MODERN SUPERFINE MEDICAL ENDOSCOPES BASED
ON GRADIENT OPTICS: CURRENT STATUS AND PROSPECTS
FOR CLINICAL APPLICATION

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Endoscopy is the most pictorial approach among other diagnostic methods such as roentgenology, ultrasonic and
tomographic imaging, etc., the approach providing reliable verification of pathological lesions.

An important problem in modern endoscopy is the reduction of endoscopy-induced trauma. This is particularly impor-
tant in case of invasive endoscopy, i.e., when it is necessary to penetrate intact biological tissue to perform endoscopic examina-
tion. For example, during endoscopic examination of the middle ear through a perforated tympanum (tympanoscopy), of the
maxillary sinus (antrum of Highmore) through intranasal or extranasal puncture (sinoscopy), of subarachnoidal liquor cisterns and
ventricles of the brain (cisternoscopy and ventriculoscopy), of abdominal cavity organs through puncture in its frontal wall
(laparoscopy), of rear structures of the eye using an endoscope inserted through a dissected flat part of the ciliary body [2, 5, 10,
12, 17], etc.

Optical tubes of invasive endoscopes have external diameter of 2.7 and 4.0 mm. Therefore, endoscopic examination is, in
fact, an operative intervention, since the cut in the examined cavity should be sufficiently large. Such examination requires
compliance with antisepsis and asepsis, infiltration anesthesia, and the use of trocars and other specific surgical instruments to
expose the examined cavity.

One of the approaches to the reduction of endoscopic trauma is to decrease the diameter of the working part of the
endoscope which is inserted into the patient's body.

Since the 1970's, such leading foreign manufacturers of medical endoscopes as Karl Storz and Richard Wolf (Germany)
have been producing rigid endoscopes with optical tube diameter of up to 2.7 mm (e.g., optical tubes of the Richard Wolf
sinoscope models 8672.433, 8672.435, 8672.431). In the mid 1980's, as a result of the development of new technologies, a number
of superfine endoscopes of 1.9 mm diameter was developed, the endoscopes being designed on the basis of optical lenses 1.2 mm
in diameter (e.g., optical tubes of the Richard Wolf sinoscope models 8660.433, 8660.431).

In the Scientific Research Institute for Medical Instrument Engineering, which is a leading domestic manufacturer of
rigid endoscopes, the Tsu-VS-1 cystoscope and Si-VS-01 sinoscope with optical tube diameter of 2.7 mm (lens diameter of 1.85
mm) have been developed recently. However, the equipment of domestic optical workshops (Almaz-15-Sh and 5-Sh-30 grinding
machines, 10P-30 polishing machine, TsS-10 and TsSM-50 centering machines) permits automatic production only of lenses more
than 3 mm in diameter [11]. Lenses of 1-3 mm in diameter are piece-worked by hand. At the same time, COCOM restrictions do
not allow foreign automated equipment for production, control, and assembly of lenses of 1-3 mm in diameter to be imported to
Russia. As a result, large-scale production of the developed domestic endoscopes based on lens optics of less than 4 mm in
diameter proved to be unrealistic. Thus, the TsiS-VS-1 observation cystoscope, presently produced by the Krasnogvardeets
Association, has a diameter of 5 mm.

A new type of optical systems, gradient optical elements (gradans), has been developed during the 1960-80's in Japan
and in Russia. They have nonuniform distribution of index of refraction over the glass volume [7, 15, 19]. The application of
gradans with specific gradients of index of refraction allows development of high-quality optical systems, the parameters of the
systems being unaccessible in traditional optical elements.

Gradient optics is often used in high intensity optical systems (fiber optic communication systems, infrared systems for
defense industry, video recording systems, etc.) [4, 9, 16].

In addition, gradient optics is used in image transfer systems. Requirements for optical characteristics of gradans in this
case are quite high [8, 14].
Gradans with radial distribution of index of refraction are presently believed to have the most advanced performance. The gradans are long cylindrical rods made of special glass and treated by a special physicochemical procedure to provide the required radial distribution of index of refraction (gradual decrease from the gradan axis to its external cylindrical surface). The rods have polished edges.

Such a gradan is optically equivalent to a lens, the cardinal characteristics of the lens (focal distances, position of principal planes, etc.) depending on the length of the gradan and the gradient of its index of refraction [3, 13].

Use of gradans in an optical system of a medical endoscope was for the first time reported in 1970 [21]. The proposed prototype model of a needle-endoscope consisted of a gradan (0.75 mm in diameter, 100 mm length) and an eyepiece.

The optical system of subsequent models of endoscopes based on gradans was substantially more sophisticated. Such elements as a high-aperture gradan-objective for projecting the image of the studied object, and a low-aperture gradan-translator for transmitting the image to an eyepiece are the elements of the endoscopes. The first two elements compose the narrow distal part of the endoscopes. Additional lenses were also incorporated into the optical system for correcting gradan aberrations.

One of the major advantages of gradient elements is the opportunity for replacing several tens of microlenses constituting the optical system of an endoscope by two gradans. Therefore, extremely laborious procedures of manufacturing and centering of microlenses can be avoided, and assembly of endoscopes can be significantly simplified.

The number of optical elements in endoscopes based on traditional optics reaches 60, and the number of glass/air interfaces reaches 35 [6]. Therefore, even if the interfaces are covered with multilayer antireflection coating, the luminous transmittance of the optical system is not more than 0.4-0.5. In the case of gradient elements, where the distal edge of the endoscope has only two reflecting surfaces, the luminous transmittance is significantly higher (0.75-0.85 with the length of the gradan-translator of 50-200 mm).

Nippon Sheet Glass Co., Ltd (Japan) is the leading foreign manufacturer of gradans. A gradan-translator costs $150-200, and a gradan-objective $20-30.

Domestic industry mass produces high-aperture gradan-objectives of 0.8, 1.0, 1.5, and 1.75 mm in diameter with angular fields of 55 and 68° and low-aperture gradan-translators of 0.8, 1.0, 1.5, and 1.75 mm in diameter with lengths from 50 to 220 mm. Special technological process allows cylindrical surface of a gradan to be darkened to a depth of 0.05-0.10 mm, thus creating a light-absorbing layer. The layer has absolute mechanical strength (lack of flaking) since it is an integral part of the internal transparent part of the gradan. Reflectance from the layer is negligible, in contrast to the case when a polished optical surface is covered with a light-absorbing varnish [1, 18].

Resolving power of the gradan-translators is 190 mm⁻¹, and in the gradan-objectives it is 300-500 mm⁻¹ (under full luminous diameter).

On the basis of gradient elements 1 mm in diameter, the Olympus company (Japan) mass produces rigid technical endoscopes with working part diameter of 1.7 and 2.7 mm and working part length of 110 and 170 mm (miniboroscopes). According to the catalogues, the angular field of such endoscopes is 53 and 70° (the actual value is not more than 65°), and the direction of observation is 0, 14, and 90°. The endoscope is a one-piece, non-hermetic unit. Endoscopes with working part diameter of 2.7 mm have enhanced illuminance of working field, which is achieved by increased diameter of the illuminating bundle.

The cost of the devices of different type varies from $1700 to $26,000.

A small batch of medical endoscopes 1.7 mm in diameter was produced by the Dyonics company (USA). The devices are used as arthroscopes and ophthalmological endoscopes [20].

Nevertheless, leading foreign manufacturers of medical endoscopes give preference to traditional lens optics because rearrangement of traditional technological processes, which has been adjusted for decades, is seemingly economically unprofitable.

The first domestic medical endoscope based on gradient optics was developed in the All-Union Scientific Research Institute for Medical Instrument Engineering in 1987. The optical system of the endoscope included a lens objective, a gradan-translator 110 mm in length and 1 mm in diameter, and an eyepiece. The angular field of the endoscopes was 19° and the direction of observation was 80°.

However, aberration parameters of presently available domestic gradient elements do not meet the requirements for medical endoscopic optics.

Our literature survey and clinical experience using gradient elements show optical systems of various superfine endoscopes for different purposes to have similar structure and performance. On the basis of the survey, a parametric series of unified gradient optical systems for medical endoscopes was developed in 1990-1991 in the All-Union Scientific Research Institute for