




# The influence of degradation in different pH buffer solutions on the optical and durability properties of Monocryl suture: (an in vitro study)

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## Abstract

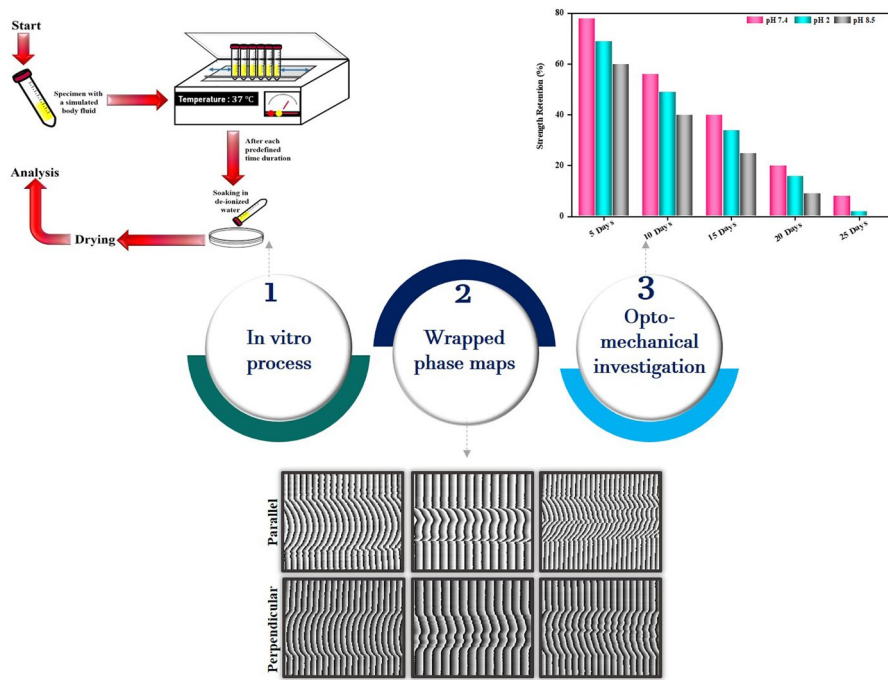
The objective of this work is to investigate the hydrolytic degradation of the Monocryl (PGA/PCL) surgical suture in different pH buffer solutions, and its correlation with the structural alterations the material undergoes. To this end, an in vitro degradation study was conducted under acidic (pH=2), physiological (pH=7.4), and alkaline (pH=8.5) conditions at 37 °C, over 25 days. Changes in the swelling rate, structural and mechanical properties of the Monocryl sample with the degradation time were characterized, from which the related degradation mechanism of the material was concluded. Results showed that the structural values of the Monocryl sample were more sensitive in the alkaline medium than the acidic and neutral ones. It exhibited a reduction in birefringence values by 11.5% from the original one in the buffer solution of pH=8.5, only 4% at pH=2, and 2.6% at pH=7.4, after 20 days of degradation durations. Over the same time period, mechanical loss in neutral, acidic, and alkaline media was decreased to 19, 14.9, and 8.3%, respectively. The obtained results revealed that the Monocryl suture exhibits enhanced degradation properties in neutral conditions rather than both acidic and alkaline ones, with a more homogeneous degradation behavior during the degradation process.

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## Graphical abstract



**Keywords** Degradation behavior · Monocryl suture · Different pH · Refractive index · Durability · Mach–Zehnder interferometer · Swelling rate

## Introduction

Resorbable poly ( $\alpha$ -hydroxy acids), namely polyglycolide (PGA), polylactide (PLA), and their copolymers with epsilon-caprolactone, has been employed in most domains of biomedical applications [1, 2]. These applications include regeneration implants, drug delivery, substrates for tissue engineering, surgical sutures, and others [1–5]. Such materials have the advantages of excellent biocompatibility, low immunogenicity, good handling ability, and biodegradability [2, 6]. Practically, the degradation behavior of these materials is considered one of the crucial steps of tissue regeneration [7]. Due to the fact that the degradation proceeds through hydrolysis of their ester bonds into compounds naturally present in the organism, which are eventually resorbed [8, 9]. Therefore, avoiding the need for a second surgery to remove the implants, which supports cell viability, cell growth, and remodeling of tissues properly [8].

Ideally, biomedical materials used as surgical sutures should have in vivo degradation matches with the new tissue formation [10]. Because if the rate of degradation

is too slow, the residue of the surgical suture will hinder cell growth and tissue differentiation. On the other hand, if the degradation rate is too fast, the suture would damage and lose its usefulness before new tissue formation [10]. Therefore, the degradation rate of the implanted material must be consistent with the tissue healing and provide adequate strength until self-function is restored [10, 11]. The degradation behavior is affected by many factors such as chemical composition, chain microstructure, temperature, enzymes, and tissues [12]. Furthermore, the pH level dramatically affects the degradation rate of the implants, particularly if the pH level of tissue or body fluids deviates significantly from the neutral level [2, 13].

The pH is an indispensable indicator for judging homeostasis in the body [14]. In the human body, blood has buffering molecules, such as hemoglobin and albumin, with a pH-scale range between 7.35 and 7.45 [15]. Moreover, the pH of the pancreatic juice in the duodenum ranges from 7.5 to 8.5. Conversely, the major components of gastric juices (gastric acid and digestive enzymes) in the stomach have a pH-scale often ranges between 1.35 and 3.5 [14, 16]. These variations in pH may change the reaction rates of polymer surgical sutures with these different organs of the human body [14]. Consequently, investigating the influence of pH variation on optical, structural, and mechanical properties is a crucial task. Clinically, studying the biomechanical properties of the surgical sutures are crucial for surgeons not only to guarantee a proper load of the used suture but also, it is useful for predicting the retention of the surgical knots [11], since it should be strong enough to resist the postoperative loading conditions in real life [10, 11]. However, the *in vivo* experiments of such implants are limited by time and experimental costs. Accordingly, the *in vitro* degradation investigation is essential for providing an initial estimate for the *in vivo* degradation behavior of the implanted materials [17].

Nowadays, the advances in optical technologies enable us to utilize interferometric techniques for quick and reliable data acquisition on the structure, opto-mechanical, and physical properties of synthetic fibers and sutures [18–21]. These techniques can be classified into two-beam and multiple-beam interference techniques, which accurately measure significant parameters including refractive index, spectral dispersion, polarizability, birefringence, and their variations with the thermal and mechanical treatments [22, 23]. All of these parameters depend mainly on demodulating the optical phase object that is encoded in the form of two-dimensional (2D) fringe patterns. Accordingly, numerous authors have proposed several algorithms for accurate fringe analysis and obtaining the desired information of tested objects [24, 25]. The spatial carrier frequency technique based on Fourier Transform (FT) algorithm is recognized as the most successful approach in phase retrieval for its high reliability and accuracy [25].

In this paper, we intensively investigate the effects of different pHs on the degradation behavior of the Monocryl (PGA/PCL) surgical suture. To perform this task, an *in vitro* degradation duration from 1 to 25 days was carried out. We systematically evaluated the structural and optical properties of the suture samples at different degradation times based on the two-beam Mach–Zehnder interferometer attached to the mechanical drawing device. Furthermore, the degradation of the mechanical properties in different simulated fluids in terms of Young's modulus ( $Y$ ), Ultimate tensile strength (UTS), and compressibility ( $\chi$ ) was calculated.

## Material and experimental techniques

### Material

The tested suture is Polyglycaprone 25(PGA/PCL) under the trade name (MONOCRYL<sup>®</sup>). It was fabricated by bulk ring-opening co-polymerization, according to a method described previously [7]. The Monocryl suture is FDA-approved for clinical use, in the form of an absorbable, and monofilament structure with a 75/25 molar ratio (PGA/PCL) with USP size 6/0 [26–29]. It has unique biocompatibility and absorbability, which make it frequently utilized in most soft tissue applications and smooth muscle tissue engineering [27, 28].

### Optical system

For investigating the opto-mechanical properties of the Monocryl suture sample, the two-beam Mach–Zehnder interferometer is constructed as given in Fig. 1a. It is composed of a He–Ne laser source of intensity of 20 mwatt and wavelength of 632.8 nm, a collimating lens, two analogous beam splitters ( $BS_1$  and  $BS_2$ ), two identical mirrors ( $M_1$  and  $M_2$ ), a spatial filter (SP), polarizer (P), microscope objective lens (MO) with magnification 10x, charged coupled device (CCD Camera), and monitor [25]. This system is provided with a mechanical drawing device to automatically draw the sample at defined draw ratios as shown in Fig. 1b.

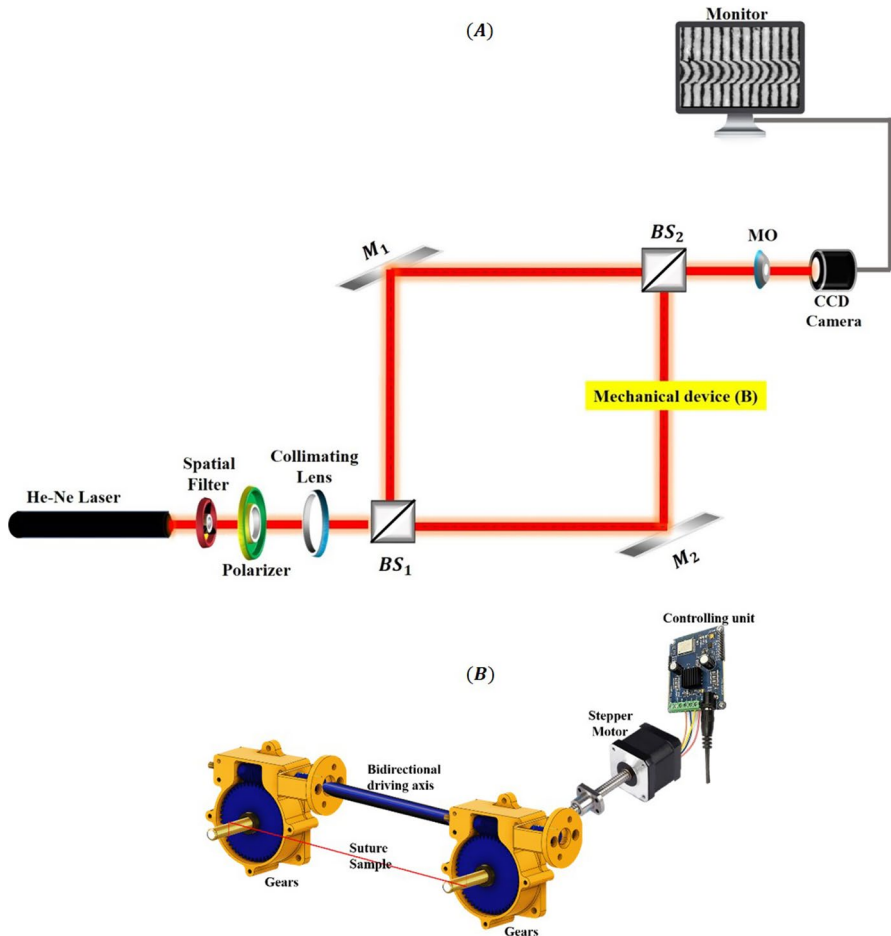
### In vitro degradation process at different pHs values

Here, samples of Monocryl surgical sutures were individually incubated in 50 ml glass vials. These vials were filled with different-buffer solutions to simulate the acidic, physiological, and alkaline conditions, which were adjusted to ( $\text{pH}=2.0 \pm 0.1$ ), ( $\text{pH}=7.4 \pm 0.1$ ), and ( $\text{pH}=8.5 \pm 0.1$ ), respectively. All samples were kept at a constant temperature of 37 °C. It was assured that the fluid completely covered the threads. At various durations of 5, 10, 15, 20, and 25 days, the samples were extracted from the medium and washed with de-ionized water. Then, these samples were blotted dry for 30 s for the following investigations and characterizations. All steps of the in vitro incubation method are illustrated in Fig. 2.

## Results and discussions

### Investigating the swelling rate in different pH buffer solutions

The degradation mechanism of aliphatic polyesters, like the Monocryl sutures, is based on a hydrolytic cleavage of the ester bonds on their backbone chains. This mechanism is mainly attributed to changes in the water uptake of the degraded samples [29]. So, we focus on investigating the swelling rate of Monocryl sutures in



**Fig. 1** **A, B** Schematic diagram for the Mach-Zehnder interferometer (**A**) and its attached mechanical device (**B**), respectively

buffer solution with different pH values. The swelling rate percentage (%) for each degradation duration and pH value for the incubated samples were calculated using the following formula [30], and the obtained results are given in Fig. 3:

$$S(\%) = \frac{(D_a - D_b)}{D_b} \times 100 \tag{1}$$

where  $D_a$  presents the diameter of the Monocryl suture at each degradation duration and pH value, and  $D_b$  refers to the original diameter of the Monocryl suture sample.

From Fig. 3, one can observe that the degree of swelling shows a different tendency at each pH value. Monocryl samples degraded at acidic conditions (pH=2), and neutral conditions (pH=7.4) underwent a two-staged change in swelling rate, increasing rapidly to saturation value in the first 15 days and then,

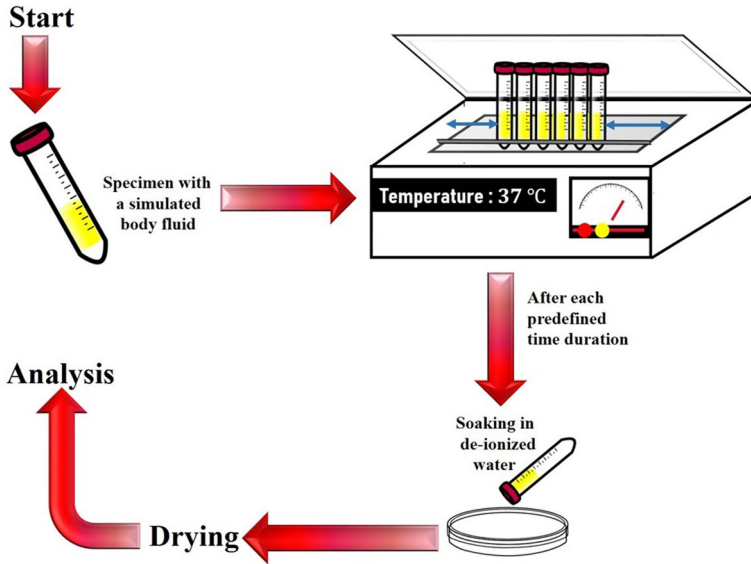


Fig. 2 Schematic illustration for the steps of the in vitro degradation test

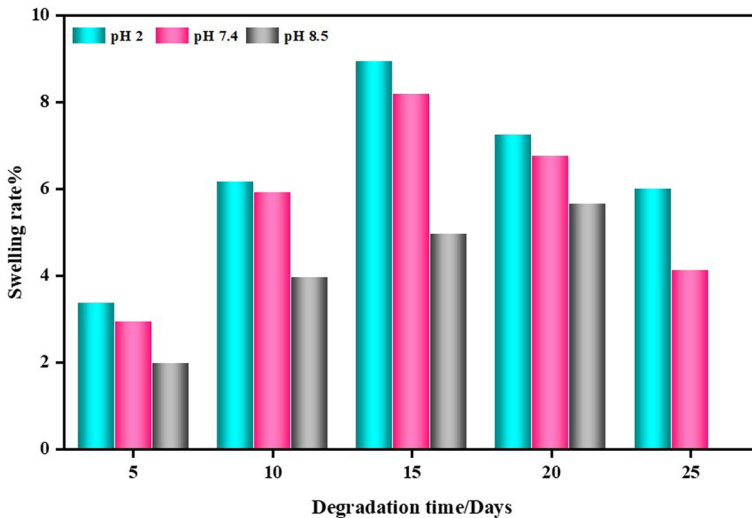


Fig. 3 Comparison of the swelling rate percent for the Monocryl surgical suture at different pHs within an incubation period from 5 to 25 days

decreasing in the rest of the time interval (25 days). In addition, Monocryl samples degraded at pH = 7.4 show a slight decrease in absorption capacity compared to Monocryl samples degraded at pH = 2. For the Monocryl samples degraded at alkaline conditions (pH = 8.5), the water uptake slowly increased with increasing the degradation duration, reaching the maximum value at 20 days. At 25 days'

post-immersion, it was not possible to handle the sample to measure its swelling degree due to its fragile state.

The variations in the degradation behavior for the Monocryl samples at different pH can be correlated with the effect of pH on hydrophilicity. The Monocryl suture is composed of 75:25 PGA/PCL molar ratio formulations. So, the hydrophilic unit of PGA is considered the predominant component in this copolymer structure. Therefore, at a neutral medium (pH=7.4), the Monocryl sample preserves its hydrophilic nature. Hence, water molecules can enter the copolymer structure via Hydrogen bonds that lead to an increase in the sample diameter. Then, the intrusion of water molecules triggers a hydrolytic attack that cleaves the bonds within chains and eventually erodes the sample. Similarly, at an acidic medium (pH=2), the hydrophilicity is increased, which promotes further water molecules entering the entire polymer matrix. This explains the observed increase in their absorption capacity. On the other hand, the copolymer in the alkaline medium (pH=8.5) changed from hydrophilic to hydrophobic (polar) in character during its implantation. Probably, because hydroxyl ions are entrapped by the ester groups on the sample surface, which lowers its absorption capacity. As a result, water molecules slowly penetrate the sample [27, 31].

### Investigating the optical properties of Monocryl suture in different pH buffer solutions

The two-beam Mach–Zehnder interferometer was used for investigating the refractive indices and birefringence of Monocryl suture at different pH values during various incubation durations. Each incubated Monocryl suture at a defined pH value and duration was fixed on a glass slide and immersed in a liquid of a suitable refractive index for reducing the refraction inside the suture. Then, they transmitted to the optical setup of Mach–Zehnder interferometer. By adjusting the polarizer, interference patterns for Monocryl suture at each incubation condition were recorded for light waves vibrating parallel (||) and perpendicular (⊥) to the suture axis. For demodulating the phase maps of these interference patterns, the spatial carrier frequency technique was implemented [25]. Figure 4a–c shows the obtained wrapped phase maps of the incubated Monocryl sutures in buffer solution of various pH values at degradation durations of 5, 15, and 25 days, respectively.

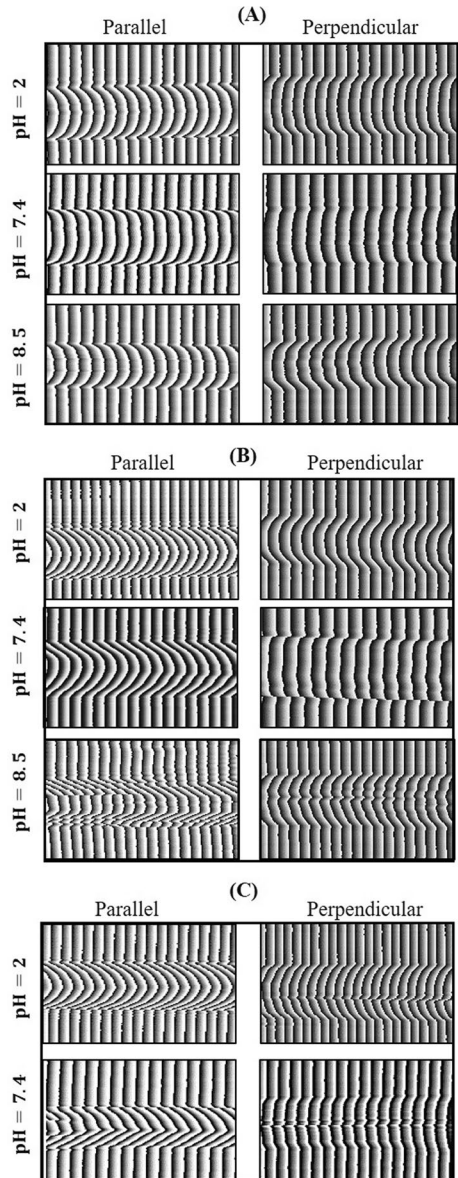
After unwrapping phase maps, the refractive indices ( $n^{\parallel}(x, y)$  &  $n^{\perp}(x, y)$ ) for || and ⊥ polarization directions and the birefringence ( $\Delta n(x, y)$ ) for each incubated Monocryl suture were calculated using the following relations [32]:

$$n^{\parallel}(x, y) = n_L + \frac{\varphi^{\parallel}(x, y)\lambda}{2\pi t} \tag{2}$$

$$n^{\perp}(x, y) = n_L + \frac{\varphi^{\perp}(x, y)\lambda}{2\pi t}$$

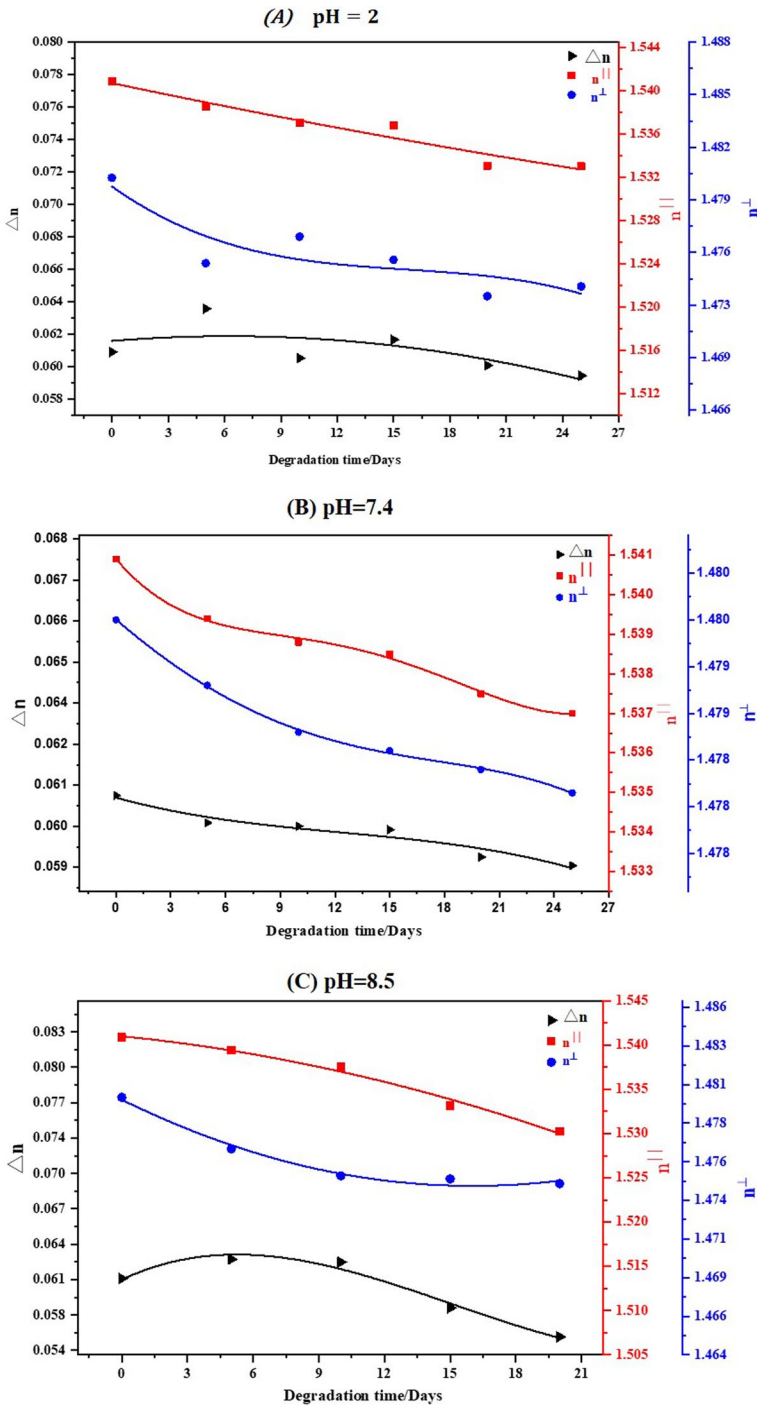
$$\Delta n(x, y) = n^{\parallel}(x, y) - n^{\perp}(x, y) \tag{3}$$

**Fig. 4** A–C Wrapped phase maps of the Monocryl surgical suture at different pHs for the ( $\parallel$ ) and the ( $\perp$ ) polarization directions to the suture axis at (A) 5 days, (B) 15 days, and (C) 25 days, respectively



where  $\lambda$  is the wavelength of the used monochromatic light source,  $\varphi^{\parallel}(x, y)$  and  $\varphi^{\perp}(x, y)$  are the demodulated unwrapping phase maps at the  $\parallel$  and  $\perp$  polarization directions, respectively,  $t$  is the thickness of the sample, and  $n_L$  is the refractive index of immersion liquid. Figure 5a–c illustrates the refractive indices and the birefringence values of the Monocryl sutures as a function of degradation durations at incubated conditions with pH = 2, 7.4, 8.5, respectively.





**Fig. 5** A–C Variation of parallel ( $n^{\parallel}$ ), perpendicular ( $n^{\perp}$ ), and birefringence ( $\Delta n$ ) of the Monocryl suture due to degradation duration from 5 to 25 days at **A** pH=2, **B** pH=7.4, and **C** pH=8.5, respectively

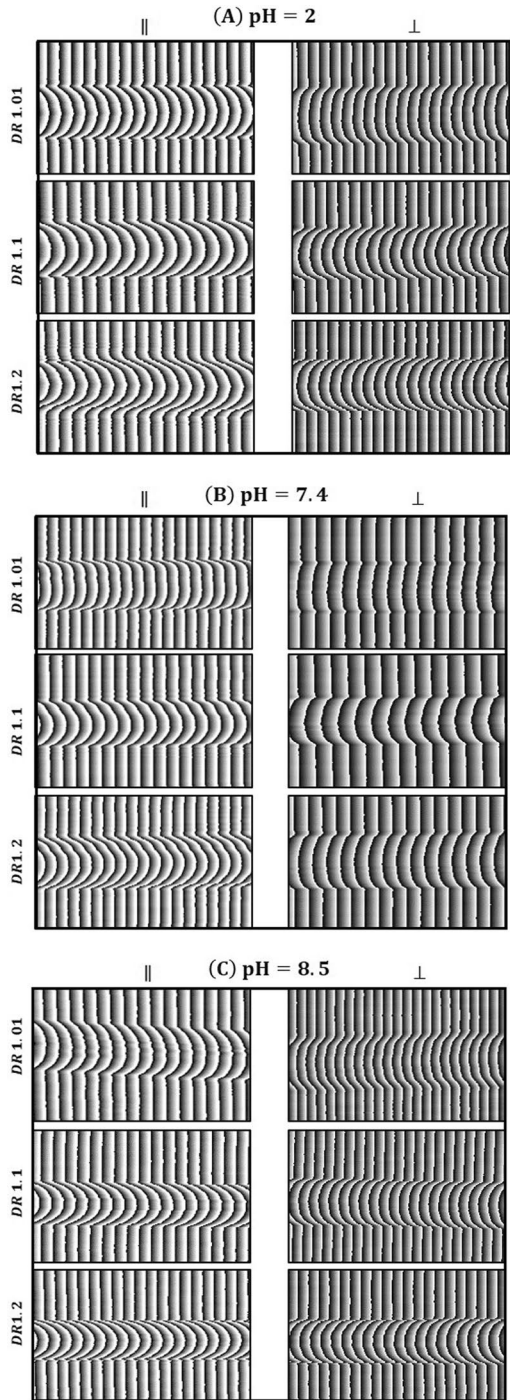
Figure 5a–c showed a significant decline in refractive indices ( $\parallel$  and  $\perp$ ) and birefringence of the Monocryl sutures with increasing the degradation time. Also, from this figure one can note that the degraded Monocryl samples under alkaline conditions exhibited much more reduction in refractive indices and birefringence values than those obtained from acidic and neutral ones, respectively. For instance, after 20 days of degradation, the birefringence values of Monocryl samples decreased by 11.5% from the original one in the buffer solution of pH=8.5, only 4% at pH=2 and 2.6% at pH=7.4. These results could be attributed to the fact that the surfaces of Monocryl samples are more susceptible to corrosive degradation in an alkaline environment, which has a negative influence on the degradation rate compared to acidic and neutral environments [10]. Thus, a possible explanation for these results is that the hydrolytic cleavage of the ester groups from the PGA/PCL block in the alkaline medium is fast compared to acidic and neutral ones. Therefore, the loss in the refractive indices and birefringence values of the Monocryl sutures in acidic and neutral media is lower than those of samples degraded in the alkaline medium.

### Investigating the opto-mechanical features and durability properties of Monocryl sutures in different pH buffer solutions

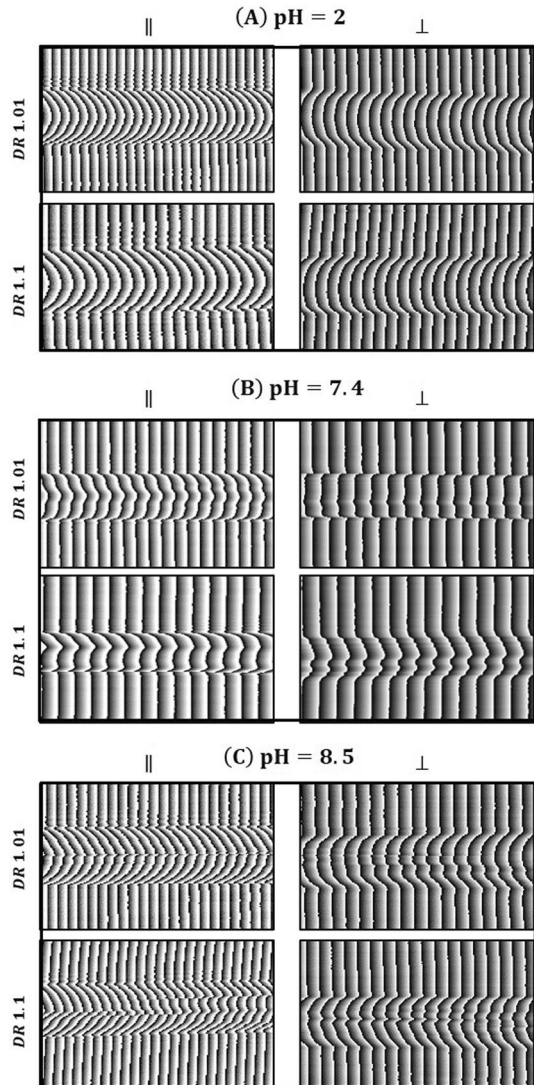
Investigating the influence of cold drawing on the structural features of the incubated Monocryl sutures in various pH media is crucial for the successful postoperative period following any suturing surgery. Therefore, the two-beam Mach–Zehnder interferometer equipped with a mechanical cold drawing device (see Fig. 1a, b) was utilized to perform this task for each incubated Monocryl suture at a defined pH value and duration. Here, each incubated Monocryl sample was fitted with the clamps of the mechanical cold drawing device and immersed in a liquid of appropriate refractive index. The mechanical drawing device was fixed into the optical system of the Mach–Zehnder interferometer. Then, the Monocryl suture sample was continuously drawn at defined draw ratios by the stepper motor of the mechanical device. As a result, the material gradually hardens until failure has occurred. To define the value of the draw ratio, the control unit of the mechanical drawing device was utilized. Interference patterns for each incubated Monocryl sample at defined draw ratios were recorded for the  $\parallel$  and  $\perp$  polarization directions.

The phase maps of these recorded interference patterns were demodulated using the spatial carrier frequency technique. Figures 6, 7a–c, and 8a, b present the wrapped phase maps of the drawn Monocryl samples at defined draw ratios and various pH media (2, 7.4, and 8.5) with degradation durations of 5, 15, and 25 days, respectively. After unwrapping the obtained wrapped phase maps in Figs. 6, 7a–c, and 8a, b, the refractive indices of the drawn Monocryl sutures are determined. Figures 9 and 10a–c show the refractive indices values of the drawn Monocryl sutures at different draw ratios as a function of degradation durations at incubated conditions pH=2, 7.4, 8.5 for the  $\parallel$  and  $\perp$  polarization directions, respectively. According to Figs. 9 and 10a–c, at the early stage of incubation (5 and 10 days), all groups showed an increase in parallel and a subsequent decrease in perpendicular refractive indices. With further increases in incubation time, the refractive indices of each

**Fig. 6** A–C Wrapped phase maps of the Monocryl surgical suture after an incubation duration of 5 days at 1.01, 1.1, and 1.2 draw ratios for the ( $\parallel$ ) and the ( $\perp$ ) polarization directions to the suture axis at **A** pH=2, **B** pH=7.4, and **C** pH=8.5, respectively



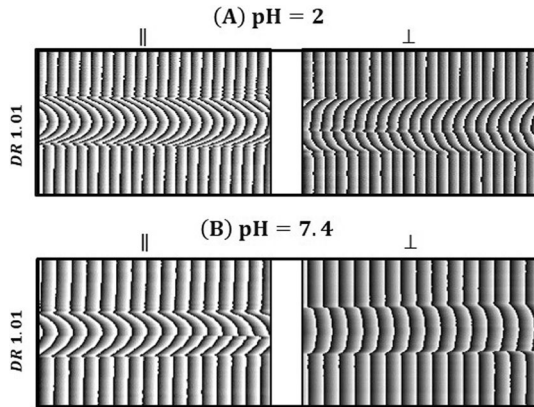
**Fig. 7** A–C Wrapped phase maps of the Monocryl surgical suture after an incubation duration of 15 days at 1.01 and 1.1 draw ratios for the ( $\parallel$ ) and the ( $\perp$ ) polarization directions to the suture axis at **A** pH=2, **B** pH=7.4, and **C** pH=8.5, respectively



group of Monocryl sutures slow down. This confirms the two naturally occurring mechanisms during degradation, recrystallization (formation of new crystalline regions), and fracture of crystallinity (attacking the crystalline phase.)

For studying the durability properties of the Monocryl surgical suture material, the Young's modulus ( $Y_E$ ) and the Ultimate tensile strength (UTS) are considered the most important factors that reflect their hardness and flexibility [33]. For calculating these parameters, the stress–strain curves of the Monocryl suture at each hydrolytic medium are investigated as presented in Fig. 11. From this figure, the Young's modulus of the incubated Monocryl samples is evaluated by finding the initial linear slope for each curve [9]. Also, the ultimate tensile strength of

**Fig. 8 A, B** Wrapped phase maps of the Monocryl surgical suture after an incubation duration of 25 days at 1.01 draw ratio for the (||) and the (⊥) polarization directions to the suture axis at **A** pH=2 and **B** pH=7.4, respectively



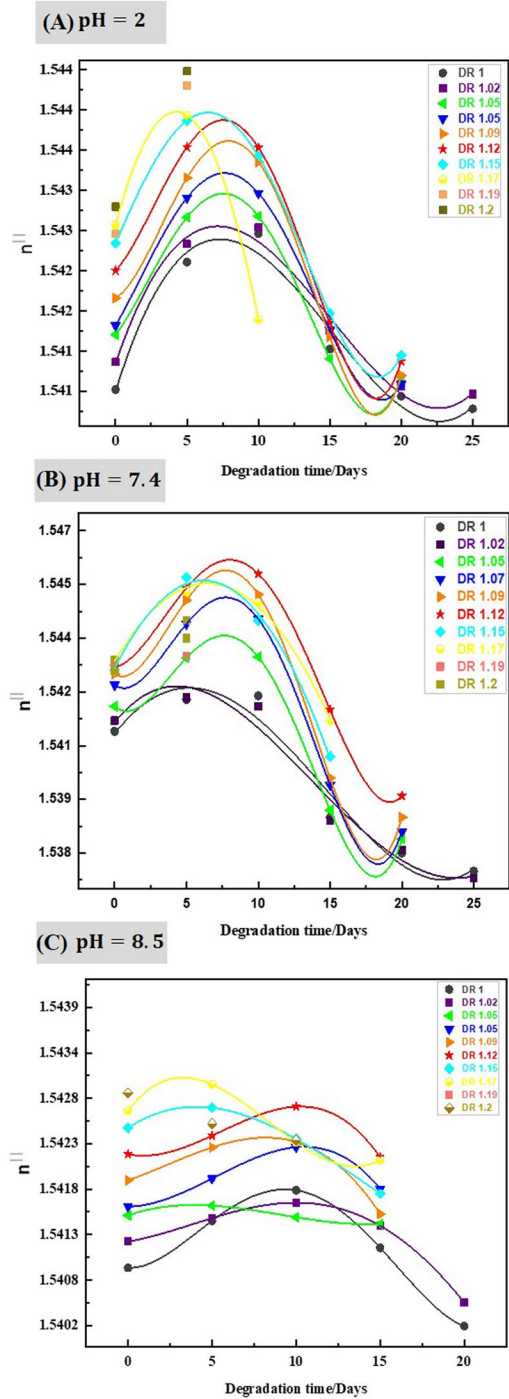
the incubated Monocryl samples can be evaluated by finding the maximum stress for each stress–strain curve, and their results are tabulated in Table 1. This table clarifies that, there is a superior mechanical strength of the Monocryl suture sample at pH=7.4 concerning both Young’s modulus and ultimate tensile strength, compared with other media. More analytically, the obtained results indicate that the degraded samples at pH=8.5 show significantly lower Young’s modulus and ultimate stress than those with pH=7.4 and 2. For instance, pH 8.5 samples exhibit a 19% decrease in Young’s modulus compared with pH 7.4 (from 270.63 to 205.76 MPa) and 9% compared with pH 2 (from 240.63 to 205.76 MPa) by day 5 of incubation time. Based on the previous results, degradation consists of two steps: Firstly, begins with random breakage of ester linkages leading to a reduction in mechanical properties. Secondly, with a further increase in ester bond breakage, the number of entangled chains decreases resulting in a faster decrease in the mechanical properties of the suture. But, the alkaline environment accelerates this reduction, suggesting that the surface of the PGA/PCL sample rapidly erodes, which catalyzes further degradation of their mechanical properties. The obtained results are in good agreement with the obtained results in Ref [16].

On the basis of Young’s modulus values, the compressibility ( $\chi$ ) of the Monocryl suture was measured using the following equation [19]:

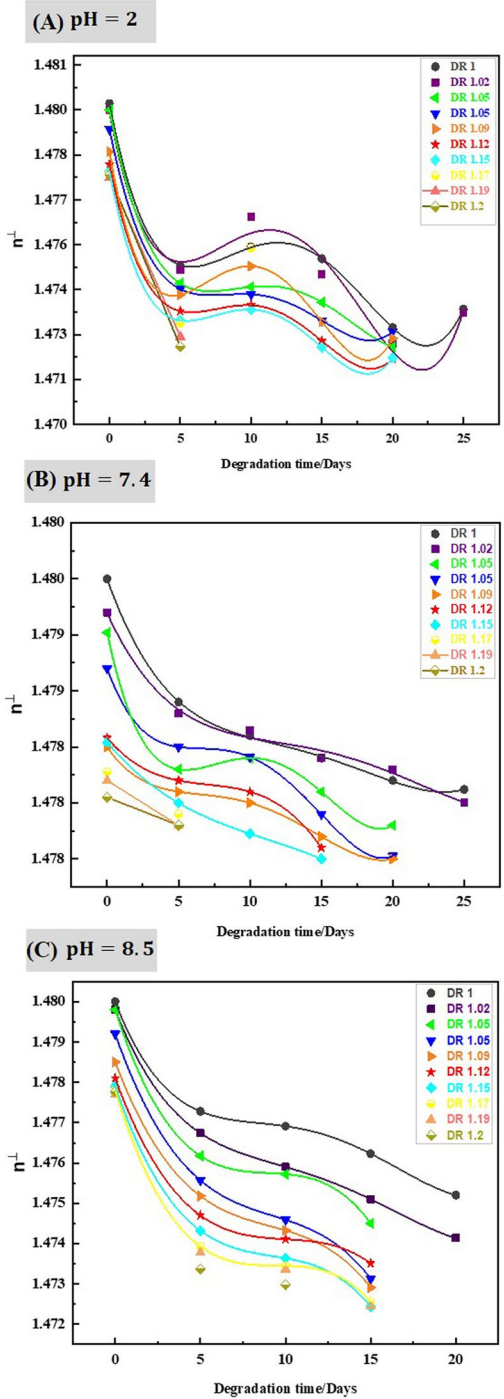
$$\chi = \frac{3(1 - 2\mu)}{Y_E} \tag{4}$$

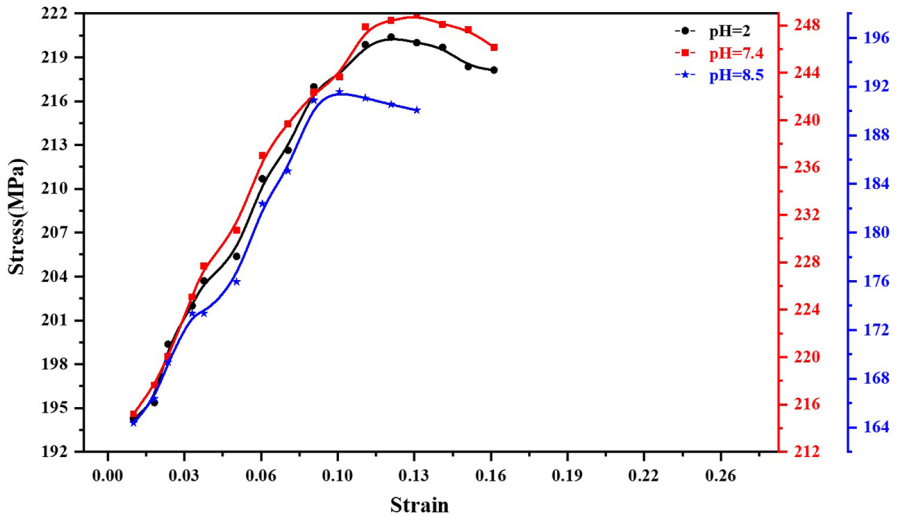
where  $\mu$  is the Poisson’s ratio (the ratio between the lateral and axial strains). Figure 12a–c illustrates the compressibility ( $\chi$ ) for the Monocryl suture as a function of the degradation time at incubated media pH=2, 7.4, and 8.5, respectively. As expected, there is an increment tendency in compressibility during the entire degradation period. Noticeably, this increment is significant with the high draw ratios. Our findings revealed that the degradation of the mechanical properties is accelerated either by an acidic or basic medium.

**Fig. 9 A–C** Variation of parallel ( $n_{||}$ ) refractive index of the Monocryl surgical suture within an incubation period from 5 to 25 days at different draw ratios at **A** pH=2 and **B** pH=7.4, respectively



**Fig. 10** A–C Variation of perpendicular ( $n^{\perp}$ ) refractive index of the Monocryl surgical suture within an incubation period from 5 to 25 days at different draw ratios at **A** pH=2, **B** pH=7.4, and **C** pH=8.5, respectively





**Fig. 11** Stress–strain curve of the Monocryl surgical suture after 5 days of incubation duration at pH=2, pH=7.4, and pH=8.5

**Table 1** Young’s modulus and Ultimate tensile strength of the degraded Monocryl surgical suture in different pH media

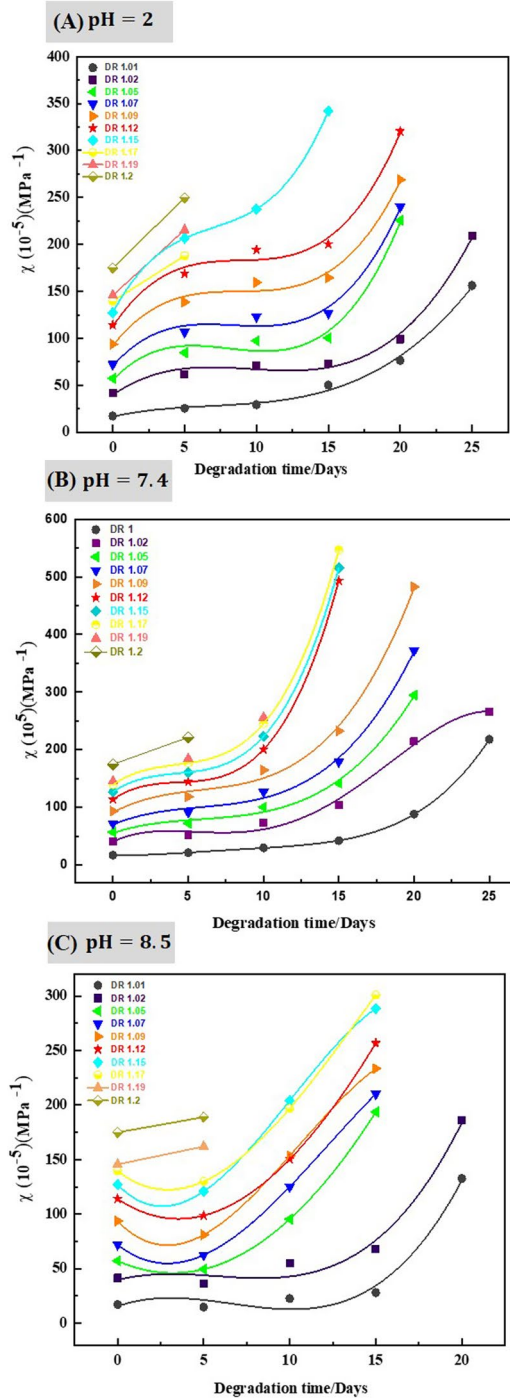
Time/day	Degradation					
	Young’s modulus/MPa			Ultimate tensile strength/MPa		
	pH=2	pH=7.4	pH=8.5	pH=2	pH=7.4	pH=8.5
5	240.63	270.63	205.76	220.11	248.82	191.4
10	171.47	195.04	133.75	156.31	178.64	124.41
15	120.03	138.17	75.45	108.46	127.6	70.18
20	56.32	66.58	30.86	51.04	60.61	28.71
25	10.29	27.14		6.38	24.52	

## Conclusions

In conclusion, a 25-day in vitro degradation experiment is conducted on the Monocryl surgical suture to study the effect of varying pH of the buffer solutions on their hydrolytic degradation. A Mach–Zehnder interferometer attached to a mechanical drawing device is utilized to examine the alterations in structural and opto-mechanical properties of the Monocryl sutures induced by the degradation process. The behavior of the Monocryl suture is varied according to environmental pH. There were considerable differences in the evolution of the degree of swelling with degradation time particularly, in the alkaline medium. Moreover, after 20 days of degradation, the reduction in the birefringence values of Monocryl samples in the buffer solution of pH=8.5 is being more advanced. Noticeably, mechanical loss



**Fig. 12 A–C** The variation of the compressibility ( $\chi$ ) of the Monocryl surgical suture within an incubation period from 5 to 25 days at different draw ratios at **A** pH=2, **B** pH=7.4, and **C** pH=8.5, respectively



values of the Monocryl suture in neutral, acidic, and alkaline media after degradation of 5 days were decreased to 78, 69, and 58%, respectively, suggesting that Monocryl suture in both acidic and alkaline environments showed a faster degradation rate in their mechanical properties than those in the neutral one. Based on the comparison of the three pH values, the neutral condition (pH=7.4) is preferable for the Monocryl suture implantation. The obtained results may provide preliminary experimental references for evaluating the degradation performance of the Monocryl surgical suture.

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**Availability data and material** Datasets used and analyzed during the current study are available from the author on reasonable request.

## Declarations

**Conflict of interest** The author declare that they have no competing interests.

**Ethical approval** It is not applicable for this study.

**Consent for publication** Not applicable.

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