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GEOMETRIC AND APPLIED OPTICS

Evaluation of the Absorbed Dose of the Discharge Lamp Radiation

V. I. Gorbunkov

Siberian State Automobile and Road Academy, Omsk, 644080 Russia
e-mail: kaf_eate@sibadi.org

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Abstract—The compliance of the spectral characteristics of a discharge lamp mounted in a light-tight metal housing with the Planck radiation law is noted. In a blackbody approximation for the radiation flux density of a discharge lamp, the absorbed radiation dose is expressed as an expansion in terms of spectral components. It is demonstrated that a photodiode can be used for evaluation of the absorbed radiation dose.

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INTRODUCTION

Low-pressure discharge mercury lamps are simple and efficient UV radiation sources. It has been demonstrated that up to 80% of the radiant energy of a discharge quartz mercury lamp is concentrated in the spectral line at $\lambda = 253.7$ nm with a narrow Lorentzian profile [1]. Radiation at this wavelength is germicidal for most of germs; therefore, open mercury lamps with a quartz bulb are efficiently used for indoor sterilization in patient care institutions [2]. Further study of the biophysical action of the radiation at this wavelength on a human organism gave rise to the expansion of its use for medical purposes. In particular, it is used for extracorporal blood irradiation and intravascular photohemotherapy [3]. For these applications, discharge mercury lamps mounted in a light-tight metal housing for safe operation have been developed and are widely used (e.g., an apparatus of *Izol'da* type [4]). In these lamps, the thermodynamic characteristics of the radiation source, that is, the discharge plasma, inevitably change as compared with the open lamps. This can result in an essential change of the spectral radiation characteristics. However, to date, no information on the spectral measurements for the housed lamps is available and, apparently, it is assumed that the radiation spectrum of these lamps does not considerably differ from that of the open lamps. Moreover, the problems of stabilization of the lamp radiation intensity and control of the radiation dose absorbed by a bioliquid or blood flowing in the vessels still remain unsolved.

This paper is aimed at study of the spectral radiation characteristics of housed discharge mercury lamps used in medical apparatus of the *Izol'da* type, the development of techniques for stabilization of their radiation, and measuring the absorbed radiation dose. This study is very important for clinical practice [3, 5].

EXPERIMENTAL

The layout of a medical apparatus of the *Izol'da* type is schematically depicted in Fig. 1. A low-pressure (0.8–0.9 Pa) cylindrical discharge quartz mercury lamp *1* of DRB-8 type is mounted coaxially inside a closed reflective metal cavity *2* with a small opening *3* in the middle of the wall for the radiation output in the environment. In the apparatus, the opening is covered by a special cell with a bioliquid (blood) flowing therein. A photodiode is placed at position *4*.

A power supply provided direct current within 0.34–0.40 A, which corresponded to a transient condition of the lamp operation from a glow discharge to arc discharge. Radiation emerging from opening *3* was directed onto the entrance slit of a prism spectrometer SP-30 with a semiconductor optical multichannel spectrum analyzer SKCCD. Spectral resolution in the vicinity of the resonance mercury line at $\lambda = 253.7$ nm was not worse than 0.005 nm (Fig. 2).

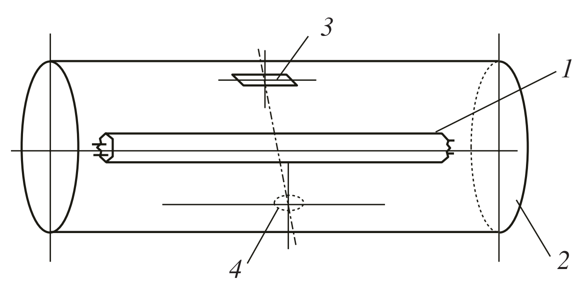

Fig. 1. Schematic layout of the radiator of a medical apparatus of the *Izol'da* type.

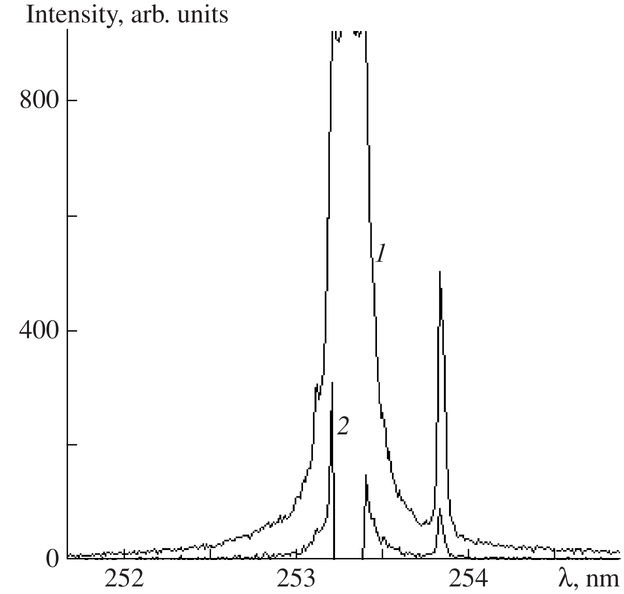

Fig. 2. Shapes of the 253.7-nm resonance mercury line profile for (*1*) arc and (*2*) abnormal glow discharges at lamp currents 0.34 and 0.25 A, respectively.

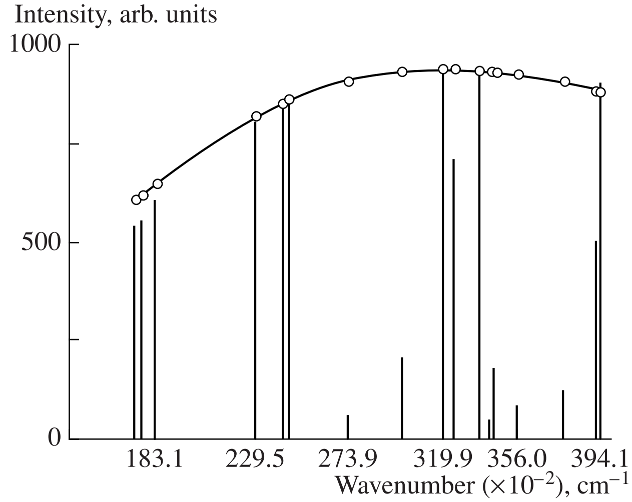

Fig. 3. Radiation spectrum of a DRB-8 lamp mounted in a light-tight metal cavity at the discharge current 0.34 A and voltage across the lamp 60 V. The spectral line peaks are enveloped by Planck's curve.

RESULTS AND DISCUSSION

The spectrum of the lamp radiation emerging from the opening in the housing cavity is shown in Fig. 3, and the characteristics of individual radiation spectral lines are listed in the table.

As can be seen in Fig. 3, except for individual lines corresponding to the transitions from the high-lying excited energy levels of a mercury atom, on the whole, the radiation spectrum of a housed discharge mercury lamp corresponds to Planck's radiation law for the blackbody at a temperature of 9270 K. This is indicated by a good fit of Plank's curve corresponding to this temperature to the envelope of the spectral line peaks.

This result could be expected, because the layout of a housed lamp (Fig. 1) is almost an ideal model of a blackbody, inside which a discharge plasma emits the line spectrum. The low pressure notwithstanding, the thermodynamic equilibrium is established in this plasma. An additional argument in favor of this inference is the strong self-reversal of the emission lines (Fig. 2) due to the detailed radiation–absorption equilibrium. In essence, a mercury lamp placed inside a metal cavity is a Planck radiator [6].

Figure 3 also demonstrates that, in a housed lamp, the radiation intensity of the 253.7-nm resonance line does not exceed 10% of the total radiation intensity, whereas the contribution of this line in an open lamp amounts up to 90% [7]. Furthermore, because of the self-reversal, the radiation profile of this line is of intricate shape with a shifted intensity peak (Fig. 2). Both

Characteristics of the individual spectral mercury lines of a DRB-8 lamp

Radiation range	Wavelength, nm	Wavenumber, cm^{-1}	Energy level, eV	Transition	Spectral line intensity, rel. unit		
					Planck law	experiment	
						a	b
UV–C	253.7	39416	4.89	$6\,^3P_1$–$6\,^1S_0$	896.92	935.47	935.65
UV–B	296.73	33701	8.85	$6\,^3D_1$–$6\,^3P_0$	956.35	937.15	955.01
	312.60	31989	8.85	$6\,^3D_2$–$6\,^3P_1$	962.15	962.20	964.20
UV–A	365.0	27397	8.85	$6\,^3D_3$–$6\,^3P_2$	942.23	60.74	81.44
Visible	404.7	24709	7.73	$7\,^3S_1$–$6\,^3P_0$	903.17	872.04	877.96
	435.8	22946	7.73	$7\,^3S_1$–$6\,^3P_1$	865.65	812.45	818.62
	546.1	18312	7.73	$7\,^3S_1$–$6\,^3P_2$	721.71	610.03	650.20

Note: at lamp current (a) 0.33 and (b) 0.39 A.

these effects should be taken into account when such a lamp is used in practice, especially in medicine. In fact, this lamp is essentially a radiation source with the line spectrum, in which the fraction of the UV radiation intensity is small. Therefore, on one hand, the results of irradiation by such a lamp will be governed not only and not so much by the UV radiation component, but by the total radiant energy. On the other hand, the shift of the wavelength peak of the exposing radiation can change the exposure effect itself, specifically, if this effect is of a resonance nature.

At the same time, in a number of cases, the investigators, noting a stable positive treatment effect, assumed the presence of nonphotochemical, i.e., nonresonance mechanisms in the biological effect of the discharge lamp radiation [8, 9]. In either of the cases, the consideration of the action on a biotissue of monochromatic radiation as a spectral constituent would be useful for biophysical research.

Under the conditions of the thermal equilibrium of the plasma of a discharge lamp and the cavity walls, the radiation emerging from the opening has a spectrum identical to that of the blackbody. The spectral distribution of the radiant energy is given by the Planck formula [10]

$$u_\nu = (8\pi h\nu^3/c^3)/[\exp(h\nu/kT) - 1], \quad (1)$$

where $\nu = c/\lambda$, c is the speed of light, h is the Planck constant, and k is the Boltzmann constant.

Up to a constant factor, this formula describes the curve that envelopes the spectral line peaks in the spectrum depicted in Fig. 3.

By using Eq. (1), the volume radiation density $\Delta u(\nu_i)$ of the ith spectral line with the peak at frequency ν_i and the intensity distribution (form factor) $S(\nu_i) = I_i(\nu)/I_{i0}$, where $I_{i0} \sim u_{\nu_i}$, and $I_i(\nu)$ is the spectral line profile, can be represented as follows:

$$\Delta u(\nu_i) = u_{\nu_i}\int_\nu S(\nu)d\nu \approx u_{\nu_i}\Delta\nu_i. \quad (2)$$

Here $\Delta\nu_i$ is the effective width of the ith spectral line.

Since the radiation of the lamp considered here is characterized by the line spectrum with a finite number N of mercury spectral lines within the frequency range ν_1 to $-\nu_N$, the volume radiation density of the lamp within this frequency range is expressed by the sum

$$U = \sum_{i=1}^{N}\Delta u(\nu_i). \quad (3)$$

According to the Lambert law, the radiant energy flow passing through the opening of area dS_n in the cavity during time dt is expressed as $U(c/4\pi)dS_n$. In this case, the radiant flux surface density is

$$P = \sum_{i=1}^{N}\Delta p_{\nu_i} = (2h/c^2)\sum_{i=1}^{N}\nu_i^3\Delta\nu_i/[\exp(h\nu_i/kT) - 1]. \quad (4)$$

If a radiation detector with a refractive index different from that of air is placed in the emitting opening, the radiant power of a monochromatic beam incident on the detector will be reduced by the radiant power of the incident equilibrium radiation reflected from the air–detector interface when the beam passes through the smooth interface. Hence, according to the Clausius condition [11],

$$\Delta p_{\nu_i}^{(2)} = (1 - \rho_{\nu_i})(n_{2\nu_i}^2/n_{1\nu_i}^2)\Delta p_{\nu_i}^{(1)}, \quad (5)$$

where $\Delta p_{\nu_i}^{(1)}$ and $\Delta p_{\nu_i}^{(2)}$ are the spectral radiances of the incident (Eq. (4)) and refracted beams, respectively; $n_{1\nu_i}$ and $n_{2\nu_i}$ are the refractive indices of the air and biological medium, respectively, and ρ_{ν_i} is the spectral reflectance of the interface. Here, the reflectance refers to all the beams reflected from the interface omnidirectionally.

The spectral radiance of the refracted beam passed through the air–bioliquid interface is expressed as the sum of N spectral components with due account of Eq. (4) as follows:

$$\Delta p_{\nu_i}^{(2)} = \frac{2h}{c^2}\frac{n_{2\nu_i}^2}{n_{1\nu_i}^2}\frac{(1 - \rho_{\nu_i})\nu_i^3\Delta\nu_i}{\exp(h\nu_i/kT) - 1}. \quad (6)$$

Generally, the refractive indices depend on frequency. Considering blood as a radiation detector, investigators attribute it to the class of the optically turbid (disperse) media with the absorption prevailing over scattering in the UV spectral range [12]. Attenuation of the ith spectral radiance component during penetration into a medium occurs by the exponential law and the total radiance is equal to

$$P(z) = \frac{2h}{c^2}\sum_{i=1}^{N}\frac{n_{2\nu_i}^2}{n_{1\nu_i}^2}\frac{(1 - \rho_{\nu_i})\nu_i^3\Delta\nu_i}{\exp(h\nu_i/kT) - 1}\exp(-\alpha_{ti}z), \quad (7)$$

where $\alpha_{ti} = \alpha_{\nu i} + \alpha_{si}$ is the extinction ratio, $\alpha_{\nu i}$ is the absorptance, α_{si} is the scattering factor, and z is the layer width.

To evaluate the irradiance of a biological detector [13] by an individual spectral line, we compare its magnitude from Eq. (6) with the response of a photodiode located in the cavity like the biological detector (Fig. 1). The energy of the ith spectral line absorbed by the photodiode in the case of its short-circuit condition [14] brings about the photocurrent equal to

$$\Delta I_{\nu_i} = (\gamma_{\nu_i}/h\nu_i)S_d\Delta p^{(1)}_{\nu_i}, \quad (8)$$

where $\gamma_{\nu_i}/h\nu_i$ is the quantum efficiency (spectral responsivity) of the photodiode, and S_d is its effective photosensitive area. The total photocurrent in the photodiode is equal to the sum of the photocurrents arising from all N radiation lines:

$$I = \sum_{i=1}^{N}\Delta I_{\nu_i}.$$

Assuming that the spectral radiance of a discharge lamp is uniformly distributed within solid angle $\Omega \approx 4\pi$, the relationship between the radiant powers of the ith spectral radiation component incident on the bioliquid and on the photodiode surface can be readily established. By using light filters and having obtained from experimental data the fraction of photocurrent ΔI_{ν_i} arising in the photodiode from the ith spectral line, this makes it possible to determine the radiant power of the spectral radiation component acting on the unit area of the biological medium

$$\Delta p_{\text{inc}} = (h\nu_i/\gamma_{\nu_i})(n^2_{2\nu_i}/n^2_{1\nu_i})(1-\rho_{\nu_i})\Delta I_{\nu_i}/S_d. \quad (9)$$

Then, using Eq. (7), the attenuation of the monochromatic radiation penetrating into the medium to depth z can be evaluated from

$$\Delta p_{zi} = \Delta p_{\text{inc}}\exp(-\alpha_{ti}z). \quad (10)$$

In this case, the necessary requirement is the constancy of the spectral distribution of the radiant energy acting on the radiation detector. Only under this condition the spectral responsivity of the photodiode for each wavelength can be assumed constant and conforming to its response characteristic.

By using a photodiode located in the cavity, it is also possible to stabilize the discharge lamp radiation, excluding the effect of external factors, such as fluctuations of the power supply voltage. In this case, if the total spectral signal is taken as an adjustable parameter and the adjustment is performed by the lamp current, the peak of the lamp spectral characteristic can be shifted due to the nonlinearity of the photodiode spectral response. This means that the radiant energy can be redistributed in the spectrum. This does not occur if the intensity of an individual spectral line is taken as an adjustable parameter. Furthermore, the adjustment response can be enhanced, for example, due to the fact that the response of an individual spectral component is higher than the response of the total signal. It follows from the data listed in the table that the response of the visible 546.1-nm spectral line is by a factor of 3.7 higher than that of the total signal.

DOSAGE

To evaluate the effect of the optical radiation on a biotissue, it is suggested in [15] to assume the radiation dose absorbed by the medium to be in direct proportion to the radiant flux surface density. In this case, the dose is determined by the product of the radiant flux density as per Eq. (4) and the exposure time t.

In photobiological research, the absorbed dose M is commonly measured in units equal to the ratio of the radiation energy to the weight of the irradiated substance. If the radiation of a discharge lamp is stable in time, the absorbed dose of the ith spectral line radiation M_{ν_i} equals

$$\Delta M_{\nu_i} = at\alpha_{\nu_i}\Delta I_{\nu_i}/\rho\exp(1), \quad (11)$$

where

$$a = h\nu_i/\gamma_{\nu_i}(n^2_{2\nu_i}/n^2_{1\nu_i})(1-\rho_{\nu_i})/S_d,$$

t is the exposure time, α_{ν_i} is the spectral absorptance of the medium at frequency ν_i, and ρ is the density of the medium. The total absorbed radiation dose equals

$$M = \sum_{i=1}^{N}\Delta M_{\nu_i}. \quad (12)$$

Equation (11) allows one to evaluate the contribution of each spectral component of the discharge lamp radiation to the phenomenon under study, as well as the additivity of their contributions. This will make it possible to determine the efficiency of the action of each of the used radiation sources on various biological media.

CONCLUSIONS

It is demonstrated that radiation of a discharge mercury lamp housed in a confined light-tight cavity is close to the blackbody radiation during transition to the arc discharge condition. The radiation features the line spectrum, fairly rich with lines.

On the assumption of the thermodynamic equilibrium of the system, the equation is derived for the radiation flux density, which is used for the evaluation of the radiation dose absorbed by a biotissue.

By using light filters, it is possible to isolate individual monochromatic spectral components of the mercury germicide lamp radiation, which are important for practice.

For dosing the 253.7-nm resonance mercury line radiation, the redistribution of the radiant power over other spectral components should be taken into account in apparatus of the closed type.

The radiation, both incident and absorbed in blood, can be evaluated from the photodiode current.

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