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Optics and photonics — Medical endoscopes and endotherapy devices —

Part 5: Determination of optical resolution of rigid endoscopes with optics

Optique et photonique — Endoscopes médicaux et dispositifs d'endothérapie —

Partie 5: Détermination de la résolution optique des endoscopes optiques rigides

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 172 *Optics and photonics,* Subcommittee SC 5, *Microscopes and endoscopes*.

This second edition cancels and replaces the first edition (ISO 8600-5:2005), which has been technically revised.

The main changes compared to the previous edition are as follows:

— document has been restructured;

— Clause 2 added;

— Clause 3 revised and updated;

— quality characteristics “Contrast Transfer Function” and “Modulation Transfer Function” as measurement methods are introduced;

— Measurement with limiting resolution moved to informative Annex A;

— informative Annex B added;

— informative Annex C added;

— normative Annex D added;

— informative Annex E added;

— informative Annex F added;

— informative Annex G added.

A list of all parts in the ISO 8600 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Optics and photonics — Medical endoscopes and endotherapy devices —

Part 5: Determination of optical resolution of rigid endoscopes with optics

1 Scope

This document applies to rigid endoscopes designed for use in the practice of medicine. Endoscopes having a fibre-optic or opto-electronic imaging system are excluded. It specifies a test method for determining the optical resolution of endoscopes.

This document provides a measurement method for characterizing three aspects of the optical resolution of a rigid endoscope. Characteristic A is used to provide a simple measurement of the limiting resolution of the endoscope image. Characteristic B provides a measurement of low spatial frequency resolution and characterizes the sharpness, or contrast, of the endoscope image. Characteristic C provides a measurement of the spatial frequency response of the endoscope image.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9334, *Optics and photonics — Optical transfer function — Definitions and mathematical relationships*

ISO 12233:2017, *Photography — Electronic still picture imaging — Resolution and spatial frequency responses*

ISO 15529:2010, *Optics and photonics — Optical transfer function — Principles of measurement of modulation transfer function (MTF) of sampled imaging systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
angular limiting resolution
smallest angle whose vertex is at the entrance pupil (can be approximated by the distal window surface if the target distance from the distal window is significantly larger than the distance between the distal window surface and the entrance pupil) of the endoscope at which a line pair (lp) at a given working distance *d* can just be resolved with normal visual acuity, with the unit of degrees/lp

Note 1 to entry: Angular limiting resolution is calculated using the formula

$$\alpha = \arctan \frac{1}{d \cdot r(d)}$$

where $r(d)$ is the limiting resolution.

3.2
camera
image detector used in the measurement, which is connected to the endoscope under test via coupling optics

Note 1 to entry: As used in this standard, the camera includes an image detector (typically CCD or CMOS image sensor), supporting electronics, and firmware/software used to obtain a digital sampling of the image formed by the coupling optics.

3.3
contrast
ratio of the difference between the intensities of the brightest and the darkest regions of a bar test target with square-wave modulation or its image divided by the sum of the intensities of the brightest and the darkest regions of the target or its image, and subsequently multiplied by 100 to measure as a percentage

Note 1 to entry: Contrast is given by

$$C(\%) = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100$$

where I_{max} and I_{min} are the intensities of the brightest and darkest regions of the target or its image, respectively.

3.4
contrast transfer function
CTF
plot of *contrast* (3.3) transfer factor, C_{TF}, as a function of *spatial frequency* (3.13), u

Note 1 to entry: Contrast transfer factor is given by

$$C_{TF}(u) = \frac{C(u)_{out}}{C(u)_{in}}$$

where $C(u)_{out}$ is the output contrast (i.e. the image contrast) and $C(u)_{in}$ is the input contrast (i.e. the target contrast).

Note 2 to entry: If the target has high contrast so that $C(u)_{in}$ is close to one, $C_{TF}(u)$ can be approximated by $C(u)_{out}$. If C_{TF} is normalized to 1 at zero frequency, constant $C(u)_{in}$ will get factored out in the normalization. The CTF of an endoscope can be obtained by measuring a series of square-wave bar targets with different *spatial frequencies*. The low-frequency contrast of the target as imaged through the endoscope may be measured with target patches of light and dark large enough that the intensity profile through the patch clearly reaches a steady value.

Note 3 to entry: For the purposes of the test specified in Characteristic B of this document, the "targets" will be the bar test targets specified in 4.2.5.2 and the measured results will be the CTF.

3.5
limiting resolution
r(*d*)
maximum number of line pairs per mm (lp/mm) which can be resolved at a given working distance *d* of the endoscope

Note 1 to entry: The limiting resolution is only applicable to Characteristic A.

3.6
maximum image height
radius of a circle which circumscribes the image

Note 1 to entry: If the image is rectangular, the maximum image height is half of the diagonal.

Note 2 to entry: If the image is circular, the maximum image height is the radius of the image circle.

3.7
maximum object height
radius of a circle which circumscribes the portion of the object which can be imaged by the endoscope

Note 1 to entry: If the image is rectangular, the maximum object height is half of the distance between the object points which map to the corners of the image rectangle.

Note 2 to entry: If the image is circular, the maximum object height is the radius of the object space circle which maps to the image circle.

3.8
modulation
M
ratio of the difference between the intensities of the brightest and the darkest regions of a sinusoidal test target or its image divided by the sum of the intensities of the brightest and the darkest regions of the target or its image, and subsequently multiplied by 100 to measure as a percentage

Note 1 to entry: Modulation is given by

$$M(\%)=\frac{I_{max}-I_{min}}{I_{max}+I_{min}}\times 100$$

where I_{max} and I_{min} are the intensities of the brightest and darkest regions of the image, respectively.

3.9
modulation transfer function
MTF
plot of the *modulation* (3.8) transfer factor, M_{TF}, as a function of *spatial frequency* (3.13) *u*, for a sine-wave target

Note 1 to entry: M_{TF} is a measure of the transfer of modulation from the object to the image.

Note 2 to entry: Modulation transfer factor is given by

$$M_{TF}(u)=\frac{M(u)_{out}}{M(u)_{in}}$$

where $M(u)_{out}$ is the output modulation (i.e. the image modulation) and $M(u)_{in}$ is the input modulation (i.e. the target modulation).

Note 3 to entry: If the target has high contrast so that $M(u)_{in}$ is close to one, $M_{TF}(u)$ can be approximated by $M(u)_{out}$. On the other hand, M_{TF} curves are always normalized to 1 at zero frequency, which make a constant $M(u)_{in}$ negligible. The MTF of an endoscope can be obtained by measuring a series of sinusoidal targets with different spatial frequencies, or by other methods such as a slanted-edge target as discussed in 4.2.5.3.

3.10
off-axis limiting resolution
limiting resolution (3.5) at an image point at 70 % of the *maximum image height* (3.6)

Note 1 to entry: See Figure A.1.

3.11
on-axis limiting resolution
limiting resolution (3.5) at the image centre

Note 1 to entry: See Figure A.1.

3.12
optical resolution
numerical measure of the image quality of an optical system

3.13
spatial frequency
u
measure of how often a structure (e.g., sine-wave or square-wave bars) on the target or image repeats per unit distance or angle

Note 1 to entry: Spatial frequency has different units (e.g. lp/mm, lp/degree, lp/pixel), depending on whether the *target period* is measured in distance or angle units.

Note 2 to entry: The narrower definition of spatial frequency only refers to the sinusoidal components of the structure.

Note 3 to entry: The units of lp and cycles are often used interchangeably; in this standard, the unit of lp is used when referring to a square-wave or bar target (limiting resolution and CTF measurement), and cycles are used when referring to sine wave components (MTF) and to spatial frequencies in general.

3.14
working distance
d
design distance defined by the manufacturer between the object and distal end of the endoscope

Note 1 to entry: For the purposes of the test specified in this document the "object" will be the resolution target specified in 4.2.5.

4 Test method

4.1 General

Three characteristics of endoscope resolution are given in the method below. At least one characteristic should be measured. Table 1 may be used as a guide to determine the appropriate characteristic. See Annex A, B and C for acceptable test methods. Other methods of measuring the characteristics are allowed; if an alternative method is used, it shall be described in the test report.

Table 1 — Characteristics and measuring

Characteristic	Where Appropriate
A – Limiting resolution	A single-valued subjective metric for rapid manufacturing testing, quality assurance (e.g. in end of line endoscope assembly testing), or for providing a simple metric that can be easily understood by end users. See Annex A for information on the measurement procedure.
B – Contrast transfer function (CTF)	A multi-valued objective metric for device validation and verification. It is less scientifically sophisticated than MTF, but it is mathematically simple, can be easily understood by end users, and can be measured with a square-wave target that can be easily produced. Multiple target images are needed to obtain CTF measurements at different spatial frequencies. See Annex B for information on the measurement procedure.

Table 1 *(continued)*

Characteristic	Where Appropriate
C – Modulation transfer function (MTF)	A multi-valued objective metric where all values can be obtained from a single target; most used in engineering (e.g. design verification), diagnostic, and image evaluation purposes and serves as an umbrella function to derive other metrics (e.g. sharpness, acutance). It is widely used in scientific fields. See Annex C for information on the measurement procedure.

NOTE Annex E gives advice on the conversion of spatial frequencies. Annex G shows examples for relay optics.

4.2 Apparatus

4.2.1 Optical bench/optical rail, with mounting apparatus for endoscope and resolution target.

4.2.2 Coupling optics, to magnify a portion of the endoscope's field of view and image it onto the camera. Examples of coupling optics designed to meet the requirements of endoscope resolution measurement are discussed in Annex F. The coupling optics shall not change the measured limiting resolution significantly (Characteristic A only). The entrance pupil diameter of the coupling optics shall be larger than the exit pupil of the endoscope; the coupling optics shall not cut off rays of the endoscope. On-axis and off-axis measurement shall be made at the same focus.

NOTE The coupling optics still can have a significant influence on the result, because of coherent coupling between the coupling optics and the endoscope.

4.2.3 Camera, with monitor and means of digitally recording the relative intensity of each pixel. As described in D.4, the response of the system shall be maintained within the linear operating range of the camera (e.g. any sharpening or image enhancement is turned off, and gamma is set to 1,0).

NOTE If the camera cannot be set within the linear operating range, the intensity of a target image can be converted to linear intensity based on the opto-electric conversion function (OECF) of the camera. The camera OECF can be measured based on the ISO 14524.

4.2.4 Light source, white light, unless the endoscope is specifically designed for a specific wavelength, in which case this specific wavelength should be used.

NOTE It is acceptable to use a magnified image of a part of the endoscope's field of view containing the target, projected onto the test camera, to reduce the resolution requirements of the camera. Examples of coupling optics designed to meet the requirements of endoscope resolution measurement are discussed in Annex F.

4.2.5 Resolution target

4.2.5.1 Characteristic A: Resolution target, having adequately graduated black and white test patterns arranged at least in two directions, tangential and sagittal. Note that, for inclined direction of view endoscopes (endoscopes having a non-zero direction of view), tangential and sagittal are defined with respect to the direction of view. A resolution target consists exclusively of on-axis and off-axis test patterns arranged as in Figure A.1. Resolution test patterns consist of two transmittance or reflective values (Figure A.2). Alternatively, a single test pattern may be used if it is moved perpendicular to the optical axis to obtain off-axis measurements. It shall be ensured that the endoscope's resolution is determined and not the resolution of the target (see D.5).

4.2.5.2 Characteristic B: CTF target, having a black and white pattern that consists exclusively of two transmittance or reflectance values (Figure A.2). The surface of a reflectance target should be a Lambertian surface. The resolution target should contain on-axis and off-axis test patterns arranged as in Figure A.1. Alternatively, a single test pattern may be used if it is moved perpendicular to the optical axis to obtain off-axis measurements. It shall be ensured that the endoscope's resolution is determined and not the resolution of the target (see D.5).

4.2.5.3 Characteristic C: MTF target, having slanted edge, slit, or pinhole meeting the recommendations for edge roughness and contrast and corrected if necessary, as described in D.5. Either a crossed target or a means for rotating the target to two perpendicular orientations shall be provided.

5 Test report

Any test report resulting from following the test method described in Clause 4 shall contain at least the following details:

a) a reference to this document, i.e. ISO 8600-5:2020;

b) laboratory or company carrying out the test;

c) name of the testing engineer;

d) place and date of test;

e) standard used (e.g. ISO 15529, ISO 12233).

f) type of endoscope, manufacturer, model and serial numbers;

g) test characteristic used (A, B or C), including a reference to the clause which explains how the results were calculated;

NOTE Results will be different for each method.

h) description of alternative test method, if used, or deviations from the procedure

i) any unusual features observed

j) test targets used and, if off-axis target orientation is not according to Figure A.1, the target orientation used;

k) coupling optics used;

l) distance between target and distal end of endoscope;

m) light source used and light source spectral curve;

n) camera used and camera spectral response;

o) value of on-axis limiting resolution and angular limiting resolution (Characteristic A only) or on-axis CTF (Characteristic B only) or MTF (Characteristic C only). If Characteristic B (CTF) is reported, the measurement shall include at least the spatial frequency of 40 lp/maximum object height. If Characteristic C (MTF) is reported, the measurement shall include at least the spatial frequency of 40 cycles/maximum image height ;

p) single values and averaged value of off-axis limiting resolution and angular resolution (Characteristic A only) or off-axis CTF (Characteristic B only) or MTF (Characteristic C only). If Characteristic B (CTF) is reported, the measurement shall include at least the spatial frequency of 40 lp / maximum object height. If Characteristic C (MTF) is reported, the measurement shall include at least the spatial frequency of 40 cycles / maximum image height;

q) Criterion used for assessing best focus (e.g. maximize on-axis value, maximize average of on-axis and off-axis values, maximize lowest off-axis value, etc.);

r) if Characteristic C has been used: description of test target, equipment and procedure. If an edge-based target is used, the contrast shall be reported;

Annex A
(informative)

Measurement procedure for Characteristic A, limiting resolution

a) Mount the endoscope on the optical bench.

b) Attach the target to a diffusive plate and mount it on the optical bench at the working distance d. Align the target at an angle perpendicular to the endoscope's direction of view. Adjust the suitable test pattern on the target to the image points to be tested (see Figure A.1). The target should be uniformly illuminated from behind with a white LED backlight or similar spatially-uniform white light source. Front illumination is permissible only if the target surface is a Lambertian surface.

c) Attach the camera and coupling optics to the endoscope. Adjust the focus to maximize resolution.

d) Display the target image on the monitor or print it with a printer.

e) Determine the on-axis (point 'A' in Figure A.1) resolution of the endoscope in lp/mm in object space. The closest spacing resolution target group which can just be perceived shall be recorded.

f) Determine the off-axis resolution of the endoscope in lp/mm in object space. For this the image is to be divided into four congruent quadrants, each of them containing one image point to be tested (points 'B1' through 'B4' in Figure A.1). The limiting resolution is determined for all image points 'B1' through 'B4'. At each off-axis image point the resolution target group at all pattern directions which can just be perceived is recorded. The results at all off-axis image points are averaged and reported independently. If the resolution target patterns were arranged to measure sagittal and tangential resolution separately, then these measurements are independently averaged and reported.

g) Calculate the angular limiting resolution for both on-axis and off-axis image points.

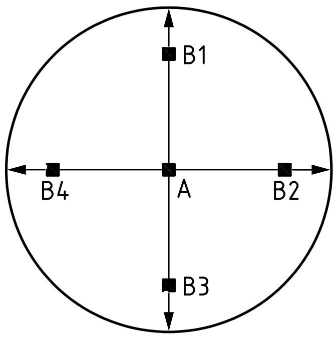

Figure A.1 — Image points to be tested for optical resolution (B1, B2, B3 and B4 are at 70 % of the maximum image height from the image centre A)

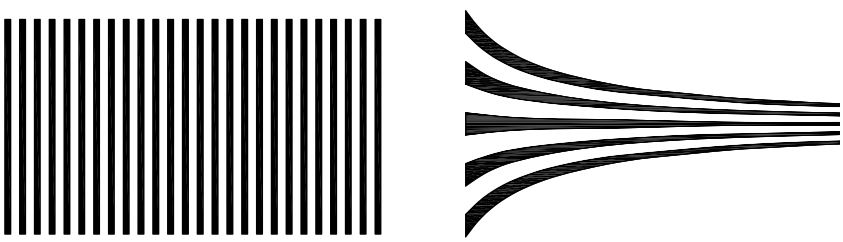

Figure A.2 — Typical limiting resolution and CTF test targets

Annex B
(informative)

Measurement procedure for Characteristic B, Contrast Transfer Function

a) Attach the coupling optics to the camera. Mount the endoscope to the camera/coupling optics on the optical bench.

b) Attach a bar target from the set of bar targets for the testing of the endoscope to a diffuse plate and mount it on the optical bench at the working distance of the endoscope. Align the bar target at an angle perpendicular to the endoscope's direction of view. Evenly illuminate the bar target from behind with a white LED backlight or similar spatially-uniform white light source. Front illumination is permissible only if the target surface is a Lambertian surface.

c) Adjust the focus to maximize resolution.

d) Digitally capture the camera image. If individual measurements are to be made with a small target moved to the correct field position, the target is moved in a plane perpendicular to the endoscope's direction of view and camera images are digitally captured for each off-axis field.

e) Calculate and record the on-axis (point ‘A’ in Figure A.1) contrast of the endoscope system ($C_{\text{on-axis}}$).

f) Calculate and record the off-axis (points ‘B1’ through ‘B4’ in Figure A.1) contrast of the endoscope system ($C_{\text{off-axis}}$). For this the image is to be divided into four congruent quadrants, each of them containing one image region to be tested. The $C_{\text{off-axis}}$ are calculated and recorded for all off-axis image points ‘B1’ through ‘B4’. The results at all off-axis image points are averaged and reported independently. If the resolution target patterns were arranged to measure sagittal and tangential resolution separately, then these measurements are independently averaged and reported.

g) Check that the combination of the camera and endoscope being tested meets the requirements for endoscope optical cutoff frequency described in D.3.

h) Repeat above steps for each bar target to measure $C_{\text{on-axis}}$ and $C_{\text{off-axis}}$ values at desired spatial frequencies.

Annex C
(informative)

Measurement procedure for Characteristic C, Modulation Transfer Function

a) Attach the coupling optics to the camera. Mount the endoscope to the camera/coupling optics on the optical bench.

b) Attach the target to a diffuse plate and mount it on the optical bench at the working distance of the endoscope. Align the target at an angle perpendicular to the endoscope's direction of view. Evenly illuminate the target from behind with a white LED backlight or similar spatially-uniform white light source. Front illumination is permissible only if the target surface is a Lambertian surface.

c) Adjust the focus to maximize resolution.

d) Adjust the system to bring the on-axis point (point 'A' in Figure A.1) onto the measurement area of the camera, and digitally capture the camera image.

e) Calculate and record the on-axis MTF of the endoscope ($MTF_{,on\text{-}axis}$).

f) Adjust the system to bring each of the off-axis points (points 'B1' through 'B4' in Figure A.1) onto the measurement area of the camera, and digitally capture the camera image for each of the points.

g) Calculate and record the off-axis MTF of the endoscope ($MTF_{,off\text{-}axis}$), for each of the off-axis points. The $MTF_{,off\text{-}axis}$ is calculated and recorded for all off-axis image points 'B1' through 'B4'.

h) The results at all off-axis image points are averaged and reported independently. If the resolution target patterns were arranged to measure sagittal and tangential resolution separately, then these measurements are independently averaged and reported.

i) Check that the combination of the camera/coupling optics and endoscope being tested meets the requirements described in D.4.

Annex D
(normative)

Contrast transfer function (CTF) and modulation transfer function (MTF)

D.1 Introduction to CTF and its application to endoscope measurement

CTF is relatively straightforward to measure from a captured image and gives quantitative information about the performance of the optical system. However, unlike MTF, the contrast measured on a two-tone bar chart is a complex function of the response of the optical system to many frequencies, at odd harmonics of the fundamental bar frequency. Therefore, the camera, endoscope and target shall meet certain conditions for the approximations used in the compensation for the camera's response to be accurate, and for the measurement of CTF to reflect the endoscope's visual performance.

D.1.1 Conditions for the application of CTF to endoscope measurement

The CTF measurement technique can be applied to endoscopes, provided that:

a) The conditions on the camera and coupling optics described in D.4 are applied.

b) The resolution (edge roughness of line or edge features) of the target used are sufficient as described in D.5.

c) The conditions on the endoscope optical cutoff frequency described in D.3 are satisfied.

d) The frequencies and field points measured include those that most affect the utility of endoscopes as typically used. The choice of off-axis field points at 70 % of the field of view is based on a distortionless system having equal area of the field inside of 70 % and the field outside of 70 % (~ $\sqrt{2}$ /2).

It is permissible, but not required, to use relay optics between the endoscope and the camera that magnify the endoscopic image, as described in Annex F, to ease the resolution requirements of the camera.

D.2 Introduction to MTF and its application to endoscope measurement

The basic definitions of MTF and related quantities are found in ISO 9334. This standard describes requirements that any optical system must meet in order for an MTF measurement to be possible. Two of these conditions are linearity and isoplanarity (invariance to image shifts), and ensuring that these conditions are met is important to obtaining repeatable results reflective of the optical performance of the endoscope.

Two types of MTF resolution measurement are possible with a system of endoscope, coupling optics and digital detector: Spatial Frequency Response (SFR, often called MTF, covered in ISO 12233:2017, Clause 6 only), and Modulation Transfer Function (MTF, covered in ISO 15529). The methods for making these measurements are well covered in the standards referenced below; the notes here contain additional applications information particular to endoscope measurement but are supplementary to the methods presented in those standards, except for the correction factor, *D*, discussed below in D.2.1. The measurement methods in ISO 12233 and ISO 15529, along with the endoscope-specific notes here, cannot cover all measurement cases. A very generic measurement description can be found in ISO 9335. The user shall ensure that the fundamental requirements for MTF measurement in ISO 9334 are met, and it is permissible to deviate from specific measurement requirements given here in order to do so, provided those deviations are noted in the test report.

D.2.1 Summary of ISO 12233 (SFR)

ISO 12233 specifies two types of SFR measurement, using two patterns: edge-based (e-SFR or "slanted edge") and sine-based (s-SFR). The s-SFR takes an image of a sine-wave target to calculate modulation at different spatial frequencies. Because of severe geometric distortion for most endoscopes, the SFR property might be significantly different at different locations of the sine-wave target image, which makes s-SFR improper to estimate a local SFR for endoscopes. Therefore, the e-SFR based on a slanted edge is recommended for endoscope SFR measurement. However, one should keep in mind that e-SFR is sensitive to several common conditions, as discussed below. The e-SFR measurement involves presentation of a test image to the system under test, where the feature being analysed is purposely not aligned to the pixel sampling, so many sampling phases are present and an oversampled image can be reconstructed.

Also, the calculation of e-SFR according to ISO 12233, describes a correction for the systematic error caused by the use of a finite difference to represent the derivative (ISO 12233:2017, Annex D). The correction is a result of using the difference between two samples spaced 1/2-pixel apart to represent the derivative of the line spread function, so in terms of the image plane frequency u_I (in cycles/pixel):

$$D(u_I) = \min\left[\frac{\eth u_I/2}{\sin(\eth u_I/2)}, 10\right]$$

As described below in D.3, in order for the measurement using e-SFR to be accurate, the image sampled by the sensor must not contain significant energy at or above the Nyquist frequency of the sampling. Thus, the maximum value of u_I of interest is 1/2, and the maximum value of correction factor $D(u_I)$ is D = 1,11.

This correction was first introduced in the previous edition of ISO 12233 (with the incorrect numerator and index *j* instead of *k*), and is only partially corrected in the last edition of ISO 12233 (the numerator is still incorrect), and for measurements made of MTF under this standard, this correction must be included, using the expression above.

The application of a specific subset of ISO 12233 to the endoscopes covered by this standard is described here. Specifically, this subset includes:

a) Measurements restricted to frequencies below the Nyquist frequency of the camera used times the magnification of the coupling optics.

b) Endoscope optical cutoff frequency also below the Nyquist frequency of the camera used times the magnification of the coupling optics.

D.2.2 Summary of ISO 15529 (MTF)

ISO 15529 describes a versatile set of measurements that can be made on a sampled data system and can be applied in general to endoscope/camera/display systems. A slit target is used (commonly implemented as a cross, so orthogonal components of MTF can be measured).

The application of a specific subset of ISO 15529 to the endoscopes covered by this document is described here. Specifically, this subset includes:

a) Measurements restricted to frequencies below the Nyquist frequency of the camera used times the magnification of the coupling optics.

b) Endoscope optical cutoff frequency also below the Nyquist frequency of the camera used times the magnification of the coupling optics.

D.2.3 Application of ISO 12233 or ISO 15529 to endoscopes

The 12233 (e-SFR) and ISO 15529:2010 (MTF) methods are in general applicable to endoscopes, provided that:

a) The conditions on the camera and coupling optics described in Annex F are applied.

b) The resolution (edge roughness of line or edge features) of the target used is sufficient as described in D.5.

c) The conditions on the endoscope optical cutoff frequency described in D.3 are satisfied.

d) For e-SFR, the correction factor for the finite difference, shall be applied, using the expression for $D(u_I)$ above; other corrections used (e.g., for rotation angle or actual pixel sampling aperture), shall be noted in the report.

e) The frequencies and field points measured include those that most affect the utility of endoscopes as typically used.

D.3 Endoscope optical cutoff frequency limitation

To meet condition c) in D.1.1 and D.2.1, and D.2.3, the spatial frequency corresponding to the camera pixel size, the Nyquist frequency (u_N, with the unit of cycles/mm), times the magnification of the coupling optics, shall be greater than or equal to the endoscope optical cutoff frequency (u_C, with the unit of cycles/mm) of the optics in the endoscope being measured:

$$M_{\text{coupler}} \cdot u_N = M_{\text{coupler}} \cdot \left(1/_{2P}\right) > u_C$$

where P is the pixel pitch of the camera with the unit of mm/pixel and $M_{coupler}$ is the magnification of the coupling optics. In this case, the system behaves as a non-sampled imaging system, the measured CTF is equal to the CTF of the combined endoscope/camera system, and the measured SFR is equal to the MTF of the combined endoscope/camera system. If the u_C is above this limit, CTF measurement and MTF measurement using the ISO 12233 measurement method are not applicable to that endoscope, and the ISO 15529:2010 measurements shall be made using the procedures in 5.3.2 to 5.3.4 of that standard.

To check that the camera system meets this requirement, it is sufficient to ensure that the measured SFR or MTF of the system (camera and endoscope), computed according to ISO 12233 or ISO 15529:2010, goes smoothly to near zero at a frequency below u_N.

D.4 Camera and coupling optics requirements

To meet the requirements of MTF and CTF measurement, the camera shall record the light intensity at the camera's image plane with good linearity and low noise. Image processing algorithms, including sharpness enhancement, noise reduction and colour processing, can affect the results when they are applied to images captured for processing into CTF or MTF measurements.

To obtain accurate measurements using either CTF or MTF measured using the ISO 12233 (SFR) or the ISO 15529:2010 (MTF) methods, the following conditions on the camera and coupling optics apply:

a) The camera used for these measurements shall be a monochromatic system. If necessary, separate filters for colour-weighted measurements may be used in the light source or elsewhere in the optical path.

b) Any image enhancement, lens correction or sharpening available in the camera software shall be disabled.

c) Raw images with minimum image processing (e.g. image compression) shall be used.

d) The camera response shall be linear (gamma correction disabled or set to 1,0), over the entire range of illumination covered by the target contrast. This may be ensured by different means, and it is up to the user to ensure that the camera responds linearly over the illumination levels present. ISO 14524 provides one method by which the OECF of a camera system may be measured, and data from measurement of stepped gray levels may be used to demonstrate the linearity of the camera system and the lack of clipping for both light and dark signals. Note that the use of high-contrast targets places larger demands on the linearity of the camera across a wider illumination range and should be avoided for e-SFR measurements done with slanted edge targets. Slit targets on the other hand should have highest possible contrast ratios, preferably higher than camera's dynamic range.

e) The response of the camera system shall not change with small shifts of the image and shall not combine information from different pixels to produce the image.

f) u_N times the magnification of the coupling optics, is greater than or equal to u_C of the endoscope being measured (Annex F).

g) The camera shall have adequate dynamic range to accurately resolve the contrast change at the edges in the image.

h) The coupling optics combined with the endoscope's aperture shall have MTF within 0,1 of diffraction limited, over the range of incident angles used, and the entrance pupil of the coupling optics shall be larger than the exit pupil of the endoscope at all field angle positions. (See Annex F for examples of coupling optics that meet this requirement).

D.5 Target requirements

If the target is printed without enough resolution, then the measurement of any of the three characteristics (limiting resolution, CTF and MTF) will be affected. To determine whether the target has sufficient resolution so that is can be safely ignored:

a) The target resolution is sufficient for visual assessment of Characteristic A if the image as viewed through the endoscope has no visible structure around sharp edges in the target, that follows the target when its image is moved slightly.

b) For Characteristic B (CTF), the target resolution is sufficient if a direct image of the target edges under magnification M (e.g., an image of sharp target features taken through a microscope), when processed directly, has a measured target C_{TF} close to 1,0 at the measurement frequency, u, divided by the magnification, M. If the target resolution is not sufficient, for CTF the results cannot be corrected and a higher resolution target must be used.

c) For Characteristic C (MTF), the target resolution is sufficient if a direct image of the target edges under magnification M (e.g. an image of sharp target features taken through a microscope), when processed directly, has a measured target M_{TF} close to 1,0 at the measurement frequency, u, divided by the magnification, M. If the measured target M_{TF} does not meet this requirement, the modulation transfer factor of the endoscope, $M_{TF,endocscope}$, can be corrected as follows:

$$M'_{TF,endoscope}(u) = \frac{M_{TF,endoscope}(u)}{M_{TF,target}(u/M)}$$

where $M_{TF,target}(u/M)$ is the modulation transfer factor of the direct image of the target under magnification M and $M'_{TF,endocscope}(u)$ is the corrected modulation transfer factor at spatial frequency, u.

For typical endoscopes, printed test targets (reflectance targets) might not be adequate, and targets such as chrome on glass (transmittance targets) are preferred. If a reflectance target is used, its resolution should be high enough and its surface shall be a Lambertian surface. All targets should be uniformly illuminated.

Summarizing the above, the target used to make the CTF measurement or SFR measurement using ISO 12233 shall meet the following requirements:

— The MTF of the target, when directly imaged with magnification M shall either have M_{TF} close to 1,0 at the highest measurement frequency divided by M, or the measured MTF of the endoscope shall be corrected at each frequency as described above in D.5 c).

— The target illumination shall be uniform across the image, and reflections and stray light in the test system shall be adequately controlled.

For SFR measurement, the target shall have a low enough contrast between black and white that the linear dynamic range of the camera is not exceeded.

