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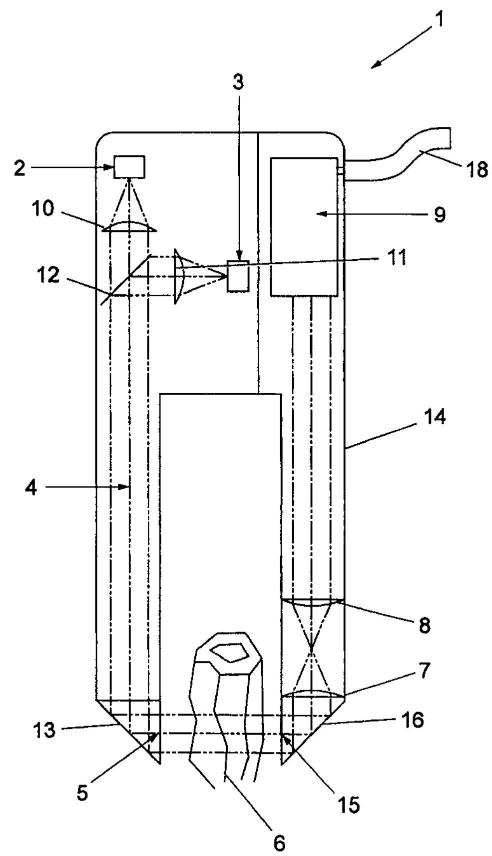
(54) Title: NON–INVASIVE DIAGNOSTIC METHOD AND APPARATUS

(57) Abstract

Two light sources (2, 3; 20, 22) of wavelenghts within the region 1.1 to 1.6 μm, modulated at the same frequency but in antiphase to each other, are transmitted through a tooth (6; 24). Transmitted light is measured by a detector (9; 26) provided with an electronic filter set (28) to pass only the modulated frequency signal corresponding to differences in absorption between the two wavelenghts. The differential absorption detection serves as a basis for caries detection. Scatter of the light in tissue is offset by the use of optical spatial filtering.



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Non-invasive diagnostic method and apparatus

This invention relates to a non-invasive diagnostic method and apparatus and in particular to a method of and apparatus for two-dimensional imaging by differential absorption detection.

Most particularly this invention relates to an infra-red imaging system which provides visualisation of hidden tooth structures for, for example, the detection and identification of dental hard tissue disease in dentistry and oral medicine.

Dental hard tissue decay or caries, although reduced by the modern use of fluorides in toothpastes or tablets and an intensive programme of dental health education, remains a major cause of tooth loss. The identification of caries at its extreme is through pain to the patient and a subsequent visit to the dentist. At this stage the disease is usually extensive and its cure requires substantial drilling and removal of both diseased and sound tissue (the latter to gain appropriate access to disease underlying enamel), before filling.

At a regular dental examination caries may be detected at a somewhat earlier stage by visual or more often mechanical means. The latter, basically probing with a pointed instrument, can find regions where overlying enamel has softened but not yet fully decomposed. It is less likely that detection will be possible when the site is at a point of contact or near contact between adjacent teeth. Unfortunately, since this region is the hardest to maintain free from lodged food particles, this is the most likely site for decay.

Earlier detection can be achieved with X-ray examination. This technique is, however, not straightforward when applied to caries detection since the discrimination levels are low and shadowing effects require both careful initial set-up and reasonably expert interpretation. Nevertheless the technique does provide for the earliest detection of caries and for detection at sites that are visually and mechanically hidden.

Various other techniques have been investigated at a research level. These include visible light transillumination and fluorescence detection. No device with imaging potential has been made available based on these techniques, a reflection of the difficulties of obtaining adequate discrimination or fluorescence site localisation.

Thus the earliest detection of dental disease is available through X-ray imaging. This has the disadvantage of requiring both very careful initial setting up and very careful interpretation. In addition, although dental X-ray images are taken at very low fluxes, the radiation is still, of course, ionising, and therefore carries a potential safety hazard.

It is an object of the present invention to provide a method and apparatus for imaging of dental tissue which overcomes the above disadvantages.

According to a first aspect of the present invention there is provided a method of two-dimensional imaging of tissue by differential absorption detection comprising the steps of transmitting radiation of two wavelengths through tissue, detecting transmitted radiation, measuring the absorption of said transmitted radiation, and comparing absorption of said two wavelengths.

Preferably the radiation has wavelengths of size sufficient to preclude scattering in tissue. The radiation is preferably infra-red light. More preferably the light comprises two wavelengths within the range 1.1 to 1.6 micrometres.

The first wavelength is preferably greater than 1.4 micrometres, most preferably within the range 1.4 to 1.5 micrometres, and may show a dominant change in transmission characteristics.

The second wavelength is preferably less than 1.4 micrometres, most preferably within the range 1.2 to 1.3 micrometres, and may act as a reference.

Preferably the two wavelengths are modulated at the same frequency. More preferably the two wavelengths are in antiphase.

The method may include detection of the transmitted radiation by optical means. Preferably the method includes the step of filtering out all transmitted radiation not at the modulated frequency.

The method may include the step of restricting detection to radiation transmitted in a substantially direct path through the tissue. Said restriction may be by optical spatial filtering.

Preferably the method is applied to the detection of dental caries. Alternatively the method is applied to distinguish between different dental structures such as enamel, dentine, root canals and pulp chambers.

Further according to the present invention there is provided an apparatus for differential absorption detection comprising two modulated light sources, each source producing light of a different wavelength, optic transmission means to train the light from said light sources to illuminate a first side of a tissue sample *in vivo,* and optic detection means to detect light transmitted through said tissue sample to a second side of said tissue sample.

Preferably the apparatus further includes means to combine the output of said sources to provide a single beam of incident light.

More preferably the optic detection means includes an electronic filter.

The apparatus may comprise means to spatially filter transmitted light.

Preferably the apparatus comprises means to display detected transmitted light as an image.

Further according to the present invention there is provided an apparatus for detection of dental caries and/or visualisation of dental structures by differential absorption detection comprising two modulated light sources, optic means to combine light from said sources to train a single beam on a first side of a tooth, receiving means on a second side of the tooth for receiving light transmitted through the tooth, an optic filter to spatially filter the transmitted light, and optic detection means to detect the spatially filtered light.

The apparatus may comprise means to display detected transmitted light as an image of the tooth. More preferably the apparatus comprises means to display the image in real time. The apparatus may comprise means to electronically enhance the image. The apparatus may comprise means to produce hard copies of said image.

Embodiments of the present invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a comparative graphic representation of transmission characteristics of light through healthy and decayed dental tissue;

Figure 2a is a schematic drawing of a laboratory arrangement of a differential absorption detection device in accordance with an aspect of the present invention;

Figure 2b is a schematic drawing of a laboratory arrangement of a differential absorption detection device in accordance with a further aspect of the present invention; and

Figure 3 is a schematic drawing of a differential absorption detection device in accordance with an aspect of the present invention.

Referring to the drawings, dental decay can give rise to significant changes in the transmission characteristics of light through enamel and dentine. These changes occur in a spectral region not previously investigated in the prior art and are substantial enough to provide the basis for the selective imaging of tooth decay.

These changes result from the breakdown of the inorganic structures associated with dental hard tissue, and their replacement with organic materials having a higher water content. This gives rise to significant changes in absorption as illustrated in Figure 1, in which line 40 shows the relative transmission of light through a sample of caries over a range of wavelengths, while line 42 shows the relative transmission of light through a sample of dentine over the same range.

For light having a wavelength of between 1000 and 1400nm, caries exhibits higher relative transmission, and hence lower absorption than dentine, while between 1400 and 1500nm, caries exhibits lower relative transmission. The crossover point 44 occurs at about 1400nm.

This change in absorption is, however, only one aspect of what is required to realise an effective image. Figure 1 refers to spectra recorded through relatively thin sections of teeth.

In practice there are substantial variations in:
(i) the thickness of teeth,
(ii) the thickness of various elements of a tooth such as the enamel and the dentine, and
(iii) the direction of light incident on the tooth from a given source point outside that tooth.

All of these variations act to disguise the smaller variations due to the presence of caries. Thus examining the tooth at a single wavelength only provides image detection of caries under the most favourable of circumstances.

This approach examines the difference in transmission between two wavelengths in the same region one of which shows the dominant changes due to caries, and the other of which acts as a less strongly affected reference.

From Figure 1 it is clear that these wavelengths are in the region 1.1 to 1.6 μm, and are most advantageously chosen to be between 1.4 and 1.5μm, and between 1.2 and 1.3μm.

However when detecting other tissue it may be found that the absorption characteristics of the tissue mean that other wavelengths are chosen. The important criterion in selecting the wavelengths is that the relative absorptions of the tissue to be detected and its surrounding tissue must be related such that the relationship at the first frequency is different from the relationship at the second frequency. In the present example the absorption of the caries tissue at the first frequency (1.3μm) is 50% greater than that of the dentine tissue, while at the second frequency

(1.44μm) it is 30% less.

The principle of differential detection of absorption is well known and documented as it applies to the detection of minor species in the presence of interfering absorbers. It is most often encountered in the laboratory and in commercial infra-red gas analyzers. Its application to two-dimensional imaging has not previously been investigated.

Figure 2 illustrates a laboratory arrangement used to demonstrate that a practical step in realising this differential absorption detection in a simple fashion is to modulate the two light sources at the same frequency but in antiphase to each other. Light Emitting Diodes (LEDs) 20 and 22, operating with relatively narrow bandwidths of several nm at wavelengths within the regions previously noted, are the preferred sources. Light transmitted through a sample 24 is viewed with a detector 26 provided with an electronic filter 28. This electronic filter 28 is set to pass only the modulated frequency and thus the detector 26 "sees" only the differential signal, that is the signal corresponding to differences in absorption between the two wavelengths. This approach provides the basis for caries detection.

The use of any optical wavelength, as opposed to an X-ray wavelength, has the added complication of the high level of light scattering in tissue. This scattering complicates the process of trying to retain detailed image information on objects buried within such scattering media. The longer wavelengths used in this method and device help to reduce the level of scatter but not to the point where even teeth become free of the problem.

Thus an additional feature of this invention is the inclusion of a means by which the effects of scatter can be significantly reduced. Specifically, the rays allowed to fall on the detector 28 are restricted to only those having direct or nearly direct paths through the sample 24 from the sources 20,22. This is accomplished through the use of appropriate optical spatial filtering 32 and a re-imaging lens 34. These rays, sometimes referred to as 'ballistic' rays, are those which pass through the sample 24 substantially unscattered and are therefore better able to preserve the information or the hidden detail associated, in this case, with differential absorption between caries and the surrounding sound tissue.

The laboratory arrangement of Figure 2b is used to observe details of carious lesions. The detector used is a CCD camera 30. This arrangement provides two dimensional imaging of the ballistic rays. The phrase "ballistic shadowgram" has been used to refer to this 2D image.

In summary, the use of a pair of wavelengths within a newly identified region, offering differing absorption characteristics between caries and sound tissue, provides a novel means for the detection of dental disease.

Figure 3 illustrates a practical embodiment of a device 1 incorporating this principle wherein two modulated light sources 2,3 at 1.25μm and 1.43μm provide simultaneous illumination of a tooth 6. The output from these sources 2,3 is substantially collimated by means of lenses 10, 11 and a transmitting mirror 12 and combined along a single axis.

The combined beams are transmitted along a first arm 4 of the device and reflected by a reflector 13 to an aperture 5 placed on one side of a tooth or teeth 6. A second arm 14 of the device has an aperture 15 which is disposed on the opposite side of the same tooth or teeth 6, and this second arm 14 contains lenses 7,8 and a reflector 16 such that a spatially filtered image of the tooth 6 is presented to a two-dimensional array detector 9. The image produced by the detector 9 is transmitted by cable 18 to a computer and/or visual display unit for display of the image.

The main features of this arrangement could be achieved equally well using fibre optic delivery for the source light, and image preserving fibre optic coupling for the detection path.

Equally the resulting image could be scanned in one dimension across a line array of detectors, or scanned in both directions across a single point detector. Such arrangements may be required since two dimensional array detectors at these wavelengths are slow and expensive.

Whatever approach is used to achieve a two dimensional image of the tooth or teeth, the resulting image is displayed, in real time, on the screen of a video monitor (not shown). The image may be subject to processing by software running on an associated computer or microprocessor (not shown) to electronically enhance the raw image, and means such as a printer may be provided for producing hard copies of images for maintaining patient records.

Since other variations in absorption occur in this spectral region, including differences between enamel and dentine, the technique may be extended to include visualisation of normal dental structures such as root canals and pulp chambers.

The embodiment described above offers significant advantages over currently available devices for the early detection of dental disease. Specifically it employs non-ionising radiation and its use is therefore intrinsically safer than the use of X-rays.

The device as described offers real time images through teeth combined with the availability of hard copies of those images. Finally the device is constructed from relatively inexpensive materials and processes resulting in a diagnostic offered at a much lower price than current X-ray machines.

Whilst the foregoing describes application of the invention to the examination of dental tissue, it is apparent that the invention is equally applicable to examination of other animal tissue structures.

Modifications and improvements may be made to the above without departing from the scope of the invention.

CLAIMS

1. A method of two-dimensional imaging of tissue by differential absorption detection comprising the steps of:

transmitting radiation of two wavelengths through tissue;

detecting transmitted radiation;

measuring the absorption of said transmitted radiation; and

comparing absorption of said two wavelengths.

2. A method as claimed in Claim 1 wherein the tissue is dental tissue.

3. A method as claimed in Claim 1 or Claim 2 wherein the tissue to be detected includes first and second tissue types having different relative transmission characteristics and wherein the first and second wavelengths are selected such that the relative transmission characteristics of the first and second tissue types at the first wavelength are significantly different from the relative transmission characteristics of the first and second tissue types at the second wavelength.

4. A method as claimed in Claim 3 wherein the relative transmission of the first tissue type is greater than the relative transmission of the second tissue type at the first wavelength and the relative transmission of the second tissue type is greater than the relative transmission of the

first tissue type at the second wavelength.

5. A method as claimed in any preceding claim wherein the radiation is non-ionising and has wavelengths of size sufficient to preclude scattering in tissue.

6. A method as claimed in any preceding claim wherein the radiation is infra-red light.

7. A method as claimed in Claim 6 wherein the light comprises two wavelengths within the range 1.1 to 1.6 micrometres.

8. A method as claimed in Claim 7 wherein a first wavelength is within the range 1.4 to 1.5 micrometres and shows a dominant change in transmission characteristics.

9. A method as claimed in Claim 7 or Claim 8 wherein a second wavelength is within the range 1.2 to 1.3 micrometres and acts as a reference.

10. A method as claimed in any preceding claim wherein the two wavelengths are modulated at the same frequency.

11. A method as claimed in any preceding claim wherein the two wavelengths are in antiphase.

12. A method as claimed in any preceding claim wherein detection of the transmitted radiation is by optical means.

13. A method as claimed in any of Claims 10 to 12 including the step of filtering out all

transmitted radiation not at the modulated frequency.

14. A method as claimed in any preceding claim including the step of restricting detection to radiation transmitted in a substantially direct path through the tissue.

15. A method as claimed in Claim 14 wherein detection is restricted by optical spatial filtering.

16. A method as claimed in any preceding claim applied to the detection of dental caries.

17. A method as claimed in any preceding claim applied to distinguish between different dental structures such as enamel, dentine, root canals and pulp chambers.

18. Apparatus for differential absorption detection comprising:

two modulated light sources, each source producing light of a different wavelength;

optic transmission means to train the light from said light sources to illuminate a first side of a tissue sample *in vivo;* and

optic detection means to detect light transmitted through said tissue sample to a second side of said tissue sample.

19. Apparatus as claimed in Claim 19 wherein said optic transmission means is adapted to combine the light from said sources to provide a single beam

of incident light on said tissue.

20. Apparatus as claimed in Claim 18 or Claim 19 wherein the optic detection means includes an electronic filter.

21. Apparatus as claimed in any of Claims 18 to 20 comprising means to spatially filter transmitted light.

22. Apparatus as claimed in any of Claims 18 to 20 comprising means to display detected transmitted light as an image.

23. Apparatus for detection of dental caries and/or visualisation of dental structures by differential absorption detection comprising:

two modulated light sources;

optic means to combine light from said sources to train a single beam on a first side of a tooth;

receiving means on a second side of the tooth for receiving light transmitted through the tooth;

an optic filter to spatially filter the transmitted light; and

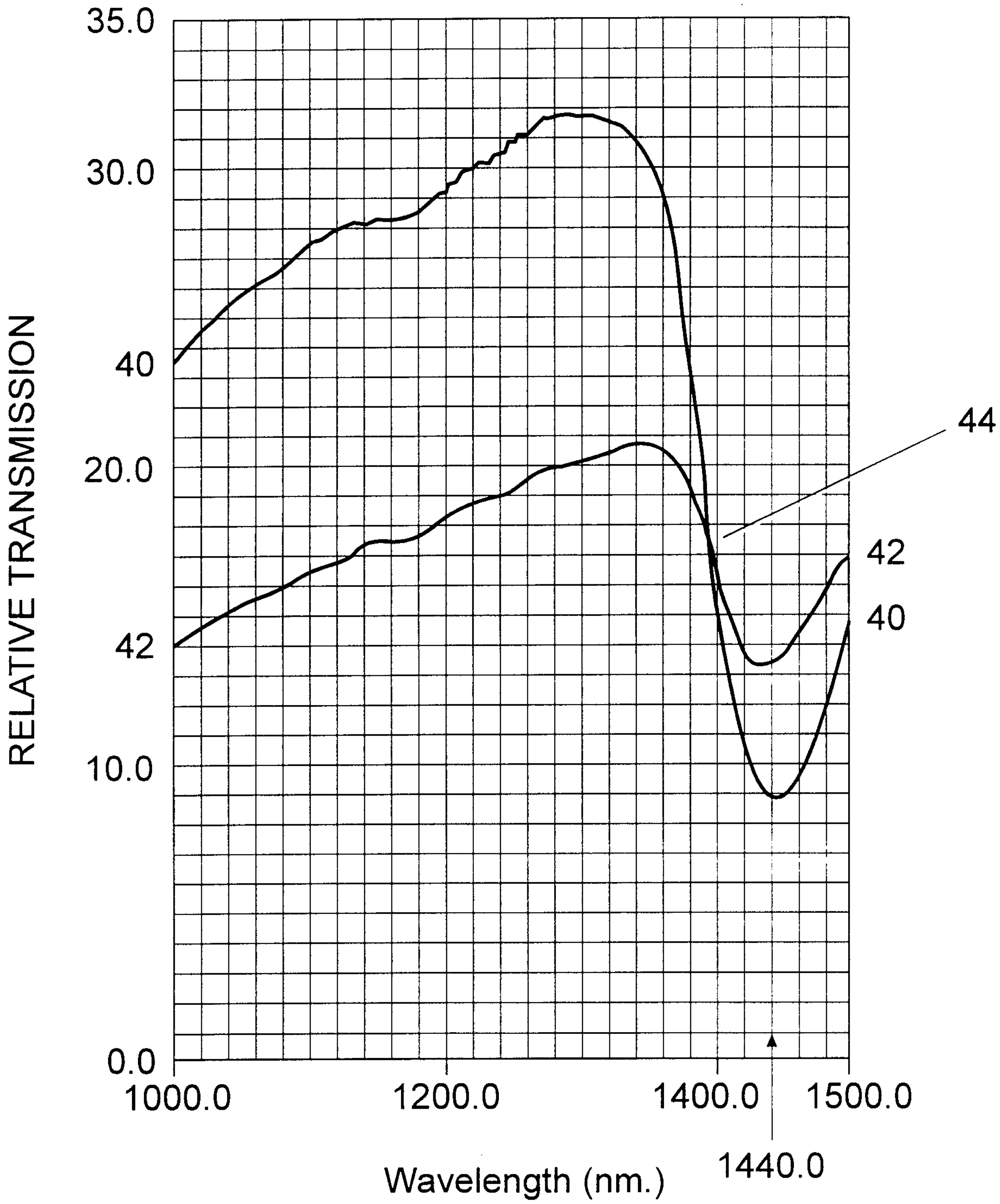
optic detection means to detect the spatially filtered light.

24. Apparatus as claimed in Claim 23 comprising means to display detected transmitted light as an image of the tooth.

25. Apparatus as claimed in Claim 24 comprising means to display the image in real time.

26. Apparatus as claimed in Claim 24 or Claim 25 comprising means to electronically enhance the image.

27. Apparatus as claimed in any of Claims 24 to 26 comprising means to produce hard copies of said image.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30.0
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20.0
42
10.0
0.0
RELATIVE TRANSMISSION
44
42
40
1000.0
1200.0
1400.0
1500.0
1440.0
Wavelength (nm.)

Fig. 1

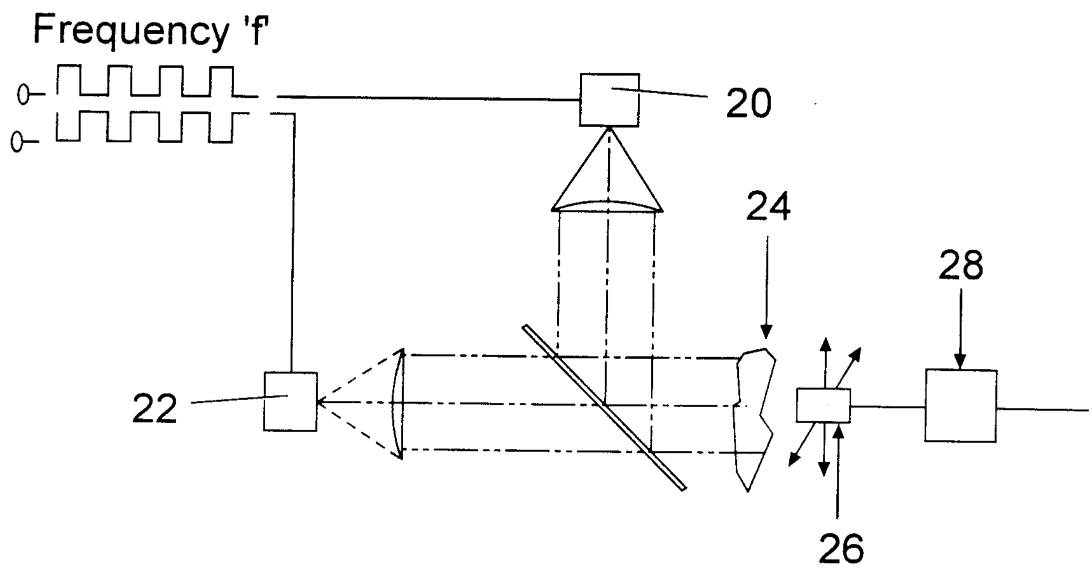

Fig. 2a

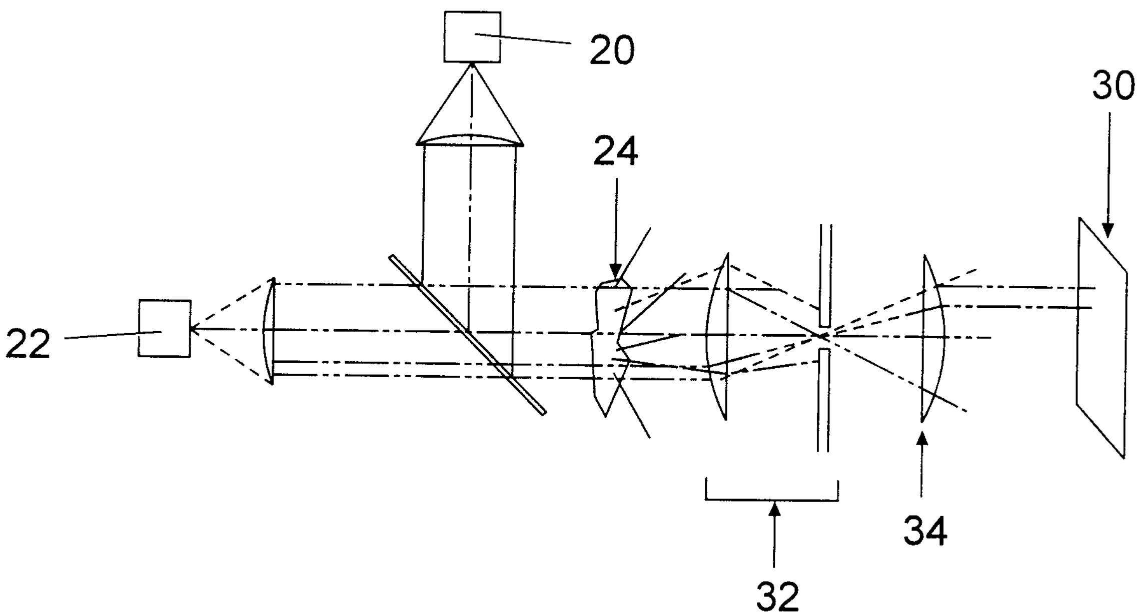

Fig. 2b

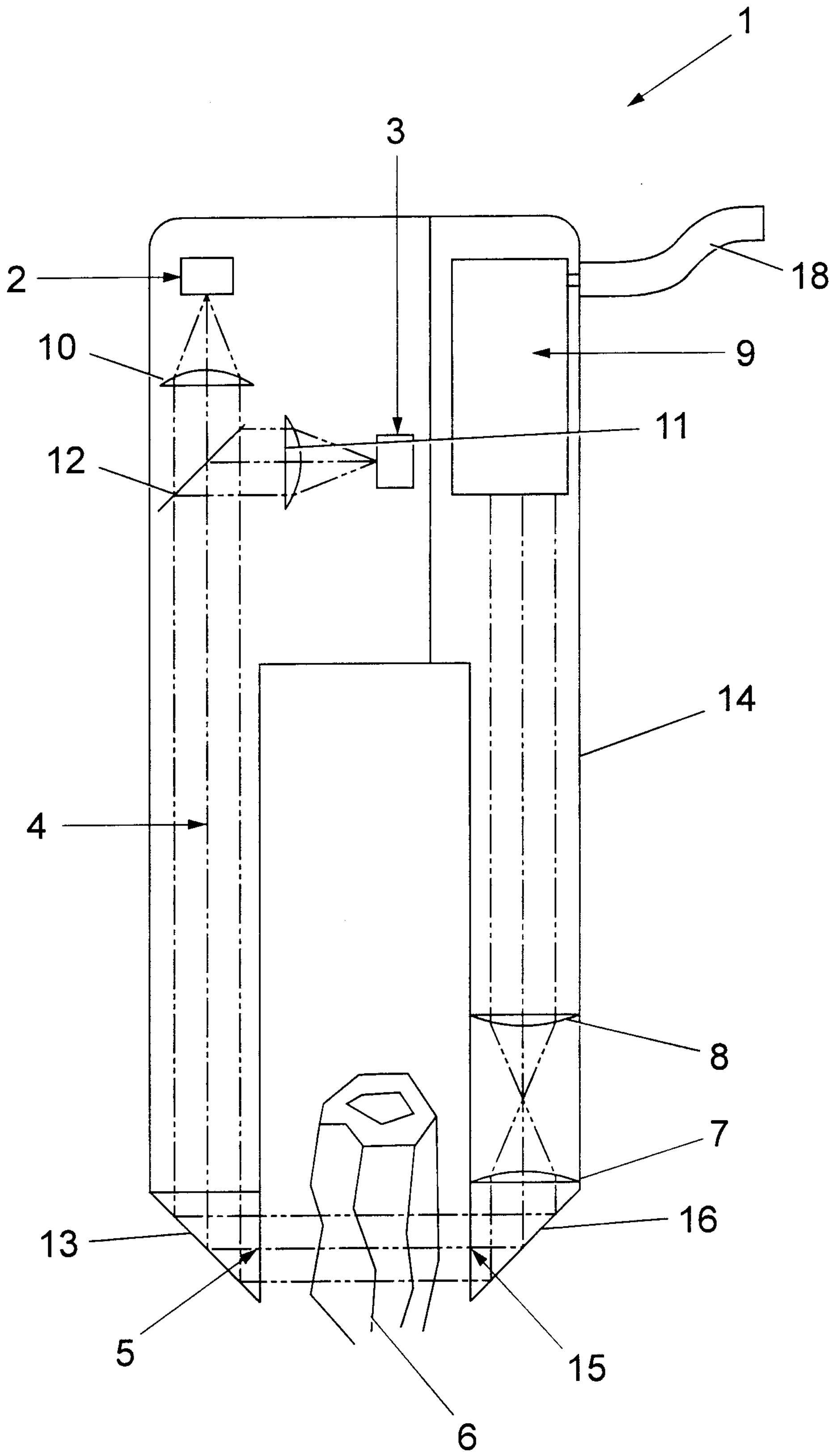

Fig. 3

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61B5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	see column 7, line 50 - column 9, line 17	17-19
A	see column 13, line 11 - line 20	23

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X	see column 4, line 4 - line 18	10-14
X	see column 8, line 58 - column 9, line 32	17-19,23
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A	see column 2, line 22 - line 63	9,12,14
A	see column 3, line 6 - line 36	16-19
A	see column 5, line 54 - column 7, line 57	22-25

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
4 September 1998	14/09/1998

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In ational Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	see column 4, line 25 - line 52	21-25
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1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Int ional Application No

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