Radioprotection 51(4), 287-292 (2016)

DOI: 10.1051/radiopro/2016076

Available online at:
www.radioprotection.org

ARTICLE

Response of TLD badges and cards for measurement of the operational quantity $H_p(10)$ to a ^{137}Cs source

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Received 9 December 2015 – Accepted 2 October 2016

Abstract – The operational quantity, $H_p(10)$, for strongly penetrating radiation was measured by a dosimeter placed on a phantom surface for individual external dose monitoring. Measurement of $H_p(10)$ was carried out with a ^{137}Cs source using $CaSO_4$:Dy Teflon-based TLD badges and cards placed on the surface of a PMMA as well as water phantom at a depth of 10 mm. The ratio of response of the TLD discs to TLD badges and that of the TLD cards under similar conditions were identical for different experimental conditions. This experiment quantified the impact of the cassette on the dose measurement. Minor changes in the PMMA phantom thickness beyond 15 cm showed an insignificant impact on the dosimeter response.

Keywords: $H_p(10)$ / TLD / PMMA / Perspex / dosimeter

1 Introduction

The personal dose equivalent, $H_p(d)$, has been recommended by different international agencies such as the ICRU, ICRP, IAEA, ISO, etc., for use in individual dose monitoring for radiation workers engaged in various nuclear facilities, research laboratories, medical facilities and nuclear power plants. The $H_p(d)$ is the dose equivalent in soft tissue below a specified point on the human body, at an appropriate depth d. The $H_p(d)$ can be measured by using a detector worn on the surface of the human body and covered with an appropriate thickness of tissue equivalent material. The recommended depths are, respectively, 10 mm and 0.07 mm for strongly penetrating and weakly penetrating radiation. However, 3 mm is appropriate for the eye lens (ICRU, 1985; 1992). Therefore, the estimation of $H_p(10)$ for strongly penetrating radiation requires measurement of the dose at a depth of 10 mm. However, for personal monitoring, the measurement of the dose equivalent below a depth of 10 mm of tissue in the body is not possible because the dosimeter is worn on the body's surface. To overcome this situation and wear the dosimeter on the surface of the body, conversion coefficients were derived using ICRU standard phantoms. For practical purposes, the conversion coefficients have been provided by the ICRU and ICRP for different photon energies at different angles for a water slab phantom and PMMA phantom of size $30 \times 30 \times 15$ cm^3 (ISO, 1996, 1998a, 1998b; ICRP, 1996; ICRU, 1998).

Personal dosimeters are required to comply with the performance criteria of $H_p(10)$ measurement. A $CaSO_4$:Dy Teflon-based TLD badge was designed and developed by BARC in India to measure the whole-body dose for strongly penetrating radiation (X- and γ-rays) and the skin dose for weakly penetrating radiation (beta and low-energy X-rays) (Vohra *et al.*, 1980). The $CaSO_4$:Dy TLD badges are worn at chest level for external X-/γ-ray and strong beta radiation for personal monitoring and records. The $CaSO_4$:Dy TLD badge has one TLD card, which is made of aluminium plate having three discs of $CaSO_4$:Dy Teflon clipped on circular hole of 12 mm dia. The TLD card along with paper is packed in the polythene pouch (thickness: 3–4 mg.cm^{-2}). The polythene pouch is placed inside an ABS plastic cassette containing filters for the three discs and is termed a *TLD badge*. The discs are clipped onto a 1-mm-thick aluminium card. Each card is numbered with a unique identity code (letters followed by numbers, *e.g.* AB01) for reference during monitoring and processing. The alphabetic reference of the cards is called the series of the card. The density of the TLD disc is 2.52 g.cm^{-3}. The three discs were placed under different filter combinations for exposure; disc D1 under Al + Cu metal filters of 1 mm thickness each, D2 under 180 mg.cm^{-2} Perspex and D3 under an open window, packed in a paper wrapper (thickness: 10–12 mg.cm^{-2}). The sensitivity of the $CaSO_4$:Dy Teflon-based TLD is 30–40 times more than LiF TLD-100, with fading of 2–3% in six months. The TLD discs in the actual dosimeter system consist of $CaSO_4$:Dy and Teflon mixed in the ratio of 1:3, Teflon being the binding material. The TLD cards were placed

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inside the plastic covers, called cassettes, to protect the discs. Disc D1 was used to measure X-/γ-ray photons, D2 to measure high-energy beta particles and X-/γ-ray photons, and D3 to measure all beta and X-/γ-ray photons. The ratio of the disc response was used to identify the type of radiation. Different algorithms were used to evaluate the whole-body and beta dose based on the type of radiation and response of the individual disc. Disc D1 was under the aluminium and copper filters on the front and back sides, respectively, to remove the backscattered photons. Different studies have been carried out to test the performance of dosimeters in terms of $H_p(10)$ using the conventional methodology (Christensen *et al.*, 1990; Miljanic *et al.*, 2003; IAEA, 2007; Busch *et al.*, 2011). All these studies indicate that the TLD badge complies with the requirements of dose measurement, except in the diagnostic photon energy region. However, there is no study related to *in situ* $H_p(10)$ measurement on a phantom except for high-energy photons (6–18 MeV), which is limited to a field size of 8×8 cm^2 (Munish *et al.*, 2008). Calibration of TLD badges for high-energy photons (>6 MeV) has also been reported (Pradhan and Bakshi, 2002). In the present investigation, $H_p(10)$ estimation was carried out using the $CaSO_4$:Dy TLD badges and cards on water and PMMA phantoms with a ^{137}Cs source to demonstrate the methodology for estimation of the operational quantity. This study provides the calibration methodology for the estimation of $H_P(10)$ on the laboratory scale.

2 Material and methods

The $CaSO_4$:Dy Teflon-based TLD badges and cards, calibrated *in situ* with a standard ^{137}Cs source, were considered for measurement of $H_p(10)$ on water and PMMA phantoms. Perspex sheets of different thicknesses (2 mm and 5 mm) with groove arrangements were prepared to place the TLD badges and cards inside them. The thicknesses of the TLD badge and card were 7 mm and 2 mm, respectively. In each experiment, four sets of TLD badges and cards were used for accuracy in the results.

The TLD cards were selected by the analysis of their response to test exposures from a set of cards which were subjected to identical treatment for annealing and background control. The selected cards had a response within an uncertainty of ±5% and the series of each of those cards were calibrated to give a uniform response.

A typical experimental setup is shown in Figure 1 for the water slab and PMMA phantoms. The phantoms are arranged on opposite sides at an equal distance of 1 metre from the standard ^{137}Cs source at the centre. The source is at a height of 1 metre from the ground to make the dosimeter, phantoms and source collinear and to avoid non-uniform scattering from any direction. The 1-metre distance between the source and phantom surface was chosen because the TLD cards for routine personal monitoring programmes are calibrated at that distance. The ^{137}Cs source was placed in a groove from which it could easily be removed after each exposure. The source was manually handled by a 1-metre-long tong. The PMMA and water phantoms were movable from the stand to arrange the appropriate distance/angle from the source facing the horizontal plane. The Perspex sheets fitted with TLD badges or cards were placed around the front surface of the phantom. The distance between the source and the surface of the phantom was kept constant and equal to 1 metre in all conditions while rotating the phantom with respect to horizontal or vertical plane surfaces. The exposure timing chosen was 60 minutes uniformly for all the experiments. The experiment was carried out for 0°, 22.5° and 67.5° angles from the horizontal position of the phantom to assess the dependency on the variation of the angle of exposure.

The experimental setup was placed in the centre of the room to avoid the backscattered photon contribution from the walls and ceiling during the exposure. The dose measured by the TLD was averaged for the horizontal and vertical badge/card positions on the phantom surface. Free-in-air exposure was carried out by removing the phantoms without disturbing the frame and placing the TLD in the grooves of the Perspex sheets using tape and thread at the centre of the frame such that the sheet surface was at the same position as it was during the phantom exposure measurement. The free-in-air measurement was carried out to assess the effect of the cassettes used in the TLD badges on dose measurement. TLD badges were placed inside a 7-mm-thick Perspex sheet and then on the phantom surface, as shown in Figure 2 and similarly, TLD cards were placed inside a 2-mm-thick Perspex sheet. The TLD badges/cards (shown in blue) were exposed in different arrangements to assess the effect of the phantom, as shown in Figure 3. The angular dependency for the response of the dosimeter was also tested by horizontal and vertical movement of the TLD badges/cards, as shown in Figure 4. In Figure 4 only two TLD badges are shown as a symbol. The experiment was done in four steps as described in Figure 3 and as given below:

(i) **Experiment A (TLD badge/card in groove for free-in-air measurement)**
The TLD badges and TLD cards were placed inside 7-mm-thick and 2-mm-thick Perspex sheets, respectively. The experimental arrangement was such that the PMMA and water slab phantoms were absent, *i.e.* the dosimeter was surrounded by air. The Perspex sheets were fixed by tape onto the stand. The dosimeters faced towards the source.

(ii) **Experiment B (phantom + TLD badge/card in groove)**
The TLD badges were placed into the grooves of the 7-mm-thick Perspex sheet and the TLD cards into the grooves of the 2-mm-thick Perspex sheet. The experimental arrangement was such that the Perspex sheets with TLD badges/cards were placed on the phantom surface facing towards the source.

(iii) **Experiment C (phantom + TLD badge/card in Perspex groove + 10-mm Perspex)**
The TLD badges were placed into the 7-mm and 2-mm-thick Perspex sheets and the TLD cards into the 2-mm-thick Perspex sheet. The experimental arrangement was similar to the previous one (Experiment B), except that an additional 10-mm-thick Perspex sheet was added in front of the detector to mimic the configuration where the dosimeter is at a depth of 10 mm for $H_p(10)$ measurement.

(iv) **Experiment D (phantom + 10-mm Perspex + TLD badge/card in Perspex groove)**
The TLD badges were placed into the 7-mm-thick Perspex sheet and the TLD cards into the 2-mm-thick Perspex sheet.

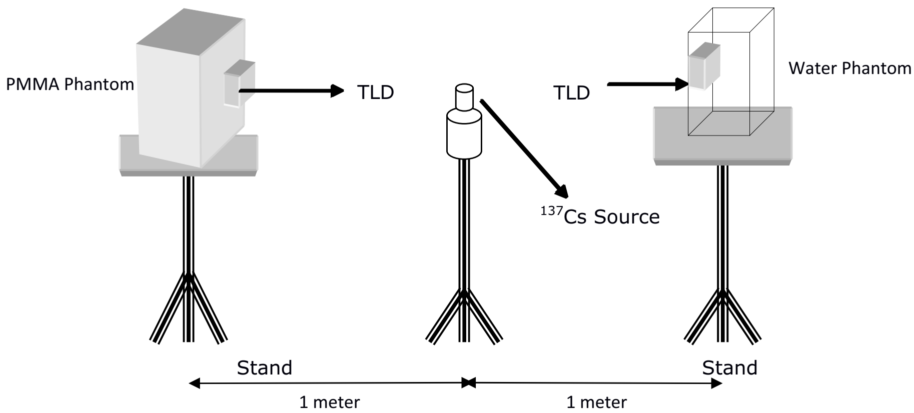

Figure 1. Experimental setup for the source, dosimeter and phantom.

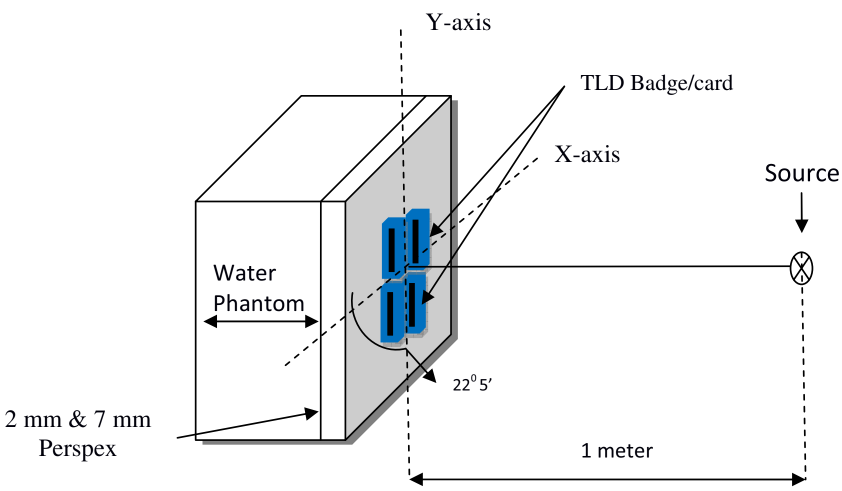

Figure 2. TLD badge arrangement in Perspex sheet grooves.

The experimental arrangement was such that the Perspex sheets with the TLD badges/cards were placed on the plane surface (facing towards the source) of the phantom, with an additional 10-mm-thick Perspex sheet on the back of the phantom to make the phantom thickness reach 16 cm. In a similar way, the thickness of the phantom can be increased up to 17 cm, 18 cm, 19 cm, etc., or even up to 30 cm. This represents personnel of different sizes for realistic situations.

3 Results and discussion

Table 1 shows the average disc response of the four TLD badges exposed in the different setups (A, B, C and D) on the water phantom. The normalised response with respect to the disc under a metal filter for the exposure setup on the water phantom with cards in grooves of the 7-mm-thick Perspex sheet and under the 10-mm-thick Perspex sheet is also shown for the relative response. The disc ratios of the respective discs of TLD badges and TLD cards for similar buildup and angles of incidence are given in Table 1. The TLD cards were in the groove of a 2-mm Perspex sheet on the PMMA phantom, whereas the TLD badges were in the groove of a 7-mm Perspex sheet on the water phantom. For personnel monitoring purposes, the TLD readers were calibrated using cards exposed under 3-mm-thick Perspex sheet, which provides uniform exposure to the three discs of the cards, and using cards exposed in the cassette, to consider the response of the disc under a metal filter (D1). In the present study, reading was carried out separately on readers calibrated by the cards of exposed TLD badges and the cards exposed in Perspex sheets. The ratio of response of corresponding discs read on readers calibrated with TLD badges (TLD cards loaded in the cassette) to that read in readers calibrated with the TLD cards exposed under Perspex buildup is also given in Table 1 to show the impact of the calibration technique employed. The spread of measurements of the respective 4 discs (1σ) is shown in the tables. Table 2 shows the results for the TLD cards when exposed in the groove of a 2-mm-thick Perspex sheet on the PMMA phantom.

It can be seen in Table 1 for setup A that the cassette used for the TLD badge shows slightly higher interference for D3 than D2, whereas it was insignificant for D1. The results for setups B and D in Tables 1 and 2 show that there was an insignificant impact on the response of D1 (under metal filters). In Tables 1 and 2, it can be observed that response variations of about 10% and 13% were observed for D2 and D3,

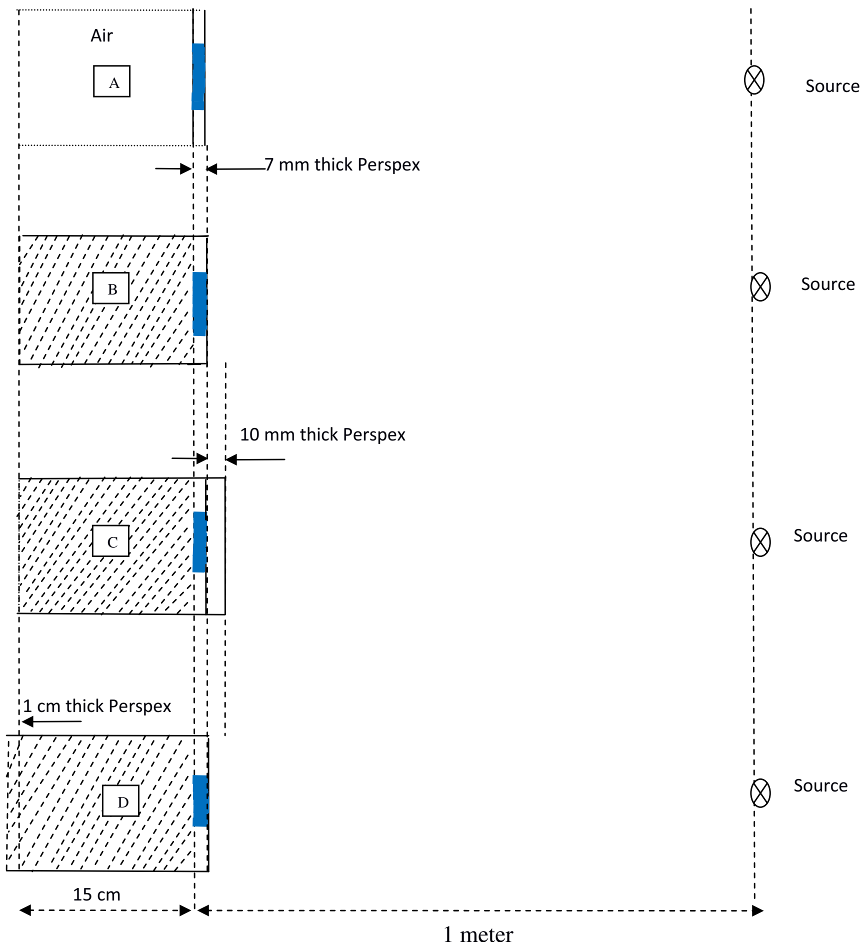

Figure 3. Experimental setup arrangement for the phantom, Perspex sheets, TLD badges/cards and source arrangement.

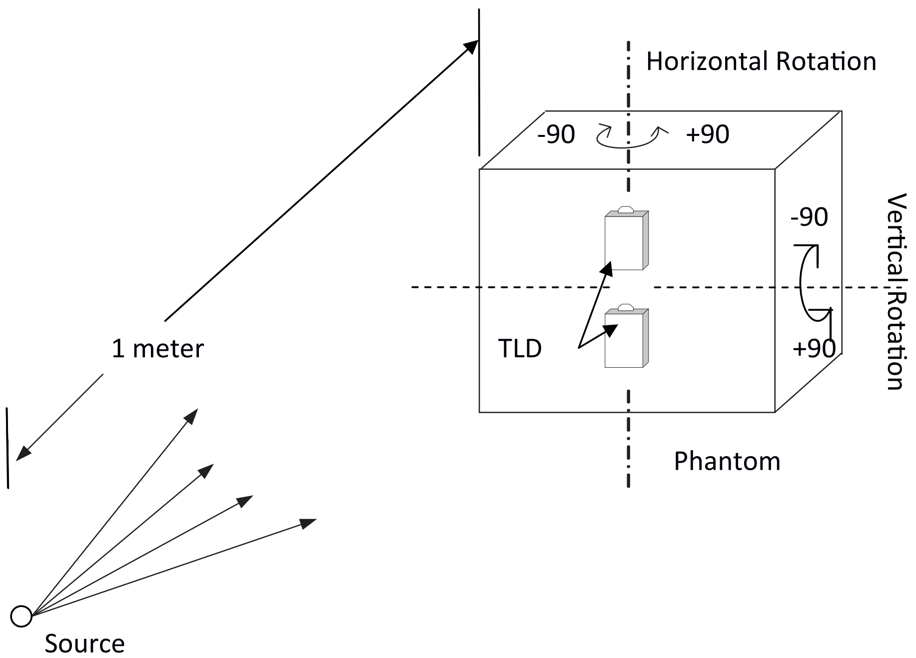

Figure 4. Angular dependence experiment setup shown for the TLD badge.

Table 1. Responses and disc ratios of TLD badges in grooves of a 7-mm Perspex sheet on a water phantom (w.r.t. stands for with respect to).

Exp. setup	Buildup	Angle (°)	Avg . read-out of three discs of the badge (net reading ± 1σ) (arbitrary unit)			Response w.r.t. D1 of Setup C1		
			D3	D2	D1	D3	D2	D1
A	without phantom	0	1921 ± 60	1792 ± 23	1741 ± 38	1.15	1.08	1.05
B	No Perspex	Normal	1836 ± 63	1799 ± 62	1666 ± 96	1.10	1.08	1.00
C1	Under 10-mm Perspex	Normal	1831 ± 38	1762 ± 43	1664 ± 42	1.10	1.06	1.00
C2	Under 10-mm Perspex	Avg. of 22.5 H 22.5 V	1733 ± 116	1728 ± 107	1799 ± 86	1.04	1.04	1.08
C3	Under 10-mm Perspex	Avg. of 45 H 45 V	1820 ± 87	1779 ± 92	1638 ± 90	1.09	1.07	0.98
C4	Under 10-mm Perspex	Avg. of 67.5 H 67.5 V	1826 ± 120	1707 ± 65	1585 ± 88	1.10	1.03	0.95
D	Phantom thickness 16 mm	0	1621 ± 34	1632 ± 40	1665 ± 42	0.97	0.98	1.00

V: Vertical**; H:** Horizontal.

Table 2. Response of TLD cards in grooves of a 2-mm Perspex sheet on a PMMA phantom.

Exp. setup	Buildup	Angle (°)	Avg . read-out of three discs of the badge (net reading ± 1σ) (arbitrary unit)			Response w.r.t. D1 of Setup C1		
			D3	D2	D1	D3	D2	D1
A	without phantom	0	1770 ± 162	1770 ± 162	1719 ± 87	0.95	0.95	0.93
B	No Perspex	Normal	1843 ± 48	1841 ± 24	1841 ± 40	0.99	0.99	0.99
C1	Under 10-mm Perspex	Normal	1849 ± 60	1808 ± 49	1855 ± 28	1.00	0.97	1.00
C2	Under 10-mm Perspex	Avg. of 22.5 H 22.5 V	1735 ± 124	1765 ± 29	1798 ± 146	0.94	0.95	0.97
C3	Under 10-mm Perspex	Avg. of 45 H 45 V	1824 ± 105	1780 ± 60	1770 ± 42	0.98	0.96	0.95
C4	Under 10-mm Perspex	Avg. of 67.5 H 67.5 V	1626 ± 84	1693 ± 47	1717 ± 56	0.88	0.91	0.93
D	Phantom thickness 16 mm	0	1637 ± 53	1674 ± 45	1855 ± 28	0.88	0.90	1.00

V: Vertical**; H:** Horizontal.

respectively, which may be attributed to the calibration methodology. However, an insignificant dose response variation was observed for D1 when the phantom thickness increased by 1 cm (see Tables 1 and 2). When the results of experimental setup B are compared with the results of setup C in Tables 1 and 2, a negligible difference is observed. This indicates that the response under a 10-mm-thick Perspex sheet (measurement of $H_p(10)$) is similar to the response of the TLD badge/card without any buildup. The effect of the orientation of the TLD badge/card was found to be negligible up to an angle of 67.5° (see Tables 1 and 2). The ratio of response of badges and cards of the corresponding discs showed a small angular dependence. The ratio for D2 of the TLD badge to TLD card increases with the angle, which shows that the metal filter in the cassette improves the angular dependence. The response of D1 indicates that the present badge design is capable of measuring $H_p(10)$ accurately using the present methodology (see Tables 1 and 2).

This study was carried out using a ^{137}Cs source (photon energy of 662 keV), which may not be applicable for the diagnostic region of low-energy gamma-ray photons, as photoelectric absorption is the dominant process (interaction cross-section $\alpha\ E^{-3.5}$), or high-energy photons, where pair-production is the dominant interaction. A recent study on high-energy photons (Pradhan and Bakshi, 2002) indicates modification of response, although the study was carried out in medical accelerators with limitation of the field of exposure, and hence may not represent the actual case as observed in panoramic exposure. Various gamma-ray energies are planned to be studied with this experimental setup for investigation of $H_p(10)$, air kerma and other interaction parameters using Monte Carlo simulation.

4 Conclusion

The response of TLD badges at a depth of 10 mm of tissue equivalent material indicates that the present $CaSO_4$:Dy Teflon TLD badge is capable of measurement of $H_p(10)$ for ^{137}Cs gamma photon. The present study is limited to the energy region where Compton scattering is the dominant interaction process. Therefore, the results are not applicable to very high and very low gamma-ray photon energies. The present TLD badge shows a nearly independent angular response in terms of $H_p(10)$. Minor changes in the phantom thickness beyond 15 cm showed an insignificant impact on the dose response. Different gamma-ray energies (low to high) are planned to be studied with this experimental setup using Monte Carlo simulation.

Acknowledgements. The authors gratefully acknowledge the encouragement provided by the Head, RP&AD, BARC, Mumbai, and the support provided by the Kaiga Site management.

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Cite this article as: V.P. Singh, R.B. Rakesh, N.M. Badiger. Response of TLD badges and cards for measurement of the operational quantity $H_p(10)$ to a ^{137}Cs source. Radioprotection 51(4), 287-292 (2016).