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Correlation between iodide dosimetry and terephthalic acid dosimetry to evaluate the reactive radical production due to the acoustic cavitation activity

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ABSTRACT

Acoustic cavitation plays an important role in sonochemical processes and the rate of sonochemical reaction is influenced by sonication parameters. There are several methods to evaluate cavitation activity such as chemical dosimetry. In this study, to comparison between iodide dosimetry and terephthalic acid dosimetry, efficacy of sonication parameters in reactive radical production has been considered by iodide and terephthalic acid dosimetries. For this purpose, efficacy of different exposure parameters on cavitations production by 1 MHz ultrasound has been studied. The absorbance of KI dosimeter was measured by spectrophotometer and the fluorescence of terephthalic acid dosimeter was measured using spectrofluorometer after sonication. The result of experiments related to sonication time and intensity showed that with increasing time of sonication or intensity, the absorbance is increased. It has been shown that the absorbance for continuous mode is remarkably higher than for pulsing mode (p-value < 0.05). Also results show that with increasing the duty cycles of pulsed field, the inertial cavitation activity is increased. With compensation of sonication time or intensity in different duty cycles, no significant absorbance difference were observed unless 20% duty cycle. A significant correlation between the absorbance and fluorescence intensities (count) at different intensity (R = 0.971), different sonication time (R = 0.999) and different duty cycle (R = 0.967) were observed (p-value < 0.05). It is concluded that the sonication parameters having important influences on reactive radical production. These results suggest that there is a correlation between iodide dosimetry and terephthalic acid dosimetry to examine the acoustic cavitation activity in ultrasound field.

1. Introduction

The ultrasound effects originate primarily in acoustic cavitation [1]. Cavitation has been classified into two types: non-inertial (stable) and inertial. In non-inertial cavitation, the radius of bubbles oscillates around an equilibrium value over a considerable number of acoustic cycles without the generation of bubble collapse [2]. Inertial cavitations are gas bubbles that grow to near resonance size and may expand to a maximum radius before violently collapsing [3]. Inertial cavitation consists of three stages: nucleation, growth and collapse of bubbles [4]. Acoustic cavitation has practical importance where this mechanism of action is responsible for therapeutic applications such as sonodynamic therapy [5–8], chemotherapy [9], drug delivery, sonophoresis and apoptosis therapy [10,11]. The collapse of bubbles can be violent enough to lead to chemical effects, known as sonochemistry [1,12]. These bubbles act as a localized hot spot generating temperatures of about 4000 K and pressures in excess of 1000 atmospheres [1].

When water is sonicated, adiabatic collapse of cavitation bubbles leads to the formation of radical species, such as hydroxyl radicals (·OH), hydrogen peroxide (H_2O_2) and hydroperoxyl radicals (HOO·). These reactions are shown below (reactions 1–5) [13]:

$$H_2O \rightarrow H\cdot + \cdot OH \quad (1)$$

$$O_2 \rightarrow 2O \quad (2)$$

$$H\cdot + O_2 \rightarrow \cdot OOH \quad (3)$$

$$O + H_2O \rightarrow 2\cdot OH \quad (4)$$

$$H\cdot + O_2 \rightarrow \cdot OH + O \quad (5)$$

These primary radicals of sonolysis mostly recombine to form hydrogen peroxide that is released in the medium (Reactions 6 and 7).

$$2\cdot OH \rightarrow H_2O_2 \quad (6)$$

$$2\cdot OOH \rightarrow H_2O_2 + O_2 \quad (7)$$

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Several methods for determining and quantifying inertial cavitation are available. Physical methods for performing these experiments are including sonoluminescence, subharmonic analysis, acoustic imaging, laser holography and electron spin resonance. Some of these methods such as electron spin resonance are an extremely sensitive method for detecting the radical produced but its application needs specialist and expensive equipments [2,14–16]. Chemical products also may be used to measure cavitation activity. Cavitation effects involve the chemical and mechanical effects. In this study, the mechanical effect does not influence the chemical effects. Chemical methods namely iodide dosimeter, terephthalate dosimeter and Fricke dosimeter are suitable to monitor the chemical effects of inertial cavitation [3,13,17]. It has been shown that terephthalic acid is suitable for detecting and quantifying free hydroxyl radicals generated by the collapse of cavitation bubbles in ultrasound fields [1–3,18]. The terephthalate ions react with hydroxyl radicals to generate highly fluorescent 2-hydroxyterephthalate ions. Terephthalic acid dosimetry is an established method for monitoring the acoustic cavitation but it is a time consuming procedure and needs to have a spectrofluorometer [2]. The dosimeters based on the photometry, iodide dosimeter and Fricke dosimeter, are not high sensitive. Fricke dosimeter, which is an established method in radiation chemistry, is used in sonochemistry too, but iodide dosimeter is very simple and widely acceptable [1,17]. In our previous study [3], the cavitation activity induced by the ultrasound irradiation on different exposure parameters has been measured by terephthalic acid dosimetry. In this method, the terephthalate ions react with hydroxyl radicals to generate highly fluorescent 2-hydroxyterephthalate ions. Therefore, it is suitable for detecting and quantifying free hydroxyl radicals generated by the collapse of cavitation bubbles in ultrasound fields [3,19]. Hasanzadeh et al. [2] reported that, there is dependence between terephthalic acid dosimetry and subharmonic analysis at different sonication parameters to examine the acoustic cavitation. Subharmonic analysis is real time, applicable and inexpensive [2], but it is not clear whether the subharmonic emission is produced by stable or inertial cavitation [14]. Iodine dosimeter has not enough sensitivity for special sonochemical applications but produces reliable and reproducible results [1]. The oxidation of potassium iodide (KI) is widely regarded as a standard to calibrate sonochemical efficiency [17,20]. In addition, preparation and handling of KI solution is simple and easy [17]. Therefore, in order to quantify the bubbles generated in 1 MHz frequency field, the cavitation activity induced by the ultrasound irradiation on different exposure parameters has been measured by potassium iodide dosimetry and terephthalic acid dosimetry. Experiments were performed in the near 1 MHz fields in the progressive wave mode and effect of ultrasound intensity, duty factor, mode of sonication, sonication time and net ultrasound energy in reactive radical production (inertial cavitation activity) were studied by two methods. Finally, the correlation between two chemical dosimetry methods; iodide dosimetry and terephthalic acid dosimetry; to examine the acoustic cavitation activity is evaluated.

2. Materials and methods

2.1. Theory

In KI dosimetry method, determination of cavitation activity is based on the fact that iodine ions in KI aqueous solution can be transformed into iodine molecules under ultrasonic irradiation [13,21,22]. Thus, the iodine release can be used to measure the acoustic cavitation. When aqueous solution of potassium iodide (KI) is irradiated, oxidation occurs and I^- ions are oxidized by the generated radicals to give I_2. The excess of I^- ions present in solution react with I_2 to form I_3^- [17,20]. The amounts of I_3^- ions can be quantified by UV spectrophotometer at 350.00 nm [4,23,24]. The main reactions occurring in this method are shown below (reactions 8–12):

$$H_2O_2 + 2I^- + 2H^+ \rightarrow I_2 + 2H_2O \quad (8)$$

$$\cdot OH + I^- \rightarrow OH^- + I \quad (9)$$

$$I + I^- \rightarrow I_2^- \quad (10)$$

$$2I_2^- \rightarrow I_2 + 2I^- \quad (11)$$

$$I_2 + I^- \rightarrow I_3^- \quad (12)$$

In terephthalic acid (TA) dosimetry, terephthalic acid solution as dosimeter solution reacts with a hydroxyl radical formed during water sonolysis, forms 2-hydroxyterephthalate ions which are readily detected using fluorescence spectroscopy with an excitation and emission wavelengths based on our previous studies [2,3,25].

2.2. Dosimetry solution

In these experiments, a modified iodide dosimeter and terephtalic acid dosimeter were prepared according to the available protocols [1,17–19]. Indeed, these chemical dosimeters are indirect methods for estimating the inertial cavitation activity in ultrasound fields.

2.3. KI dosimetry

To enhance the oxidation of iodide [4], chloral hydrate 0.2 mol ($CCl_3CH(OH)_2$, 33 g, Merck, Darmstadt, Germany) was added to potassium iodide solution potassium iodide 0.1 mol (KI, 16.6 g, Merck, Darmstadt, Germany).

Distilled water was used as a solvent for experiments and resulting solution was made up 1 dm^3. In our experiments, 50 ml of KI solution were added to the reaction cell [17,24].

Periodically during sonication, samples were removed and the absorbance intensity of each sample was measured using a spectrophotometer (Optizen 2120 UV Plus spectrometer, Mecasys Co. Ltd., Daejeon, Korea). Sonication was carried out at 22 °C and before irradiation dosimeter solution was aerated for 15 min. The sonicated solutions were analyzed for I_3^- by spectrophotometer. The absorbance values were measured in the individual samples immediately after sonication at 350 nm spectrophotometry. Initially, a solution consists of iodine and potassium iodide was prepared and diluted gradually. This solution was used to prepare a calibration curve of iodine in KI versus absorbance measured at 350 nm, with KI solution as a blank. A plot of absorbance versus different KI concentrations yielded a straight line of positive slope for concentration from 0.005 to 0.100 M (Fig. 1). It can be assumed that the absorbance is proportional to I_3^- ions formation. Thus, inertial cavitation activity may be estimated by the absorbance of sonication samples. The straight line for the calibration is represented by the following equation: (Absorbance = 2.147 × Concentration + 0.088, R^2 = 0.998).

2.4. Terephthalic acid dosimetry

Terephthalic acid (TA) 2×10^{-3} mol (0.33 g, Aldrich) dissolved by heating, NaOH 5×10^{-3} mol (0.20 g) and phosphate buffer (pH = 7.4); prepared from KH_2PO_4 4.4×10^{-3} mol (0.58 g) and Na_2HPO_4 7.6×10^{-3} mol (0.98 g). The resulting solution was then made up to 1 l with distilled water. Before use, the solution was kept in refrigerator (~4 °C) and in the dark to prevent a

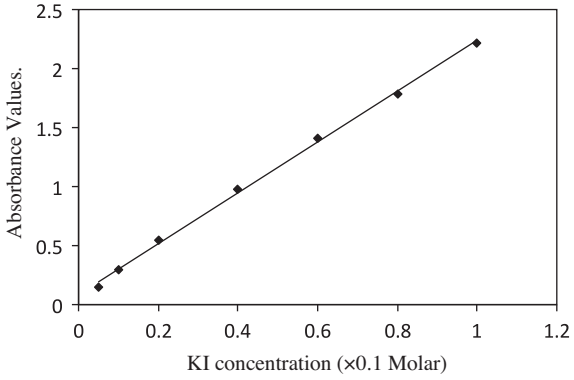

Fig. 1. Calibration curve for KI solution with different concentration.

photochemical reaction. During sonication, samples were removed and the fluorescence intensity (counts) of each sample was measured using a spectrofluorometer (Shimadzu, Model RF-1500, Japan). In experiment, the sonicated TA solutions were kept in darkness and their fluorescence intensities were measured immediately after sonication. To obtain calibration curve, 2-hydroxyterephthalic acid was synthesized and a stock solution of the standard 2-hydroxyterephthalic acid (HTA) was prepared by reaction of bromoterephthalic acid with sodium hydroxide according to Ref. [2,3,25]. Using this stock solution, several known concentration were made. The fluorescence of each known concentration was measured using spectrofluorometer with an excitation and emission wavelengths of 310.0 and 425.6 nm, respectively. Fluorescence intensity versus 2-hydroxyterephthalic acid (HTA) concentration was plotted to obtain calibration curve. Fluorescence intensity versus 2-hydroxyterephthalic acid (HTA) concentration yielded a straight line of positive slope for concentrations from 1×10^{-6} to 8.5×10^{-6} mol dm^{-3} [25]. Using the terephthalic acid dosimetry method, we evaluated the effects of various irradiation parameters and their efficacies on the inertial cavitation activity in medical ultrasound fields by monitoring OH radical formation which was recorded as fluorescent counts.

2.5. Equipment setup

The ultrasound source unit was a 1 MHz therapeutic unit (Sonopuls 492, Enrof Nonius Co., Rotterdam,The Netherland) with a 30 mm diameter probe and 5 cm^2 effective radiation area (ERA). Acoustic calibration for the frequency and intensity of the device was carried out in degassed water in the tank, using a calibrated PVDF-type hydrophone (PA124, Precision Acoustics Ltd., Dorchester, Dorset, UK, calibration range: 10 kHz–20 MHz, with a sensor diameter of 25 mm at a distance of 5 mm from the surface of the probe) on the transducer axis to record the ultrasonic signals. The hydrophone was connected to a digital oscilloscope and spectrum analyzer (TNM 20080, TNM Electronics Ltd., Tehran, Iran) and then to the computer for the measurement and processing of the spectrum. Each signal from the experiments comprised of 16384 data points collected with a sampling rate of 2.5 MHz. To extract frequency contents, signals were analyzed in MATLAB software version 7.0.1 (Math Software Co., Mathworks, USA) using FFT function with hamming window. The level of background noise was subtracted from the signal amplitude in each of the measurements. The real frequency and actual intensity of this therapeutic unit are 980.95 kHz and 2.03 W/cm^2 for fundamental frequency based on calibration certification test result, respectively. All reported experimental intensity values are the spatial average temporal average intensity (I_{SATA}). By this apparatus, we were able to change intensity (0–2 W/cm^2), duty cycle (20–80%), mode of sonication (continuous and pulsating) and sonication time (0–60 min). For comparing the mode of sonication at different duty factors (D.F.%) in the inertial cavitation activity in equal ultrasound energy, the ultrasound energy (E) is defined as:

$$E(J) = I(W/cm^2) \times T(s) \times D.F.(\%) \times ERA(cm^2) \quad (13)$$

where, I, T and ERA are intensity, time of exposure and effective radiation area, respectively. The time of sonication and intensity were compensated for pulsed wave mode to keep the net ultrasound energy for exposure constant.

For sonication of dosimeter solution, a cubical cell with a volume of 50 cm^3 was constructed from Perspex and attached inner surface of the cubic $15 \times 15 \times 10$ cm^3 Perspex tank. In order to maximize the intensity of the acoustic waves entering the reaction cell, the ultrasonic transducer was attached directly to the reaction cell. To perform experiments under progressive wave conditions and to limit the action of acoustic reflection from the wall of reaction cell, the inner surface of the front of probe was covered by absorbent ultrasound materials.

The ultrasound probe was fixed onto the tank wall, and the ultrasound was emitted vertically. In all experiments, the cubic tank was filled with degassed water and the temperature of the solution in the reaction cell was monitored during sonication and no change of greater than 3–5 °C was noted.

Using the KI dosimetry and the terephthalic acid dosimetry methods, we evaluated the effects of various sonication parameters and their efficacies on the inertial cavitation activity in medical ultrasound fields by measurement of absorbance and fluorescence counts. Also, the correlation between these chemical methods to examine the acoustic cavitation activity is evaluated. For this purpose, efficacy of different exposure parameters such as intensity (0.0–2.0 W/cm^2), time of sonication (10–60 min), sonication mode (continuous and pulsating), duty factor (20–80%) and net ultrasound energy on produced cavitations by 1 MHz ultrasound has been studied.

2.6. Statistical analysis

The absorbance of the KI dosimetry solution and the fluorescence intensity of the terephtalic acid dosimetry solution with changing ultrasonic parameters were measured before and after sonication for five independent runs. Summary statistics for all normally distributed variables were presented as the mean ± standard deviation (SD). After having verified a normal distribution and homogenicity variances, to analyze differences between groups, ANOVA analysis were done with a significance level of 0.05. Analyses of the Pearson correlations between ultrasonic parameters and absorbance were carried out and Pearson correlation coefficients were estimated. Reproducibility of each experiment was reported as percent coefficient of the variance (CV). Also dependence between iodide dosimetry and terephthalic acid dosimetry were studied by Pearson correlation analysis. Pearson correlation coefficient (R) and linear regression functions were estimated with p-value less than 0.05. All tests were performed with SPSS software package (SPSS V.16, Inc., Chicago, IL, USA).

3. Results

The effects of 1 MHz sonication duration (min) on absorbance values immediately after irradiation with continuous mode are shown in Fig. 2. Sonication was performed in times of 0–60 min with steps of 10 min. It is well known that absorbance value increases for longer sonication times. The results of absorbance value due to sonication duration changes, with a intensity equal to 2.0 W/cm^2, are shown in Fig. 2. The results show that there is a sig-

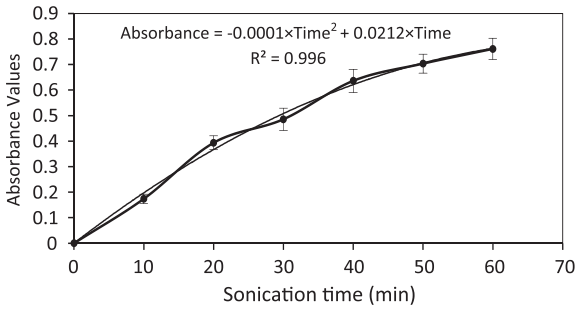

Fig. 2. Absorbance values (CV = 5–10%) due to sonication duration (min) for the continuous mode in 1 MHz ultrasound irradiation. Error bars show the standard deviation of mean values obtained from 5 independent experiments.

nificant correlation between the absorbance value and sonication duration change ($R = 0.998$, p-value < 0.05). The Pearson correlation coefficients and regression function were presented in Fig. 2.

The absorption spectra of KI solution with various sonication times are shown in Fig. 3. With increasing the irradiation time, an absorption peak appears at 350 nm, and becomes strong with time. The absorption peak is ascribed to the I_3^- ions formation according to the Eq. (12).

It is expected, the inertial cavitation activity increased at higher intensities. For this purpose, by selecting continuous mode of irradiation, we evaluated the effect of sonication intensity (0.5–2.0 W/cm^2, in 0.5 W/cm^2 steps) on cavitation activity during 20 min of sonication. Fig. 4 shows dependence of absorbance value on sonication intensity. The reason of increasing of absorbance value is sonication cavitation activity. The results show that there is a significant correlation between the absorbance value and sonication intensity ($R = 0.993$, p-value < 0.05). The Pearson correlation and linear regression analyses between the absorbance value and sonication intensity were shown in Fig. 4. No absorbance were seen, when dosimeter solution was sonicated with 0.5 W/cm^2 intensity. This experiment determined the threshold intensity for tri-iodide ion (I_3^-) production.

The results of absorbance (I_3^- production) measurements related to generated by 1 MHz ultrasound waves ($I_{SATA} = 2$ W/cm^2 and sonication duration 20 min) at different duties (20%, 50%, 80% and 100%) are shown in Fig. 5. The pulse duration (PD) is constant in all experiments. As can be seen, the amount of absorbance generated by 1 MHz continuous ultrasound field is significantly more than by the pulse mode at different duty cycles (p-value < 0.05).

With compensation of the sonication duration by pulsed ultrasound at different duty cycles, the absorbance value in the 1 MHz ultrasound field was measured (Fig. 6). In this experiment, the sonication intensity was constant ($I = 2$ W/cm^2) and the sonication duration was increased according to duty cycles (continuous mode (20 min), 80% pulsating mode (25 min), 50% pulsating mode (40 min) and 20% pulsating mode (100 min)).

During the experiments, the energy was constant for different duty cycles so there is no significant difference between the absorbance values in the pulsing sonication (p-value > 0.05) except for pulse 20% duty cycle (p-value < 0.05).

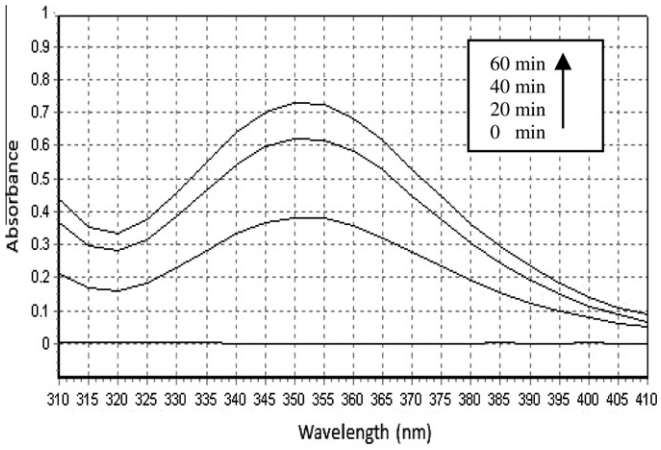

Fig. 3. Temporal evolution of absorption spectra for iodide dosimeter under sonication (1 MHz, 2 W/cm^2). The maximum absorption is related to 60 min sonication.

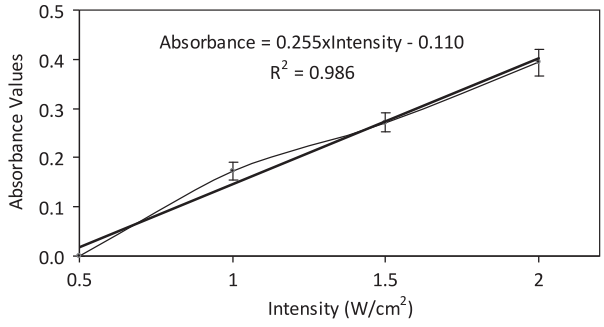

Fig. 4. Dependence of absorbance value on sonication intensity (0.5–2.0 W/cm^2) for the continuous mode of ultrasound irradiation (CV = 6–10%). Error bars show the standard deviation of mean values obtained from 5 independent experiments.

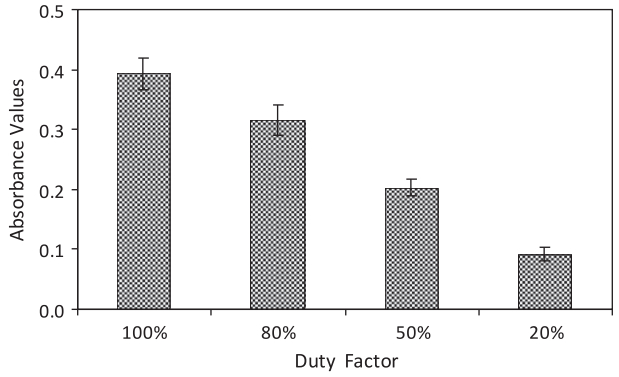

Fig. 5. Mean ± SD of the absorbance by 1 MHz irradiation at different duty cycles ($I_{SATA} = 2$ W/cm^2 and sonication duration 20 min). The absorbance values were recorded based on 5 independent runs (CV = 6–12%).

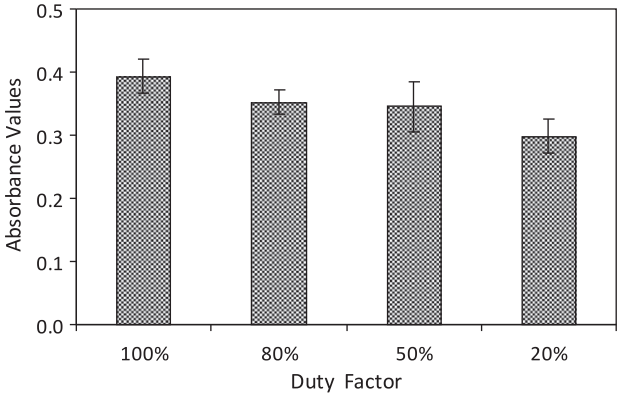

Fig. 6. Mean ± SD of the absorbance value by 1 MHz pulsed irradiation with compensated sonication duration at different duty cycles ($I = 2$ W/cm^2). Values obtained from 5 independent experiments (CV = 5–11%).

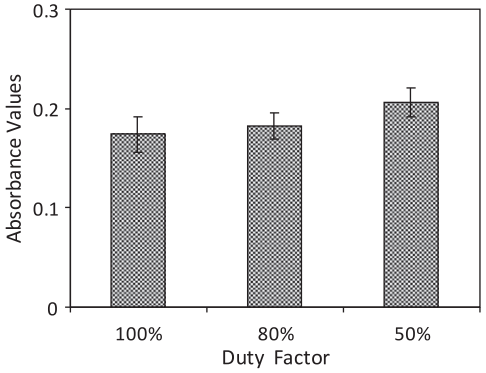

Fig. 7. Mean ± SD of the absorbance value by 1 MHz pulsed irradiation with compensated intensity; continuous mode (1 W/cm^2), 80% pulsating mode (1.3 W/cm^2) and 50% pulsating mode (2 W/cm^2). Values obtained from 5 independent experiments (CV = 7–10%).

For compensated intensity of sonication, experiments were carried out at different duty cycles with compensated intensity (Fig. 7). In this experiment, the sonication duration was constant (20 min) and the sound intensity was increased according to duty cycles. It can be seen that the absorbance in these cases are approximately equal. During experiments the ultrasound energy was constant for continues mode, 80% duty cycle and 50% duty cycle, thus, the difference between the amounts of absorbance is not significant (p-value > 0.05).

To evaluate correlation between iodide dosimetry and terephthalic acid dosimetry [3] methods, both in continuous mode of sonication with different intensities (0.5, 1.0, 1.5 and 2.0 W/cm^2) and constant intensity (2 W/cm^2) and different duties (20%, 50%, 80% and 100%), correlation and regression analyses between these two methods; iodide dosimetry and terephthalic acid dosimetry; were carried out and correlation coefficients and regression functions were estimated (Figs. 8 and 9).

The results show that there is a significant correlation between the absorbance and the fluorescence intensity at different intensities (R = 0.971, p-value < 0.05) and different duty cycles (R = 0.999, p-value < 0.05). The fluorescence intensity could be estimated as follows: (258.2 × Absorbance + 14.3) in different intensities and (789.47 × Absorbance^2 − 140.88 × Absorbance + 50.01) in different duty cycles. The reason of increasing of fluorescence intensity and absorbance is cavitation activity. As it is considerable from Fig. 8, when the absorbance in KI dosimeter is zero at low sonication Intensity (0.5 W/cm^2), the terephthalic acid dosimeter shows detectable fluorescence intensity. It shows that the terephthalic acid dosimeter is more sensitive than KI dosimeter.

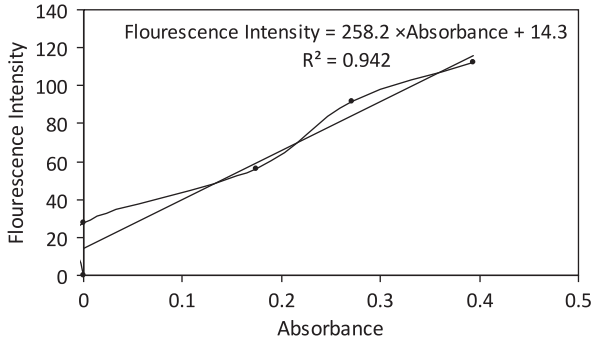

Fig. 8. Correlation and linear regression analyses between absorbance and fluorescence intensity (count) at different intensities with continuous mode (20 min sonication).

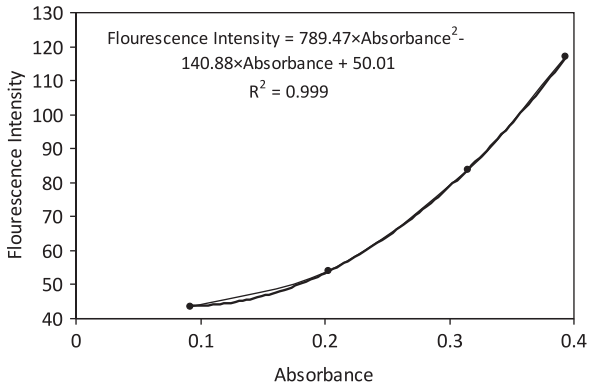

Fig. 9. Correlation and polynomial regression analyses between absorbance and fluorescence intensity (count) at different duty cycles with constant intensity (2 W/cm^2) and 20 min sonication.

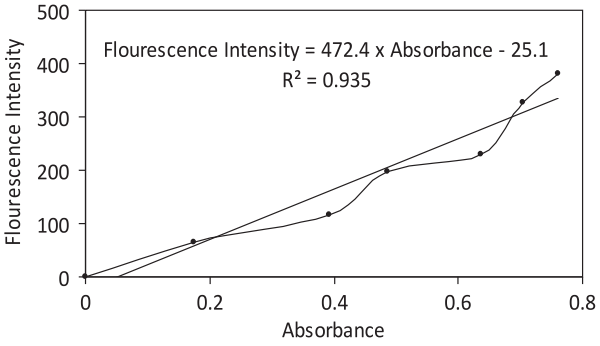

Fig. 10. Pearson correlation and linear regression analyses between absorbance and fluorescence intensity (count) at different sonication duration with constant intensity (2 W/cm^2).

For evaluating of correlation between two methods, we changed irradiation duration in the times of 10–60 min with steps of 10 min (Fig. 10). The results show that there is a significant correlation significant between two chemical dosimeter methods at different sonication duration (R = 0.967, p-value < 0.05). The fluorescence intensity due to terephthalic acid dosimetry could be estimated with the absorbance value due to iodide dosimetry as follows: (Fluorescence intensity = 472.4 × Absorbance − 25.1). It is expected, the sonochemical effects of inertial cavitation activity is influenced by sonication parameters. Also, the KI dosimeter and the terephthalic acid dosimeter are based on sonochemical reactions. Therefore, the correlation between these chemical methods is rational.

4. Discussion

Ultrasound is widely utilized for therapy and diagnosis in many medical fields such as gene therapy, enhancement of the effects of chemotherapy, sonodynamic therapy and other novel therapeutic applications [26,27]. Recently, there has been a growing interest in the use of the low level intensity ultrasound. Commonly, low level intensity ultrasound is a term given to intensities below 3 W/cm^2 [25,28]. Absorption of ultrasound energy leads to tissue heating, and this has been used with therapeutic intent in many conditions. Recently, it has been realized that benefit may also be obtained from the non-thermal effects, especially cavitation. Investigation of inertial cavitation in medical ultrasound has practical significance where is this mechanism of action is responsible for therapeutic application [2,29,30]. So, it is necessary to find out

the effect of acoustical parameters on cavitation. The collapse of cavities can produce chemical effects. The several chemical methods such as iodide dosimetry and terephthalic acid dosimetry were used to detect the reactive radical in sonochemistry [1]. All chemical methods are based on oxidation reactions occurring in an aqueous solution [13]. Terephthalic acid dosimetry is an sensitive method for monitoring the acoustic cavitation but it is a time consuming procedure [2]. The iodide dosimetry is simple and widely acceptable too [17]. Sonochemical reactions are strongly depend on the operational parameters [3]. In current study chemical effects of ultrasound were investigated using the liberation of iodine (I_2) from potassium iodide (KI) solution which is a classic endpoint of cavitation. The KI solution was sonicated and its absorbance at a wavelength of 350 nm was measured spectrophotometrically [4,24]. Also another chemical dosimetry, terephthalic acid dosimetry, for monitoring the free radical was used [3]. Finally, we have evaluated correlation between two chemical dosimeter methods. Kratochvil and Mornstein [24] studied the effect of sonication duration on the oxidation of KI at 1 MHz (2 W/cm^2) and observed that the yield of tri-iodide increased approximately in proportion to sonication duration.

Merouani et al. [13] studied influence of several operational parameters on the sonochemistry dosimetries such as KI oxidation, H_2O_2 production and Fricke reaction using 300 kHz ultrasound. The main experimental parameters showing significant effect in KI oxidation dosimetry were initial KI concentration, pH and acoustic power. The solution temperature showed restricted influence on KI oxidation. In present study, we have demonstrated that sonication with 1 MHz irradiation induces inertial cavitation, even at low level intensities (I < 3 W/cm^2). At different duty cycles, the absorbance increased with higher duty cycles (80% > 50% > 20%). Also, in the continuous mode, the absorbance is more than in the pulse mode. The results of experiments related to the sonication duration show that in continuous mode, the absorbance is linearity increased. It is well known that degree of gas saturation, type of gas and temperature of sonicated dosimeter solution play an important role in determining the extent of inertial cavitation occurrence [1]. As can be seen from Fig. 2 for long sonication times (30–60 min), the extent of cavitation is saturated gradually with time. It may be stated that the dosimeter gas content is decreased and its temperature increased with time.

The amount of absorbance show that, the inertial cavitation activity at higher ultrasound energies is more than at lower ultrasound energies. Kirpalani and McQuinn [12] determined the threshold acoustic power for iodine production, which coincides with the appearance of cavitation bubbles. It was 1.17 and 3.14 W/cm^2 for 100 ml of KI solution in the 1.7 and 2.4 MHz systems respectively.

We observed that ultrasound intensity is an important parameter for reactive radical generation. In this study, with increasing the sonication intensity, the absorbance increased when intensity was greater than 0.5 W/cm^2. Barati et al. [3] investigated the effects of 1 MHz ultrasound exposure parameters on free hydroxyl radical production by terephthalic acid dosimetry. They showed that with increasing the duty cycles of pulsed field, the fluorescence intensity is increased. The fluorescence intensity for continuous sonication is more than for pulsed mode and with increasing time of sonication or intensity, the fluorescence intensity is increased. In comparison we observed same results in our study. Hasanzadeh et al. [2] studied the correlation between terephthalate acid dosimetry and subharmonic spectrum analysis at 1 MHz low level intensity ultrasound field. In different sonication parameters, they showed significant correlation between fluorescence intensities and subharmonic signals. Also, in our study, it seemed that there was a significant correlation between modified iodide dosimetry and terephthalic acid dosimetry when effect of sonication parameters on reactive radical production was investigated. It has been known that the measurement of reactive radicals, which is mainly generated by collapse of cavitation, is an effective tool to evaluate sonochemical effect. The detection of the inertial cavitation by chemical dosimetry methods is widely used because gives the direct sonochemical efficiency and produced reliable results [1,17]. In current study, chemical effects of ultrasound waves were investigated using iodide dosimetry and terephthalic acid dosimetry. With respect to the results, both these methods were suitable for investigation of reactive radical detection in ultrasound field. The terephthalic acid dosimetry is more sensitive than iodide dosimetry, but it is a time consuming procedure. The iodide dosimetry has not enough sensitivity for detection of free radical at low intensity (below 1 W/cm^2) 1 MHz sonication, but this method is simple and easy. Results revealed that there is significant dependence between these methods.

5. Conclusion

With respect to the results measured, it may be stated that the iodide chemical dosimetry and terephthalic acid dosimetry methods were suitable for investigation the sonication parameters. This study addressed the effect of ultrasound irradiation parameters such as mode of sonication, intensity, duty factor, sonication duration and ultrasound energy density are effective in reactive radical production and in turn, in inertial cavition production. It was revealed that there is significant dependence between iodide dosimetry and terephthalic acid dosimetry to examine the cavitation activity and so the terephthalic acid dosimetry is more sensitive than iodide dosimetry.

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