Multimodal analysis of pearls and pearl treatments by using optical coherence tomography and fluorescence spectroscopy

Myeong Jin Ju,1 Sang Jin Lee,1 Yuri Kim,2 Jun Geun Shin,1 Hae Yeon Kim,3 Yiheng Lim,4 Yoshiaki Yasuno,4 and Byeong Ha Lee1,2,*

1School of Information and Mechatronics, GIST, 261 Cheomdan-gwagiro, Buk-gu, Gwangju 500-712, Korea
2Graduate Program of Medical System Engineering, GIST, 261 Cheomdan-gwagiro, Buk-gu, Gwangju 500-712, Korea
3Korea Pearl Laboratory, 141-1, Bongik-dong, Jongno-gu, Seoul 110-390, Korea
4Computational Optics Group, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan.
*leebh@gist.ac.kr

Abstract: We present an integrated optical system that consists of optical coherence tomography (OCT) and laser-induced fluorescence (LIF) spectroscopy for multimodal analysis of pearls and pearl treatments. The OCT source and the LIF excitation beams were aligned together to illuminate the same spot of a pearl fixed on the sample stage that was under rotation. As a result, both OCT images and LIF spectra of the pearls were detected at the same time and also at the same place. For OCT, a 1310 nm-centered swept laser source was used. For LIF, a 405 nm laser diode was used and a lensed multimode fiber was utilized as a fluorescence probe. The tomographic investigation on the internal structure of a pearl allowed us to evaluate and categorize the pearl nondestructively as was previously reported. In addition, the measurements of fluorescence spectrum and its decaying rate helped to determine the species of mother oyster. The proposed multimodal analysis made it possible to classify the pearls and also to disclose the treatments made on the pearls.

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1. Introduction

Pearls are some of the most beautiful gemstones in the world. They are created from living organisms, thus, giving them the name of organic gemstones [1]. Today, almost all pearls used for jewelry are cultured by planting nuclei into mother oysters. The widely used mother oysters are: seawater bivalves; *Pinctada fucata* (Akoya oyster), *Pinctada maxima* (white lip oyster), *Pinctada margaritifera* (black lip oyster), *Pteria penguin* (mabe); seawater gastropod; genus *Haliotis* (abalone); freshwater bivalve; *Hyriopsis shlegeli et al* [2]. Among them, the following four kinds of cultured pearls are most frequently encountered in market: Akoya, South Sea, Tahitian, and freshwater pearls [3].

Figure 1 shows the photograph of four representative types of pearls in different sizes and colors, which have been actually used for this study. The sizes of Akoya and freshwater pearls are small but pretty similar to each other, whereas the sizes of the South Sea and the Tahitian pearls are relatively large—the Tahitian ones are the largest. As developing techniques of pearl cultivation and treatment, small South Sea pearls similar to Akoya ones in size and Tahitian pearls resembling in color to South Sea ones have recently been cultured and/or treated. Therefore, the methodologies that can classify varieties of pearls and disclose the treatments made on the pearls are definitely required. Of course, it should be performed in nondestructive ways in order not to degrade the value of pearls as gemstones.

![Photographs of pearls](image)

**Fig. 1.** Photographs of pearls actually used for this study. There are four representative types, and ten pearls in different sizes and colors for each type.

The most frequently adopted analytical method is X-ray fluorescence (XRF), which can quantify the mineral content of the pearls. The XRF is very effective in discriminating between freshwater and seawater pearls, since the freshwater pearls contain far more manganese than the seawater ones [4]. However, after the measurement, the pearl tends to become blackish in color as a result of the X-ray irradiation, though the degree is not severe [5]. Besides, it cannot make a distinction among different kinds of seawater pearls because their mineral compositions are very similar to each other. To overcome these drawbacks, as a
nondestructive method, the measurement of fluorescence spectrum under N₂ laser excitation has been tried [6]. It could classify the pearls produced from *P. fucata*, *P. maxima*, and *P. margaritifera* as well as freshwater pearls by ascertaining the parentage of pearls [5–7]. Nevertheless, several pearls in specific colors and the ones γ-ray irradiation processed are still difficult to be distinguished [5,6].

Various techniques of pearl treatments have been developed also. In general, most pearls are cleaned and washed to remove residues and odors; they are typically tumbled in rotating barrels with salt [8]. The tumbling must be closely monitored; otherwise some of the nacre may wear off. Other processes such as bleaching, buffing, and filling are not considered a routine but occasionally conducted [9]. Because these pearl treatments are directly related to the pearl price, verifying or disclosing any treatments made on the pearls becomes essential. In addition to the XRF, therefore, X-radiograph and electron microscopy have been applied as well. As far as we know, however, there has been no report on the nondestructive and also effective ways for identifying the pearl treatments in detail.

In our previous work [10], with optical coherence tomography (OCT), we have reported the distinction of beaded and non-beaded pearls, verification of defects inside of pearls, measurement of the nacre layer thickness, and identification of nucleus through the nacre layer. In this study, we attempt to classify the species of a pearl with OCT and laser-induced fluorescence (LIF) spectroscopy, and at the same time, to disclose the treatments made on the pearl. For these dual modality measurements, the integrating system composed of OCT and LIF is implemented. By adopting a motorized rotation stage as the communal sample scanning stage, the multimodal analysis at the same place and also at the same time could be possible. With these functionalities, we classify the pearls and identify the treatments made on them.

2. Experimental setup

2.1 Multi-modality instrument

The experimental setup is shown in Fig. 2, which highlights the paths of various light beams. The red line represents the light beams for OCT, the blue line symbolizes the excitation beam for LIF, and the green line signifies the path of the emitted fluorescence light.

Fig. 2. Schematic of the optical integrating system. SS: swept laser source, PC: in-line polarization controller, C: circulator, L1–3: collimation lenses, DF: dichroic filter, RM: reference mirror, OL: objective lens, MRS: motorized rotation stage, BPD: balanced photodetector, LD: laser diode, LPF: long-pass filter, LF: lensed fiber probe.

The optical paths of the OCT and the LIF subsystems are separated until being combined in the sample arm. And the analog processing electronics for the subsystems are controlled with a central computer. By utilizing a motorized rotation stage in the sample arm,
simultaneous measurements can be performed without using any specialized optics and complicated synchronization process of two different subsystems.

2.2 OCT subsystem

The light source for the OCT subsystem is a wavelength sweeping laser (HSL-2000, Ver. 1.0, Santec) having a center-wavelength of 1310 nm, wavelength bandwidth of 110 nm, scanning rate of 20 kHz, and average output power of 9 mW. The input light is partially coupled to the reference arm and the sample arm through the 50:50 single mode fiber coupler. The lights returning from both arms make interference with each other, which is detected by the balanced photo-detector (Model 1817, New Focus Inc.). The signal is band-pass filtered from 1.5 MHz to 40 MHz, and digitized with a data acquisition board (NI-6156, 100 MS/s, National Instruments). After that, the digitized signal is rescaled into the wave number domain [11]. To produce a single A-scan image, windowing, zero-filling, and inverse Fourier transforming are sequentially performed. The experimentally measured axial resolution of the system was 11.5 μm, and the sensitivity was 105 dB.

2.3 LIF spectroscopy subsystem

For the LIF subsystem, a laser diode (DL3146, Thorlabs, Inc.) having a wavelength of 405 nm and average output power of 10 mW is used as the excitation source. The laser beam is collimated and then combined with the OCT beam with the 45° dichroic filter (E47-264, Edmundoptics, Inc.), which has a high reflectivity at the excitation wavelength and a high transmission at longer wavelengths. The fluorescence light emitted from the sample is collected by the lensed-fiber probe that is made with a piece of multimode fiber [12]. The collected light is then long-pass filtered at 450 nm for rejection of the excitation beam, and then detected by the spectrometer (QE65000, Ocean optics, Inc.). The integration time of the spectrometer is set as 50 ms.

2.4 Integrating sample arm optics and devices

The sample arm optics and devices are designed so that the OCT source and the LIF excitation beam are co-aligned on the sample. In general, appreciable amount of optical components are required to work over the wide wavelength range of a combined system [13,14]. For the OCT system, a long depth of focus and a small spot size comparable to the coherence length of the source are desired. For the LIF system, a little larger spot size is desirable to avoid too much high irradiance and possible damage to the sample. The collection efficiency of the fluorescence light emitted from the sample is needed to be as high as possible. Finally, the sample should be scanned for two-dimensional measurements in both modalities.

In the setup of Fig. 2, a scanning lens having a long effective focal length (LSM04, Thorlabs, Inc.) was applied, and a 45° reflective dichroic filter was positioned next to the lens. These optical components created the spot sizes of 23 μm for OCT and 436 μm for LIF subsystems, and the illumination powers at the sample plane as 1.92 mW and 7.5 mW, respectively. By forming a lens at the end of the multimode fiber probe [12], the collection efficiency was considerably improved. The fluorescence emission light was collected at 90° angle from the excitation to prevent the detection of the light coming directly from the excitation source. For the simultaneous OCT and LIF measurements, a motorized rotating stage (PRM1 Z7E, Thorlabs, Inc.) was adopted as a common scanning stage. At this time, the galvanometric scanner was fixed, and the pearl was scanned as rotating it up to 360° using the rotation stage.

3. Performance and Result

Since diverse pearl culturing and manipulation methods have been developed, categorization of pearl and determination of treatments become more difficult and complicated even for a
professional appraiser. In addition to simple cleaning and washing treatments, there are some representative treatments as following [3,9]:

1) Bleaching: Medium- to low-quality Akoya pearls are often bleached with chemicals after drilling to whiten the color and make them look more even. However, improper bleaching can soften the nacre and reduce their luster and durability.

2) Buffing: Occasionally, pearls are buffed to improve their luster and remove superficial scratches. Beeswax or chemical polisher is sometimes used during buffing to add luster. However, the wax wears off easily and the chemicals may eat away the nacre.

3) Coating: There have been reports on the pearls coated with lacquer to improve their luster temporarily. In a few instances, pearls can be darkened with thin plastic coating, which makes them look like Tahitian pearls. However, the pearls coated in these manners are not allowed to be traded.

4) Filling: Low-quality cultured pearls are occasionally filled with epoxy resin when they have partial hollows or loose nuclei. It makes the pearls more solid and improves their durability as helping the bead nuclei to stay in position.

5) Dyeing: Off-color Akoya and South Sea pearls are sometimes darkened with dye to improve their appearance.

These treatment processes mainly change the appearance of pearls, which can make the pearls have better shapes and look like more valuable kinds. Accordingly, identifying the origin of a pearl as determining its mother oyster and exposing the manipulation operated on the pearl become significant for accurate categorization and precise evaluation.

3.1. Tomography image analysis

It was already presented that OCT could evaluate a pearl by identifying its nucleus, checking the presence of any flaws inside the pearl, and measuring the thickness of the nacre layer [10]. Figure 3 shows the 3D OCT images of Akoya (a), freshwater (b), South Sea (c), and Tahitian (d) pearls; visualized by using the Amira software (Visage Imaging Inc., CA). From these OCT images, as was reported, the existence and types of nuclei and the scratches inside could be clearly identified.

![3D OCT images of pearls](image_url)

Fig. 3. 3D volume OCT images of the pearls which are single frames excerpted from video recordings; (a) Akoya, (b) freshwater, (c) South Sea, and (d) Tahitian pearls. Nuclei and cracks inside the pearls are clearly identified and confirmed.

To check the feasibility of using OCT for identifying the treatments made on the pearls, 3D OCT images of several pearls were obtained with a measurement range of 5 mm (horizontal) × 5 mm (vertical) × 3.5 mm (depth) corresponding to an OCT volume of 435 × 435 × 1024 pixels. At first, identification of the pearl treated with filling process was attempted. Since the processed pearl was hard to obtain commercially, a prototype produced by modeling was examined. The pearl having a loose nucleus was filled with epoxy resin to fix the nucleus. Figure 4(a) and (b) show the photograph of a cross section and the 3D OCT image.
image of the filling processed pearl, respectively. The 2D images extracted along three orthogonal planes are shown in Fig. 4(c)–(e). We can see that the interfaces among nacre, epoxy, and nucleus are clearly identified with the OCT images.

Fig. 4. (a) Photographs and (b) 3D volume OCT image of the filling processed pearl, and its 2D tomography images taken along; (c) XY-plane, (d) XZ-plane, and (e) YZ-plane.

Subsequently, quantitative examination of bleaching treatment was performed. Morphological point of view, seawater cultured pearls are composed of nacre layer, organic layer, and nucleus. The bleaching is mainly applied to Akoya pearls having relatively thin nacre thicknesses; usually, the organic layer between the nacre and the nucleus of a pearl is chemically worn off during the bleaching process. Accordingly, the bleaching treatment might leave some hollows inside the pearl, which is ultimately associated with the durability of the pearl as a gemstone.

Fig. 5. Segmented OCT volumes of three representative Akoya pearls.
To validate the performance, three Akoya pearls processed with the bleaching treatment were three dimensionally imaged. Due to the strong refractive index contrast at the hollow layer boundaries, we could have very clear OCT images. The nacre and the hollow layers were identified and segmented by using a simple differentiation—based edge detection algorithm which was utilized in Ref. 15. Figure 5 shows the segmented volume images of the three Akoya pearls. Each image was pseudo-colored with orange for the nacre layer, magenta for the hollow layer, and bluish green for the nucleus. The segmented OCT volumes were realigned to be flattened in the right side of each image for better visibility. The figures provide the distributions of the nacre thickness and the hollow depth, and also the type of nucleus. The quantitative parameters of the pearls measured with the segmented volumes images are listed in Table 1. The nacre thickness and the hollow layer thickness were adjusted by using a refractive index of 1.53 (nacre) and 1.00 (air), respectively [10].

| Diameter [mm] | Mean thickness of Nacre layer [μm] | Mean thickness of hollow layer [μm] | Type of nucleus |
|---------------|-----------------------------------|-----------------------------------|----------------|
| Subject (A)   | 7.21                              | 569.15                            | 88.96          | G.C.           |
| Subject (B)   | 7.10                              | 539.04                            | 201.16         | F.S.           |
| Subject (C)   | 7.12                              | 751.12                            | 163.44         | F.S.           |

G. C.: Giant Clam nucleus, F. S.: Freshwater Shell nucleus

3.2. Fluorescence analysis

It has been reported that the nacre of a mother oyster shows a similar fluorescence spectrum with the one of the pearl produced from the same mother oyster, or from the same species [5–7]. By examining the pearl itself, therefore, it is possible to identify its host oyster and to categorize the pearl by species. Additionally, it is also feasible to differentiate between natural and artificially colored pearls by investigating the fluorescence spectra.

Figure 6 shows the time-integrated fluorescence spectra of Akoya (a), South Sea (b), Tahitian (c), and freshwater (d) pearls. A single and smooth peak is observed at 527, 548, and 602 nm in the Akoya, South Sea, and freshwater pearls, respectively. Especially, two sharp peaks are observed at 620 and 652 nm in the black Tahitian pearl.

![Fluorescence spectra](image)

Fig. 6. The fluorescence spectra of pearls under 405 nm excitation; (a) Akoya, (b) South Sea, (c) Tahitian, (d) freshwater pearls. Peak intensities are normalized.

In order to examine the fluorescence properties further, the fluorescence peak wavelengths were measured with a fair number of pearls; ten samples per each type of pearls. As Fig. 7 shows, interestingly, the peak wavelength distributions of Akoya (red), South Sea (green), and freshwater (blue) pearls are very distinctive. Since the fluorescence spectrum of the Tahitian pearl was clearly different from the other pearls, it is not included in the distribution chart. The mean peak wavelengths and the standard deviations (mean ± S.D.) of Akoya, South Sea, and freshwater pearls are 527.58 ± 2.74, 549.11 ± 3.45, and 603.50 ± 4.59 nm, respectively.
Fig. 7. Distribution of the peak wavelengths of fluorescence spectra from three kinds of pearls; Akoya (red), South Sea (green), and freshwater (blue) pearls.

As shown in Fig. 7, the peak wavelengths of these three kinds do not overlap each other, which can prove the possibility of distinction among these pearls. However, the difference between the peak wavelengths of Akoya and South Sea pearls is not big enough to be clearly determined as comparing with the difference between freshwater and other seawater pearls.

It is generally accepted that the nacre property of a pearl highly depends on the place where its mother oyster is grown. South Sea pearls are grown in a tropical or semi-tropical region called the South Seas; usually the area around the coasts of Australia, Indonesia, and the Philippines. On the other hand, Akoya pearls are grown around Japan, where the sea water temperature is much lower than the tropical region of South Sea pearls. The cooler condition causes Akoya pearls to develop their nacre layers more slowly but with more compact crystal structures, which affects the optical properties of the pearls [9]. Therefore, the decay rates of fluorescence emitted from Akoya and South Sea pearls were examined and compared to each other. With each pearl, a series of fluorescence spectra were measured for 60 s with a time interval of 1 s. As Fig. 8 shows, the intensity of the spectrum decayed considerably with time; Figs. 8(a) for Akoya pearl and (b) for South Sea pearl. The normalized intensities at the peak wavelengths were plotted together at Fig. 8(c). We can clearly see that the decaying rates of Akoya (red) and South Sea (blue) pearls are fairly different to each other.

Fig. 8. Series of fluorescence spectra of (a) Akoya and (b) South Sea pearls, and (c) the plot of normalized peak wavelength intensities. The decaying rate of South Sea pearl (blue) is faster than the one of Akoya pearl (red).
These results indicate that the decay rate of the fluorescence can be considered as an additional modality for distinguishing South Sea pearls from Akoya ones. However, additional studies with a great number and diversity of pearls are necessary to make a full evaluation of this method since the number of samples considered in this study was only 3 for each species.

In general, the nacre thickness of Akoya pearl is thinner than those of other seawater varieties such as South Sea and Tahitian pearls, and Tahitian ones are darker than other species. Therefore, classification among the pearls is widely performed by comparing the nacre thickness and the color. When it comes to differentiate white Tahitian pearls from South Sea pearls, however, the methods are not effective anymore. Figure 9 shows the fluorescence spectra of South Sea (a), black Tahitian (b), and white Tahitian (c) pearls. The black Tahitian pearl (b) shows the typical two sharp peaks at 619 nm and 651 nm. While the white Tahitian pearl (c) has a strong and smooth peak at 544 nm, similar with the typical peak of South Sea pearl (a) at 547 nm, so that the white Tahitian can be looked as a South Sea pearl. However, since the white Tahitian pearl has a small 616 nm peak, close to the 619 nm peak of the black Tahitian pearl (b), it can be distinguished from the South Sea pearl even with the resemblance in the surface colors. According to the literature [16], the typical peak wavelength around 620 nm is resulted from porphyrin contained in the shells of P. margaritifera and P. penguin.

![Fig. 9. The fluorescence spectra of pearls under 405 nm excitation; (a) South Sea, (b) black Tahitian, (c) white Tahitian pearls. Peak intensities are normalized.](image)

Fluorescence spectra of freshwater pearls with a wide range of colors were previously measured [5]. According to the earlier report, with fluorescence spectra, some freshwater pearls were difficult to be distinguished from some seawater pearls. In our study, ten freshwater pearls in various colors were examined with the LIF subsystem, under 405 nm excitation. As shown in Fig. 10, the fluorescence peaks are located in the range from 595 to 613 nm, which is well separated from the ones of seawater pearls of Fig. 6(a)–(c). Therefore, we can carefully say that identification of freshwater pearls from other seawater pearls is possible regardless of their superficial colors.

In contrast to natural color, artificial coloring techniques have been introduced in order to increase the commercial value of cultured pearls. The γ-ray irradiation and dyeing are some of the representative methods; however the pearls processed with the dyeing treatment are rarely found in the market. Previously, it was difficult to identify the origins of the processed pearls [6]. In this experiment, identification of pearls exposed to γ-ray irradiation is attempted. Fluorescence spectra of γ-ray irradiated pearls are shown in Fig. 11: Akoya (a), South Sea (b), and Tahitian (c) pearls; however, any noticeable difference between unprocessed (Fig. 6(a)–(c)) and γ-ray irradiated pearls is not found. The results indicate that classification of the pearl can be successfully performed even for the γ-ray irradiation processed pearls because any appreciable difference induced by the irradiation was not found in the fluorescence spectra.
3.3. Multimodal analysis

To demonstrate the simultaneous measurements of the proposed multimodal system, the LIF was repeatedly measured while OCT subsystem was imaging all around of a pearl. Figure 12 shows the photograph (a) of representative pearls and the OCT images of them: Akoya (b), South Sea (c), Tahitian (d), and freshwater (e) pearls. The measurement range of the OCT image was 360 degree × 2.5 mm in the transverse and the longitudinal directions, respectively. From the obtained images, the existence of nucleus and defects are clearly confirmed in addition to the fact that Akoya pearl has a relatively thin nacre layer compared with South Sea one even though the surface colors and the diameters are very similar to each other. Figure 13 is the map of pseudo-colored fluorescence spectra of each pearl, which was measured simultaneously with the OCT images of Fig. 12. We can see that each pearl shows the typical fluorescence spectrum of its own species all around the pearl.
Fig. 12. (a) Photographs of four typical pearls and OCT images of (b) Akoya, (c) South Sea, (d) Tahitian, and (e) freshwater pearls. Each OCT image represents an area of 360 degree (horizontal) × 2.5 mm (vertical) along the angle and the depth, respectively (all pearls are in round shapes).

Fig. 13. Maps of fluorescence spectra of (a) Akoya, (b) South Sea, (c) Tahitian, and (d) freshwater pearls, which were simultaneously measured with the 2D OCT images of Fig. 12. At each angle across the pearl, the fluorescence spectrum was measured and plotted with pseudo-colors.

Since the simultaneous measurement scheme allows us to investigate the whole circumference of a pearl, it was applied to identify the buffing treatment. Figure 14 shows a
photograph of the buffing-processed Akoya pearl (a), two-dimensional OCT image (b), its segmented OCT image (c), map of fluorescence spectra (d), and two representative fluorescence spectra (e) measured at 72 and 252 degrees along the pearl. The segmentation of Fig. 14(c) was performed with the segmentation algorithm of [15], and the red and blue lines represent the surfaces of nacre and nucleus, respectively. Even though the pearl has a very round appearance in the photograph (a), the nacre thickness has a very severe deviation from round in the OCT image (Fig. 14(b) and (c)). These facts are also revealed with the map of fluorescence spectra given in Fig. 14(d). The intensity of the fluorescence spectrum becomes weak at the place where the nacre layer is thin. As shown Fig. 14(e), the strong fluorescence intensity was measured at 72 degree (thick nacre region) and the relatively much weak one was measured at 252 degree (thin nacre region). From these, we can say that the fluorescence intensity is related with the nacre thickness. Of course the measurements revealed that the examined pearl was manipulated by the buffing process.

Fig. 14. Multimodal analysis of buffing processed pearl; (a) photograph, (b) OCT image, (c) segmented OCT image, (d) multiple site of fluorescence, and (e) fluorescence spectra at 72 and 252 degree.

4. Discussion and Conclusion

We have presented the multi-modality optical system that combines the inter-structural imaging capability of optical coherence tomography (OCT) with the functional imaging capability of laser-induced fluorescence (LIF) spectroscopy. The integrated optical system was capable of simultaneously acquiring OCT images and fluorescence emission spectra all across of a pearl.

From two- and three-dimensional OCT images, firstly, the morphological analyses were attempted to disclose the treatments made on pearls. For quantitative analysis, especially, the mean nacre thickness and the depth of the hollow layer appeared by bleaching process were measured with OCT and signal processed with the segmentation algorithm of [15]. Since the hollow layers directly affect the durability of pearls, the distribution and mean thickness of the hollow layer can be important factors for grading or evaluating pearls.

Subsequently, the time-integrated fluorescence spectrum of a pearl was measured to identify its origin. Since the nacre of a host oyster emits the fluorescence spectrum similar with that of the pearl cultivated from the same type of host oysters [5–7], it is very possible to
categorize pearls by measuring and comparing their fluorescence spectra. According to the results of the fluorescence measurements, we can say that pearls tend to have typical fluorescence peak wavelengths and shapes depending on their species: Akoya (single peak at 527.58 ± 2.74 nm), South Sea (single peak at 549.11 ± 3.45 nm), Tahitian (double peaks at about 620 and 650 nm), and freshwater pearl (single peak at 603.50 ± 4.59 nm). Since the difference of the peak wavelengths between Akoya and South Sea pearls was too much close to be clearly distinguished, the decay rate of the fluorescence intensity was also examined; Akoya pearls had slower decay rates than South Sea ones. In addition, identification of several colored freshwater pearls and γ-ray processed pearls were also tried; they did not affect the identification of mother oysters.

Lastly, simultaneous measurements of OCT and LIF were achieved by applying a communal rotation stage to investigate all around of the pearl. From the results of the concurrent measurement, it comes out into the open that Akoya pearls have thinner nacre thicknesses than other species in general, and the fluorescence intensity is closely related to the nacre thickness.

In conclusion, it is becoming very difficult to evaluate and differentiate pearls by using conventional analysis methods since the techniques of culturing and treatments have been highly developed. Even though the tomography analysis shows several feasibilities for appraising and identifying pearls without hurting them, there are still several limitations. Therefore, for getting more accurate and quantitative measurements, it is necessary to get help from other modality. In this study, we have implemented the integrated optical system capable of doing the functional fluorescence analysis along with the tomographic examination of pearls and pearl treatments. This integrated system eliminated the manual repositioning of the pearl for the multi-modal measurements and allowed us to get the data from the same position of the sample and also at the same time. OCT images clearly delineated the internal structure of a pearl, and the fluorescence spectrum and its decaying rate gave great help in evaluating and identifying pearls, and also in disclosing the treatments made on the pearls.

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