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GUIDELINES

Guidelines for dosimetry and calibration in ultraviolet radiation therapy: a report of a British Photodermatology Group workshop

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Summary This report examines the dosimetry of ultraviolet (UV) radiation applied to dermatological treatments, and considers the definition of the radiation quantities and their measurement. Guidelines are offered for preferred measurement techniques and standard methods of dosimetry. The recommendations have been graded according to the American Joint Committee on Cancer classification of strength of recommendation and quality of evidence (summarized in Appendix 5).

Key words: dosimetry, guidelines, phototherapy, psoralen ultraviolet A, radiation, ultraviolet

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Disclaimer

These guidelines on recommendations for good practice have been prepared for medical physicists, dermatologists and phototherapists, following a Workshop meeting of the British Photodermatology Group. Caution should be exercised in interpreting the data; the results of future studies may require alteration of the conclusions or recommendations in this report. It may be necessary or desirable to depart from the guidelines in special circumstances. Just as adherence to guidelines may not constitute defence against a claim of negligence, so deviation from them should not necessarily be deemed negligent.

Optimal ultraviolet (UV) radiation therapy requires close control of the variables that may influence the clinical outcome. An essential part of control is the accurate measurement of these variables, in particular the spectral content of the UV sources employed, the UV energy applied to the patient's skin, and the psoralen administration [in psoralen UVA therapy (PUVA) therapy]. These variables are interlinked so that changing any one will lead to a change in clinical outcome, unless the others are also adjusted. These Workshop Guidelines address the importance of UV dosimetry and calibration in the delivery of effective phototherapy (used to describe both UVB and PUVA therapy, unless otherwise stated).

Background to ultraviolet radiation measurements for phototherapy

These guidelines presume that measurement and control of all therapy variables (not only UV radiation) are necessary for the safe and effective delivery of phototherapy. Variables that can influence outcomes are grouped into three main areas: (i) the UV irradiation equipment used to treat skin; (ii) the accuracy of measurements made and their practical application; and (iii) the human influences, including patient differences, treatment techniques and clinic management.

Ultraviolet irradiation equipment

An informal survey of phototherapy clinics in the U.K. and Republic of Ireland was conducted immediately prior to the workshop, to identify: (i) types of UV equipment in current use; (ii) measurement methods used to manage them; and (iii) test equipment used to make the measurements.

It is apparent that, since the survey[2] of Dootson *et al.* in 1993, unfiltered mercury discharge lamps have now been mostly replaced by fluorescent tube irradiators, and that broadband UVB lamps are being replaced by narrowband UVB types. Spectra of the commonest UV lamp types are given in Figure 1.

Ultraviolet radiation measurement equipment

The focus of this report concerns UV measurement in order to optimize therapy, including routine consistency checks of UV irradiation equipment and methods for measuring UV radiation in phototherapy units. Most phototherapy departments own or have access to a UV radiometer, usually hand-held, indicating a mean irradiance in mW cm^{-2} over some UV waveband.

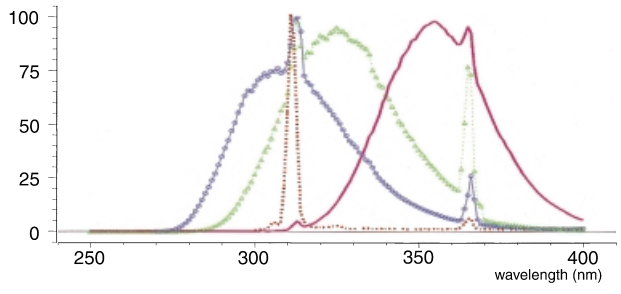

Figure 1. Spectral outputs of typical fluorescent ultraviolet (UV) therapy lamps: UVA; narrow-band TL-01; TL-12/Waldmann UV21; Waldmann UV6.

Several clinics surveyed had no meter, and relied on a manufacturer's engineer or a hospital physicist to measure irradiance. Some made no irradiance measurement, delivering treatments by exposure time only.

Those clinics with access to UV radiometers used different techniques to measure irradiance, at intervals varying from daily to annually. The pattern of UV radiometer calibration practice also showed wide variation, although a good quality meter in good condition should not require recalibration more frequently than annually. Unexpected measurement outcomes are usually the result of changes in the source (such as broken or dirty tubes and reflectors) or temperature changes. Meter malfunction is often due to failing batteries, intermittent connections or failure to configure the instrument correctly, especially where sensors, filters and diffusers can be interchanged, or a premeasurement 'zeroing' function is provided.

The irradiance of a UV therapy device measured with a hand-held meter depends upon the type of lamps fitted to the device and the calibration standard used. The device may have a UV radiometer built-in, which may be calibrated to a different standard, but which may not be readily adjustable. The international[3] and other standards in use, given in Table 1, are confusing, resulting in poor correlation between irradiance values where the calibration definitions are different or unknown. The wide range of published minimal erythemal dose (MED) values for narrow-band (TL-01) UVB radiation suggests that there are difficulties in measuring irradiance accurately, and in defining and determining MED.

Diffey's review[4] of ultraviolet dosimetry published in 1978 noted that the term 'irradiance' has been used to describe the UV intensity over all emitted wavelengths (100–400 nm), or within a restricted band (315–400 nm, for example), or 'weighted' by an action spectrum (where this is known) resulting in different numerical values for the same radiation. It is recommended that a standard definition be used for all UV radiation measurements (see Appendix 3).

Table 1. The ultraviolet (UV) radiation spectrum lies between wavelengths of 100 nm and 400 nm, by international agreement. The Commission Internationale de l'Eclairage (CIE) adopted[3] the following general definitions

Band	CIE definition	Alternative definitions in use
UVA	315–400 nm	320–400/320–410 nm
UVB	280–315 nm	280–320/290–320 nm
UVC	200–280 nm	150–280/100–280 nm

Wavelengths shorter than about 200 nm propagate only in a vacuum and are not relevant to phototherapy.

MacKenzie's review[5] of UV dosimetry in 1985 identified the factors influencing UV irradiance values, emphasizing the importance of differentiating between measurements made to demonstrate consistency or repeatability (which need not be calibrated) and those made to establish absolute values (which must be calibrated).

Factors influencing measured ultraviolet outputs from irradiation equipment

The variety of shape, size and lamp geometry of typical UV irradiation equipment implies that no single measurement method will provide a meaningful irradiance value at the patient's skin surface, which is itself not a unique value in most practical situations.

On a small panel irradiator, designed for treating palmar and plantar skin, the source–skin distance is defined by the contact glass or grille, so measurements should also be made in contact with the same surface. The value varies across the plane of the contact surface, being maximal near the centre of the panel and less towards the edges. Hands and feet usually occupy an area that includes this maximum value, but may also cover areas of reduced irradiance. It is recommended that the maximal value be used for exposure calculation, to avoid 'hot-spots' from areas that exceed the mean.

The situation is more complex for larger panels designed to treat the whole body, requiring the patient to stand in front of a lamp array. Maximum irradiance is on the skin closest to the lamp array, around the centre of the lamp length (waist height for typical patients). Irradiance on the patient's skin facing away from the array will be zero, so that uniform treatment requires rotation of the patient, and careful attention to posture and exposure times, to avoid risk of underdosing or overdosing. To minimize these risks and radiation hazards to others, it is recommended that whole-body treatments be given in enclosed cabins wherever possible.

In whole body treatment cabins, 1800-mm long fluorescent lamps line the walls, usually in front of reflective metal surfaces, surrounding the patient with radiating elements. This improves dose uniformity, but 'sanctuary sites' can still occur if the patient remains in a fixed posture with arms close to the body. The patient is not uniformly cylindrical and the intensity of the lamps is lower near the ends, so the body-surface irradiance is not a single value.

Whole-body cabin measurement methods

Two measurement methods are in common use, requiring either a cabin occupant to hold the meter, or a support on which the meter is mounted.

The Direct Method (with a cabin occupant)

A measurement protocol proposed by Moseley *et al.*[6] and summarized by Diffey and Hart[7] requires several measurements with a hand-held meter to be taken on the surface of a protected cabin occupant, at the levels of the head or shoulders, waist and knees. This is repeated for several orientations within the cabin, and the mean of all of these values is taken to be the skin irradiance. This assumes that the treatment's effectiveness is dependent only upon the quantity of energy incident on the patient's skin, and not on the rate of delivery. This reciprocity relationship has been established[8] for UV radiation on human skin over several orders of magnitude.

Alternative protocols use a simpler waist-height measurement for several orientations within the cabin to obtain a maximum value of the irradiance. This protocol gives a slightly higher value than that obtained by the previously described protocol, but reduces the risk of localized overdosing, by avoiding 'hot-spots' around the buttocks and genitalia where the irradiance exceeds the mean value.

For any whole-body treatment cabin, the skin irradiance is dependent upon the geometry of the cabin and reflectors, and the number and arrangement of the lamps inside. These influences have been described[9,10] and attempts made[11] to develop a mathematical model to calculate patient irradiance from a knowledge of the cabin characteristics.

The Indirect Method (without cabin occupant)

It is preferable to measure irradiance without entering a cabin during operation, particularly for UVB lamps. The absence of an occupant, however, significantly increases[10] the measured irradiance (by about 20%, depending on the cabin design), because of multiple internal reflections.

Moseley's protocol gives correction factors for some popular cabin designs, to enable empty cabin measurements to be converted into skin irradiance values. The factor may be readily determined for any cabin by measuring irradiance on a protected occupant and

then in the empty cabin, with the meter in the same location(s), and calculating the ratio of the values. The factor should be verified periodically (annually is adequate) to take account of changes in the optical properties of the cabin components.

An alternative method of obtaining a Direct Method value, but without risking exposure to a cabin occupant, has been described by Fulljames and Welsh,[12] employing a simple phantom cabin occupant constructed of readily available materials. The meter sensor is mounted on the phantom in the same locations defined by Moseley, giving irradiance values within ± 5% of typical occupant values. Currie *et al.*[13] described a computer-controlled and motorized device to measure indirect irradiances automatically.

Note that the irradiance of canopies and panel units is not affected by the presence of the patient, as the radiation does not experience multiple reflections. The mean irradiance over an extended area is usually significantly less than the peak irradiance near the centre of the lamp array, so it is recommended that the highest value be used for exposure calculations, as for extremities units (above), to reduce localized overdosing.

Influences on irradiance values

Irradiances from UV therapy equipment are generally not constant. Mechanisms that can change the measured value over a treatment course include: (i) intermittent or total failure of one or more lamps; (ii) supply voltage variation (the control circuits are not regulated); (iii) intensity diminution with rising lamp operating time; (iv) dirt on lamps/reflectors or damage to reflective surfaces; and (v) temperature changes. This last is a common cause of short-term differences in irradiance, as the emission of fluorescent phosphors is strongly temperature dependent. Lamps will be cold after 15 min inactivity, and can overheat if poorly ventilated or operated in hot environments, both leading to changes in irradiance. To minimize this effect, the manufacturer's advice on ventilation and lamp warming should be followed, particularly at the beginning of a treatment session.

Built-in cabin dosimetry

To compensate for the uncontrolled effects on irradiance described above, cabins may be equipped with built-in UV dosimeters, to monitor the irradiance throughout treatment and terminate exposure after a set dose has been accumulated. This can result in more accurate dose delivery, but only if the built-in metering device closely matches Direct Method measurements made with a calibrated meter.

Users should not assume that the dose displayed on the cabin's control panel is correct, or that the cabin does not require regular performance checking. Some built-in meter devices may indicate irradiances different from those obtained directly. Measurement devices cannot be assumed to perform consistently over many years' use, especially those frequently irradiated with UV, which degrades optical and electronic components.

Any built-in device should be checked for correlation with direct body-surface measurements. If there is significant (> 10%) disagreement, the built-in dosimeter should be adjusted, or the cabin can be operated in time-exposure mode, using irradiance values obtained by the Direct or Indirect Methods described above. It is preferable to adjust built-in meter circuits to agree with a defined dosimetry standard, especially where more than one cabin may be used for successive treatments of a patient. If a correction factor is to be applied, it is probably safer to apply it to the cumulative dose at the conclusion of a treatment course, rather than at every dose calculation, which may lead to arithmetic errors.

Ultraviolet radiometry instruments

Most UV measurement devices are based on photodiode sensors having electrical characteristics varying with the radiation intensity falling on their active surfaces. For accurate and consistent performance, a meter should have adequate sensitivity to its designed spectral band but negligible sensitivity outside that band, linear operation over a useful range of irradiance values, and adequate sensitivity to radiation at all practical incident angles. Other features that may improve the flexibility and convenience of a meter, including angular response,[14] are discussed in Appendix 1.

Patient-related variables

Each patient presents a different set of skin characteristics, dependent on the skin disorder, skin type and personal life-style. These guidelines make no attempt to differentiate between different treatment protocols for all of these variables, as they are outside the scope of UV dosimetry considerations. The patient's skin type, however, does have a bearing on dosimetry, as this

parameter is related to the patient's skin sensitivity and is often used to determine prescribed doses. A study[14] by Gordon *et al*. of MED measurement prior to narrow-band UVB therapy showed that skin-type assessment (a subjective value) is not always a useful predictor of erythema sensitivity obtained from testing (an objective value).

The estimation of MED [minimal phototoxic dose (MPD) in PUVA therapy] is a valuable guide to sensitivity but is not measured and reported uniformly. This subject is beyond the remit of this report, but patients' cutaneous responses to UV radiation exposure provide additional information that can inform routine radiometry practices. When skin sensitivity tests are performed and their results given in clinical reports, it is important to define all the relevant parameters and the judgement criteria. A suggested format for defining an MED/MPD test is given in Appendix 2.

Except for the photodermatoses, usually provoked by suberythemal doses, erythema defines the upper limit for most UV phototherapy treatments. The erythema action spectrum for UV is therefore critical in determining the maximum dose without causing pain or burning. A proposal[16] to incorporate human skin erythemal response into UV dosimetry, by using a weighted radiometric unit, makes weighted irradiances in the UVB region numerically larger than similar intensities of UVA, which are less erythemogenic. The weighting curve for erythema in human skin has been formalized as simple mathematical functions and applied in a Commission Internationale de l'Eclairage standard.[17] The pattern of the majority of published values, however, and the recommendation of these guidelines, is that unweighted doses in SI radiometric units of J cm^{-2} (or derived units) should be used.

Defining the irradiance of broad-band UVB fluorescent lamps is particularly difficult. The peak output of these lamps falls near the boundary between UVA and UVB, so that minor changes in band width definition cause significant changes in apparent irradiance. This problem does not arise to the same extent for UVA lamps and narrow-band TL-01 lamps (Table 2).

To avoid false comparisons between irradiances defined under different calibration standards, it is recommended that spectroradiometric calibrations should include a value for the total irradiance of the source over the entire UV band from 250 to 400 nm. Other band widths may be used to match an existing meter calibration, but if the 250–400 nm value is always included in a specification of UV radiation, the differences in preferred band width become irrelevant, allowing the comparison of irradiance data from different workers.

For example, a cabin fitted with Philips TL-12 (or equivalent) fluorescent lamps might be described as having an irradiance at the skin surface of 4·5 mW cm^{-2} (UVB band defined as 280–315 nm) or 8·8 mW cm^{-2} over the whole UV band (250–400 nm). Another worker may state the irradiance of these lamps to be 5·4 mW cm^{-2} (UVB band defined as 280–320 nm) but would still find the total UV irradiance of 8·8 mW cm^{-2}.

The data in Table 2 include relative irradiance values for various band widths and the total UV band width for commonly used UV lamps, to permit this full-width irradiance to be derived, provided the lamp type and the calibrated irradiance are known.

A suggested form of defining the calibration method and traceability for UV radiometers is given in Appendix 3. The calibration laboratories identified in Appendix 4 are able to provide this total band irradiance as part of a meter calibration report. These laboratories have also agreed to collaborate with national standards agencies to align and rationalize UV calibration, to be the subject of further investigations.

Phototherapy is potentially hazardous, and successful phototherapy requires some clinical, nursing, physics and technical knowledge for optimum outcomes. The increase in published clinical trials and research into fundamental aspects of phototherapy have allowed this discipline to be practised more safely and effectively, with treatment protocols and practices that are evidence based. More needs to be done, however, to move away from clinical practice based on anecdote. UV dosimetry and calibration form a part

Table 2. Partial and total irradiances for commonly used ultraviolet (UV) lamps, normalized to 250–400 nm band width

Lamp type	280–315 nm	280–320 nm	315–400 nm	320–400 nm	320–410 nm	250–400 nm
Waldmann UV6	0·23	0·33	0·77	0·67	0·72	1·00
Waldmann UV21	0·51	0·61	0·48	0·39	0·43	1·00
Philips TL-01	0·77	0·80	0·23	0·20	0·25	1·00
Waldmann UVA	0·004	0·008	0·99	0·98	1·02	1·00
Cosmolux UVA	0·008	0·02	0·99	0·98	1·01	1·00
Arimed B	0·04	0·08	0·96	0·92	0·96	1·00

of this process, and should be considered in the context of consistent and repeatable practice and adherence to written local rules and instructions. The recommendations given here are based on the cumulative experiences of the medical physics departments and phototherapists represented by the workshop contributors, and are offered as current best practices.

Recommendations and guidelines

1 Whole-body treatments should be given in ventilated cabins surrounding the patient with radiation sources wherever possible, and it is recommended that obsolete apparatus be replaced. (American Joint Committee on Cancer classification: BIII)

2 Phototherapy clinics should use a UV radiometer to measure irradiances from all UV treatment equipment. The meter should have minimal response outside the UV band and be chosen for dynamic range, linearity and angular sensitivity. (BIII)

3 The meter should be calibrated annually for each type of UV source in use, identifying the method, its traceability to known national standards and the waveband over which irradiance is measured. Irradiance over the full UV band of 250–400 nm should also be measured, in addition to any other band width, to facilitate intercomparisons. (BIII)

4 Built-in UV dosimeters in cabins should agree closely with directly measured irradiance values. Where agreement is outside reasonable tolerance (± 10%), the built-in meter may need adjusting. The supplier or the person responsible for the equipment should be consulted for advice. (BIII)

5 Electrical equipment should be tested for compliance with electrical safety standards, and staff should be trained to operate the equipment correctly. Annual checks are acceptable, and written records should be kept. (BIII)

6 Regular consistency checks of all UV irradiation apparatus should be performed, by checking for failed lamps and measuring UV irradiance in a standard reference location to identify any changes. Failed lamps should be replaced promptly, and consistency verified at least monthly. (BIII)

7 Skin irradiances should be measured regularly by the Direct or Indirect Methods, and used to calculate exposure times and to check built-in meters. Measurement every 25–50 h of usage is acceptable, but after installing new lamps, which degrade more quickly when new, re-measure after 10–15 h. (BIII)

8 Patient doses should be prescribed in J cm^{-2} (or derived units), and cumulative doses calculated and recorded at the end of treatment courses, to quantify lifetime exposure to therapeutic UV. (BII-i)

9 MED/MPD techniques should be described fully, including the site(s) of test(s), the criteria used to assess erythema, the methodology of masking and exposing test sites, including any devices used for this, and the sequence of doses used (or the ratio between adjacent exposures). (BII-iii)

10 The recommendations in this report should be subject to routine audit, as part of the clinic's audit programme, to verify that objectives are being met, and to optimize clinical outcomes.

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Appendix 1

Ultraviolet radiometer characteristics

UV radiometers mostly employ photodiodes sensitive to wavelengths from about 300 nm up to about 1000 nm. Wavelengths outside the UV bands are removed by filters, reducing unwanted spectral components, although not with a sharp cut-off. Some proportion of unwanted radiation may therefore be included in the measured radiation.

The meter should have a dynamic range appropriate for therapy sources (0·05–50 mW cm^{-2} is adequate) and should be linear (< 2%) in that range. The meter should also respond accurately to radiation independently of its angle of incidence on the sensor (< 5% deviation from true cosine weighting).

Spectroradiometers are widely used as references for the calibration of hand-held meters. The spectra in Figure 1 were obtained from typical fluorescent UV phototherapy lamps using a spectroradiometer. The irradiance of a source is represented by the area beneath the spectral irradiance curve, so the irradiance over any chosen bandwidth is represented by the area beneath the curve in that band, permitting calibration of UV radiometers to any standard.

Hand-held meters and built-in cabin dosimeters should be calibrated regularly, by comparison with a spectroradiometer or UV radiometer with calibration traceable to recognized standards. Appendix 4 gives contact details of medical physics laboratories in the U.K. and Republic of Ireland Ireland willing to perform calibration of meters against standard UV lamp types commonly in use in phototherapy clinics.

Ultraviolet radiometer sensor characteristics

Manufacturers are encouraged to design better meter sensors and to minimize the angular sensitivity errors. The ideal sensor will have an optical diffuser that avoids specular reflection from polished flat surfaces, and accurate angular sensitivity at all incident angles.

A sensor should indicate irradiance values proportional to the cosine of the angle of incidence of the radiation. In practice, sensors often indicate significantly less than this value at angles of incidence greater than about 45° from the normal, and therefore underestimate the wide radiation field in a whole-body cabin, which arrives at a waist-height meter from nearly all angles. Inadequate angular response is identified as one of the causes of metering error.

Martin and Pye[18,19] studied the angular response of several popular UV sensors, and found that they underestimated irradiances at angles greater than about 30°. Sensors having convex or protruding diffusers usually perform better than those without a diffuser or having optical components recessed within the casing.

A UV radiometer must be calibrated for every type of UV source to be measured, typically UVA, broadband and narrowband UVB fluorescent tubes. If mercury discharge or metal halide lamps are also employed, these must also have separate calibration factors, as their spectral outputs are different from those of fluorescent tubes.

Appendix 2

Suggested form of minimal erythemal dose/ minimal phototoxic dose definition in clinical study reports

Terms in *italics* represent variables that should be modified to match the local technique employed. Each term should be identified so that all relevant details are clearly defined.

'Patient minimal erythemal dose (MED) values were determined by a sequence of *eight* trial exposures made on normal skin on *the buttocks*, using UV radiation from *a flat array of six 600 mm long fluorescent lamps (Philips TL-01)*, spectrally identical to the lamps used for

treatment. A *thin opaque flexible plastic* template with *eight square* apertures *1 cm square* was placed directly in contact with the skin, and each exposure was *in a ratio of √2 (1.41) to the next* in the sequence. Erythema was judged in bright indoor lighting conditions by eye after 24 hours. The MED was taken to be the dose given to the aperture showing just perceptible erythema, with no erythema visible on the adjacent lower dose aperture. The irradiance of the test source was determined at the test distance using a meter calibrated against the lamp type being used.'

Appendix 3

Suggested form of ultraviolet calibration definition in clinical study reports

Terms in *italics* represent variables that should be modified to match the local technique employed. Each term should be identified so that all relevant details are clearly defined.

'The irradiance of the UV cabin(s) used for treatment (*manufacturer and type*) was measured directly by body surface measurements on a protected occupant of average height and build, at *shoulder, waist and knee height*, while the occupant faced each of the *four* main arrays of lamps in sequence. The *maximum/mean* of these readings was taken as the patient's skin irradiance, and used to calculate exposure times (*or was compared with the value indicated by the automatic dosemeter in the cabin control, and a correction factor derived*). The meter used for all measurements was calibrated against the lamp type used, by comparison with a *spectroradiometer measurement* of the irradiance over the wavelength intervals *280–315 nm and 250–400 nm*. The *spectroradiometer* calibration is traceable to national standards.'

Appendix 4

Contact details of medical physics departments in the U.K. and Ireland able to calibrate ultraviolet radiometers

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Appendix 5

American Joint Committee on Cancer classification of strength of recommendation and quality of evidence.

A There is good evidence to support the use of the procedure.

B There is fair evidence to support the use of the procedure.

C There is poor evidence to support the use of the procedure.

D There is fair evidence to support the rejection of the use of the procedure.

E There is good evidence to support the rejection of the use of the procedure

I Evidence obtained from at least one properly designed, randomized control trial.

II-i Evidence obtained from well-designed control trials without randomization.

II-ii Evidence obtained from well-designed cohort or case–control analytical studies, preferably from more than one centre or research group.

II-iii Evidence obtained from multiple time series with or without the intervention. Dramatic results in uncontrolled experiments (e.g. the results of the introduction of penicillin treatment in the 1940s) could also be regarded as this type of evidence.

III Opinions of respected authorities based on clinical experience, descriptive studies or reports of expert committees.

IV Evidence inadequate owing to problems of methodology (e.g. sample size, or length or comprehensiveness of follow-up, or conflicts in evidence).