotating stage; therefore, the horizontal axis of the figure is the rotating angle. Of course, it can be presented in a polar coordinate also. In Fig. 2(a), the internal structure could be clearly identified. Especially, the interface between the nacre and the nucleus is obviously visible as a dark line. As shown in Fig. 2(b), on the contrary, any identifiable interface structure is not found. Therefore, we can conclude that the OCT can be used inspecting the existence of the nucleus in an already cultured pearl.

Besides the verification of the interface between the nacre and the nucleus, OCT images could be used to analyze the nacre formation pattern. As shown in Fig. 2, the nacre layer has many fine sub layers in it as the annual rings of a tree. To appreciate the sub layers in more detail, two freshwater pearls were OCT imaged and compared with Fig. 3. The nacre layer of the first pearl, as shown in Fig. 3(a), is formed uniformly without any crevice and blemish in it. On the other hand, in Fig. 3(b), the second pearl has appreciable cracks in the nacreous layer. To visualize the internal structures more effectively, Figs. 3(a) and (b) are presented in a polar coordinate as Figs. 3(c) and (d), respectively. In the polar coordinate, it becomes clear that the first pearl has a highly uniform nacre formation pattern, Fig. 3(c), and the distribution state of the crevices and defects of the second pearl could be identified at a glance, Fig. 3(d).
Fig. 2. OCT images of a bead-nucleated saltwater pearl (a) and a non bead-nucleated freshwater pearl (b), respectively. The image represents an area of 360 degree (horizontal)x2 mm (vertical) along the angle and the depth, respectively. The pearls are in round shapes of course.

Fig. 3. OCT images of freshwater pearl that retains no defects and cracks (a), and the one contains thick crevices (b). The image represents an area of 360 degree (horizontal)x3 mm (vertical) along the angle and the depth, respectively. The same OCT images are presented in a polar coordinate; (c) is for (a) and (d) is for (b), respectively.

Since the proposed system is also possible to perform galvanometer scan, we could go over the pearl in three dimensions. Figure 4(a) and (b) show the 3D OCT images of the freshwater pearls, single-frame excerpted from video recordings, that were used to get Fig. 3(a) and (b), respectively. To get it, the rotating stage was fixed and the galvanometer was scanned in two directions. A volume image was measured in $6 \times 6 \times 3$ mm$^3$ (horizontal $\times$ vertical $\times$ depth) with $500 \times 500 \times 550$ pixels. From the OCT volume image, the distribution state and the range of a chink are revealed very clearly. Therefore, we can say that the proposed system could be used to grade pearls as observing the laminated pattern of the nacre layer, and the defects, blemishes or crevices located inside of the pearls.
3.2. Measurement of the nacre thickness of a pearl

Measuring the nacre thickness of a pearl makes significant sense in identifying and qualifying the pearl, quantitatively. When it comes to measure the nacre thickness, the refractive index of the pearl should be firstly concerned. Therefore, the experiment for measuring the refractive index of pearl was performed. At first, a pearl was mechanically sliced and polished. Then, with a microscope the physical thickness of the nacre was measured as shown in Fig. 5(a). Secondly, from the A-scan profile corresponded with the yellow line drawing in Fig. 5(a) the optical thickness was measured as shown in Fig. 5(b). From these two measurements, the refractive index of the pearl was achieved as dividing the optical thickness by the physical thickness. Figure 5 gives that the refractive index of the pearl is 1.53. For getting a more general value, three representative types of saltwater pearls, Akoya, Tihitian-black, and South-sea cultured pearl, were measured at 90, 180, 270, and 360 degrees. The measurement results presented with Table 1 allow us to conclude that the average refractive index of the pearls is about 1.53. However, due to nonuniformity of each individual pearl and the discrepancy in the measuring points, a more careful measurement is necessary to get a better accuracy.

| Angle | Akoya O.T. [µm] | Akoya P.T. [µm] | Akoya n | Tihitian-Black O.T. [µm] | Tihitian-Black P.T. [µm] | Tihitian-Black n | South-Sea O.T. [µm] | South-Sea P.T. [µm] | South-Sea n |
|-------|----------------|----------------|--------|--------------------------|--------------------------|----------------|---------------------|---------------------|----------|
| 90°   | 570.96         | 373.11         | 1.53   | 1625.04                  | 1061.02                  | 1.53           | 1207.08             | 789.44              | 1.53     |
| 180°  | 636.84         | 416.09         | 1.53   | 2003.85                  | 1307.77                  | 1.53           | 1273.68             | 832.19              | 1.53     |
| 270°  | 576.45         | 376.63         | 1.53   | 1465.83                  | 962.08                   | 1.52           | 1202.31             | 785.72              | 1.53     |
| 360°  | 527.04         | 343.30         | 1.54   | 1537.20                  | 1008.51                  | 1.52           | 1284.66             | 839.09              | 1.53     |

O.T.: Optical thickness, P.T.: Physical thickness, n: Refractive index
Fig. 5. Microscope image of a sliced Tahitian-black cultured pearl (a), and the corresponding A-scan OCT taken along the yellow line (b).

Fig. 6. The OCT image of a bead-nucleated saltwater pearl (a). The image represents an area of 360 degree (horizontal) x 2 mm (vertical) along the angle and the depth. Its A-scan images taken at the scan angles of 90 (b), 180 (c), 270 (d), and 360 (e) degree, respectively.

Figure 6 shows a 2-D OCT image of a saltwater pearl and some A-scan images of it. In Fig. 6 (a), the horizontal-axis is the angle of the rotation stage and the vertical-axis is the penetration depth. Figures 6 (b), (c), (d), and (e) are taken at the scan angles of 90, 180, 270, and 360 degree in (a), respectively. The characteristics of the A-scan profiles can be summarized as: 1) The signal of the surface of the pearl shows a much stronger intensity than...
others. 2) The signal of the surface of the pearl nucleus is strong also and clearly identified from the signals resulted inside of the nucleus. 3) There are fine structured sub-layers in a nacre layer. The available range of the nacre thickness measurements was up to 3 mm, though it depends on individual pearls.

3.3. Identification of nucleus through the nacre layer of a pearl

A nucleus of a pearl, although it is not externally visible in the cultured pearl, is known as extremely important in the culturing process and the pearl grading. Figure 7 shows photographs of a typical freshwater shell nucleus (a) and a Giant Clam nucleus (b), and their 2-D OCT images (c) and (d), respectively. The OCT images were obtained by scanning the galvanometer in one direction. As shown in Fig. 7 (a) and (b), identification of nucleus seems almost impossible by the photographs. However, the difference of these two nuclei is clearly confirmed in the tomography images; randomly distributed cracks are watched in Fig. 7(d) while some part of striations is observed in Fig. 7(c). Based on these measurements, we can say that the nucleus, or bead, of Fig. 7(c) is slightly low-graded but the one of Fig. 7(d) is appreciably low-graded. The same scheme can be used to identify or evaluate the nucleus through the nacre layer of an already cultured pearl.

![Photographs and 2D tomography images](image)

Fig. 7. Photographs of a typical freshwater shell nucleus (a) and a Giant Clam nucleus (b), and their 2D tomography images (c) for (a) and (d) for (b), respectively.
Figures 8 and 9 show X-ray radiography images and the galvanometer-scanned 3D OCT images of the saltwater pearls which contain a standard freshwater shell nucleus, similar to the
one of Fig. 7(c), and a Giant Clam nucleus, similar to the one of Fig. 7(d), respectively. Their 2D images extracted along three orthogonal planes are also shown in the figures. From the radiography images of two pearls, any structural information was not clearly observed. The interface between the nacre layer and the nucleus was faintly visible only in Fig. 8(a). From these OCT measurements, meanwhile, we can clearly conclude that we could unquestionably identify and evaluate the nucleus implanted into a pearl even though it is externally invisible due to the color of the pearl. The 3D OCT volume was $6 \times 6 \times 3 \text{ mm}^3$ (horizontal $\times$ vertical $\times$ depth) corresponding to $500 \times 500 \times 550$ pixels.

4. Conclusion & discussion

Recently, OCT technology is applied for researching pearls. Especially, the measurement of the nacre thickness of a pearl makes a significant sense in qualifying the pearl quantitatively. We have tried, in this work, to functionally expand the advantage of the well-developed OCT system for grading pearls and identifying their nuclei. The system was based on swept-source OCT (SS-OCT). By using a motorized rotating stage, we could observe the tomography images of a pearl along its whole circumference. Of course, by scanning with a 2D galvanometer, we could see the 3-D internal structure of the pearl. The experiments allowed us to conclude that OCT can be used for categorizing, measuring, and identifying pearls and their nuclei: 1) We could categorize the pearls into beaded and non-beaded ones. Even though not always, a saltwater pearl had a nucleus in it. 2) We confirmed the refractive index of pearls as 1.53 in average. 3) We measured the nacre thickness of a pearl from an A-scan OCT image. 4) We inspected the inside of the nucleus bead. The bead from a Giant Clam, known as fragile and protected, had many flaws in it. Beyond all, identifying and evaluating the nucleus through the nacre layer of an already cultured pearl has been firstly tried and confirmed. Experimental results verify the feasibility of the proposed OCT scheme for evaluating, analyzing and identifying pearls without hurting them.

Acknowledgements

This work was supported in part by a grant from the institute of Medical System Engineering (iMSE) in the GIST and the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MEST) (No. R01-2007-000-20821-0).