Part One

Laboratory Experiments in Medical Physics

Introduction

1. Laboratory Objectives.

The laboratory is the workshop of the student，the place where he gets a firsthand knowledge of physical principles and experimental methods through the handling of apparatus designed to demonstrate the meaning and application of these principles. Some of the more specific objectives are：（1）to acquire training in scientific methods of observation and recording of data；（2）to acquire techniques in the handling and adjustment of equipment；（3）to get an understanding of the limitation and strengths of experimentation；（4）to obtain experience in the use of graphical representation；and （5）to take data，and develop confidence in one's ability to compute reliable answers，or determine valid relationships. When one develops the skill of computing answers from experimental data which check with known values of the desired quantities，he acquires the confidence needed to perform an experiment and determine some quantity or relationship which was previously not known to anyone.

2. Development of character and Sense of Responsibility.

The physics instructor makes his evaluation of these traits such as character、attitude，honesty and dependability of students from observations of the student's performance in class and in the laboratory. The laboratory is a place for serious thought and investigations，and the following suggestions should help you to develop the above mentioned traits.

a. Be prompt in arriving at your station of work and be well prepared concerning the principles of the experiment. If，for some good reason，you are late or absent，report the matter to the instructor.

b. Work quietly and attempt to make the most careful observations possible by adjusting the equipment so it will give its best possible performance.

c. Be honest in making and recording observations. Record data as indicated by your equipment and not as you thought it was supposed to be，if they differ. If your

results seem to be outside the limits predicted by the experimental uncertainties，recheck your measurements and computations. If this does not give the answer，make the best possible explanation for the discrepancy.

d. Have the entire procedure well in mind and perform the various steps in the order that will make the best use of your time. Cooperate with your partner in such a way that each of you gets experience in manipulating the equipment. Then each of you computes your results independently so as to check on the accuracy of your work.

e. Always remain at your assigned station and do not disturb other people in the class concerning any part of the experiment. Do not disturb other equipment that may be in the room but not a part of your present experiment.

f. Always abide by any precautions that your instructor may have given you regarding the proper handling of the equipment. Delicate equipment may be easily damaged.

3. Preparation for the Actual Laboratory Work.

The efficiency of performance in the laboratory depends largely on the preparation made before the experimental work begins. This preparation may consist of a careful individual study of the principles involved and a general idea of the procedure to be followed，or，your instructor may give a lecture on the experiment. In the lecture period which may，or may not，immediately precede the laboratory work，the instructor will state the purpose of the experiment，discuss the underlying theory in the "Introduction" section，and outline the experimental approach for obtaining the necessary data. He may also suggest techniques that should be used to get the best performance from the apparatus. The details of how to perform the experiment will be found in the "Procedure" section.

4. Checking Out Apparatus.

A list of apparatus is given with each experiment，and the items listed as special apparatus will usually be checked out of the storeroom by the student. Perhaps only one student will sign for the equipment issued，but all students working as a partnership will be held equally responsible for its care. Check each item of the equipment received and make sure that you have all articles required and that all are in good condition. Also check apparatus already on the table and compare with the items listed under general apparatus. Report any irregularities to the instructor or his assistant at once.

5. Materials which the Student Will Supply.

Equipment which is not considered as general laboratory apparatus will be needed at various times. These items consist of graph paper，straight edge，protractor，slide rule，and watch with sweep second hand. You should always have your textbook available for reference purposes.

6. Performance of the Experiment.

Before beginning the experimental work you should always read the entire procedure

so as to get a general idea of what is to be done. You should always arrange and adjust the apparatus to give the best performance possible and then make and record readings as precisely as the apparatus will permit. Always estimate on significant figure beyond the smallest graduation on the instrument being read.

Data should never be recorded on scrap paper and then transferred to your record form. If,after you have recorded a reading,you decide that it is in error and should be discarded,mark through it and record the corrected reading below it. Always record the proper unit beside the number or at the heading of a column when a whole column of readings use the same unit.

Do not hesitate to discuss any details of the experiment with the laboratory instructor during the laboratory period. You may want to question certain procedures or suggest improvements in the method. A good question may be more important than a good answer.

7. Report of Experimental Work.

The form of the report required will be designated by the instructor in the course. In any case the original data should be presented in neat form,such as that suggested at the end of each experiment in this manual. The data should be followed by sample calculations showing the method of obtaining the results. If the experiment requires several computations of the same type,only one of each type need be shown in the report.

When all calculations have been made and curves (if any) plotted,the student should study the results and draw some conclusions concerning what relations are indicated and what physical principles are demonstrated. Many of the questions at the end of each experiment are intended to stimulate thought and to guide the student in drawing conclusions concerning the results. These questions are to be answered in discussion style and the answers so worded that the reader can ascertain the question from the answer.

8. Proficiency in the Laboratory.

This will be determined by the neatness of the report,accuracy,conduct in the laboratory,technique in operating equipment,ability to grasp the fundamental principles demonstrated by the experiment,answers to the questions at the end of the experiment, and answers given to any quiz questions that may be asked on the laboratory work.

9. Questions concerned with the experiment.

The questions which follow each experiment are designed to aid the student in making more careful observations and to train him to analyze these observations and interpret the results. Many of them are questions which the student cannot answer unless he has been a careful observer. The author believes that the answers to these questions give a very clear indication of the student's grasp of the experiment,and are a very important part of the report handed in to the instructor.

Errors and Significant Figures

1. Errors and uncertainties in measurement.

Because of human and instrumental limitations no measurement is absolutely accurate or exact. A measurement or experimental result is of little value if nothing is known about its accuracy. If we are concerned about the reliability of a certain measurement, we must know something about the probable errors and uncertainties that were involved in obtaining it. There are many types of errors which enter into measured quantities and there are several ways of classifying them. One way is to classify them as (a) errors in calibration of the instruments, (b) errors inherent in reading the scale, (c) errors inherent in the insensitivity of the indicator to changes, and (d) errors due to fluctuations in the environment which affect the experiment.

a. Errors in the Calibration of the Instruments.

These errors may result from an instrument being used under conditions different from those for which the calibration was made. If a measuring tape is calibrated to be used at 20℃, indicated measurements made at 30℃ will not be the correct values. Some very delicate instruments must have the calibration checked at periodic intervals. Instruments may also be worn by use to such an extent that accurate settings cannot be made. One must also choose an instrument which is calibrated to give the precision required in the measurement. For example, an ordinary meter stick would not be appropriate for measuring the diameter of a small wire, which may be on larger than the smallest division on the stick.

b. Errors Inherent in Reading the Scale.

A student's personal bias is often responsible for inaccurate results. When a series of trials are to be made for a certain measurement, students very often assume the first trial to be about correct and attempt to make all the others agree with it, thus giving more significance to the first reading than any of the succeeding ones. Other personal errors are introduced because of insufficient care being used in adjusting instruments, inaccurate estimations of fractional divisions, and parallax.

The apparent distance between two objects will depend on the position of the eye. Two objects may appear to be in line when viewed with one eye but out of line when viewed with the other eye or when the head is moved to one side. This apparent change in position due to sidewise motion of the eye is called *parallax*.

If one is attempting to read the position of the mercury level in a tube near a scale (see Figure A)
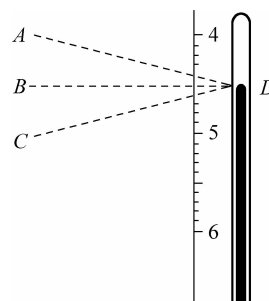
Figure A　Errors in scale Readings
due to parallax

the line of sight must always be perpendicular to the scale. If one should sight along the line AD, he would read 4.4; if along line CD, he would read 4.6; the correct reading is 4.5, as read along the line BD.

The chance of error due to parallax between scale divisions and the object being measured may be reduced to a minimum by placing the measuring scale as near as possible to the object being measured. A meter stick should always be placed edgewise against the object being measured, in order to reduce such errors.

Other problems associated with reading instruments might come under the heading of *random fluctuations*. As one attempts to read a voltmeter connected across some circuit element in the $A.C.$ power line, the needle may fluctuate back and forth while one attempts to get a reading. The same situation exists in attempting to read the scale on a count rate meter connected to a Geiger tube. Methods of handling statistical fluctuations will be discussed in connection with the appropriate experiment in this book.

c. Errors Inherent in the Insensitivity of the Indicator to Changes.

In some experimental setups one indicating portion of the equipment may not show sufficient response to changes in other indicating parts. When a certain amount of weight is added in one place, friction in the connecting links may prevent a scale indicator from showing the proper response. It may be that some instrument is slow in responding to a change in temperature and readings must not be made too quickly. The usual laboratory thermometer, calibrated in one degree divisions, could not be expected to show sufficient response to a temperature change of 0.01 degree.

d. Errors Due to Fluctuations in the Environment.

If one is attempting to read an instrument out in the open where the adjustment is affected by gusts of wind an accurate reading would be difficult to obtain. These types of errors, due to changes in the environmental conditions, can only be reduced through proper control of such conditions as temperature, humidity, noise background, vibration, stray electric fields, wind, and so forth. Sometimes these are beyond the control of the experimenter.

e. Percentage Error.

The error in a measurement is the amount by which the student's experimental value differs from the accepted value listed in some official record, such as a handbook. It should be clearly understood that the amount of the error is not a true index of the precision of the measurement. For example, suppose someone measures the distance between two streets to be 390 m, while a professional surveyor's record shows the distance as 400 m. In another case, a person estimated the width of a table as 1.8 m when it should be very near 2.0 m. The absolute error in the first case is 10 m, and in the latter case, 0.2 m. Which one would you say did the best job in his measurement? The one who measured the table made an error of 0.1 m in each meter measured. On this

basis, he would have made an error of 40 m in the street measurement. The fractional error, which is the ratio of the absolute error to the accepted value, is the quantity which shows the precision of the measurement. In the above cases we have the following:

First case, fractional error $= \dfrac{10 \text{ m}}{400 \text{ m}} = 0.025 = 2.5$ parts in 100, or 2.5%

Second case, fractional error $= \dfrac{0.2 \text{ m}}{2.0 \text{ m}} = 0.10 = 10$ parts in 100, or 10%

In general, percent error $= \dfrac{\text{absolute error}}{\text{accepted value}} \times 100\%$

f. Percentage difference.

There are cases in which we want to compare the results of two equally trustworthy measurements, that is, to find the percentage difference between the two. For example, suppose two measurements of a length give 4.0 cm and 4.2 cm, respectively, the exact value not being known. The percentage difference is found by comparing the deviation (or difference) with the average of the two. Hence, we have

Percentage difference $= \dfrac{4.2 - 4.0}{4.1} \times 100\% = 0.049 \times 100\% = 4.9$ percent.

g. Estimated Uncertainties.

The accuracy with which a given measurement can be made is increased by obtaining the average of number of independent readings. This average is likely to be scale being read and deciding by what fraction of a more reliable value for the measurement than just one single reading. These fluctuations (or deviations) in the individual readings indicate that uncertainties do exist in experimental measurements. The average deviation may be obtained by finding the absolute value of the difference between the mean and the individual values and then averaging these deviations. If M is the mean value and d is the average of the deviation from the mean, then the measured value of the quantity Q should be recorded as

$$Q = M \pm d$$

For example, suppose one measures the length of a small body for five times and gives the results as follows:

$x_1 = 3.41 \text{ cm}, \quad x_2 = 3.43 \text{ cm}, \quad x_3 = 3.45 \text{ cm}, \quad x_4 = 3.44 \text{ cm}, \quad x_5 = 3.42 \text{ cm}$

So the mean value would be

$$M = \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

$$= \frac{1}{5} \times (3.41 + 3.43 + 3.45 + 3.44 + 3.42) \text{ cm}$$

$$= 3.43 \text{ cm}$$

The deviation for each time would be

$$d_1 = |3.41 - 3.43| \text{ cm} = 0.02 \text{ cm}$$

$$d_2 = |3.43 - 3.43| \text{ cm} = 0.00 \text{ cm}$$

$$d_3 = \mid 3.45 - 3.43 \mid \text{cm} = 0.02 \text{ cm}$$
$$d_4 = \mid 3.44 - 3.43 \mid \text{cm} = 0.01 \text{ cm}$$
$$d_5 = \mid 3.42 - 3.43 \mid \text{cm} = 0.01 \text{ cm}$$

The average value of deviation would be

$$d = \Delta x = \frac{1}{n} \sum_{i=1}^{n} d_i = \frac{1}{5} \times (0.02 + 0.00 + 0.02 + 0.01 + 0.01) \text{ cm} = 0.01 \text{ cm}$$

The measured value of the length can be expressed into this form:

$$d = x \pm \Delta x = M \pm d = (3.43 \pm 0.01) \text{ cm}$$

The percent uncertainty is equal to $\dfrac{d}{M} = \dfrac{0.01}{3.43} \times 100\% \approx 0.3\%$

If only one reading is made, one may estimate the uncertainty by examining the scale division a reading could be in error. This may vary from 0.1 to 0.5 of the smallest scale division.

The percentage uncertainty, in terms of the above symbols, is expressed by the relation

$$\text{Percentage uncertainty} = \frac{d}{M} \times 100\%$$

2. Significant figures.

The digits required to express a number to the same accuracy as the measurement it represents are known as significant figures. If the length of a cylinder is measured as 20.64 cm, this quantity is said to be measured to four significant figures. If written as 0.0002064 kilometers, we still have only four significant figures. The zeros preceding the 2 are used only to indicate the position of the decimal point. The zero between the 2 and 6 is a significant figure, but the other zeros are not. If the above measurement is made with a meter stick, the last digit recorded is an estimated figure representing a fractional part of a millimeter division. ***All recorded data should include the last estimated figure in the result, even though it may be zero***. If this measurement had appeared to be exactly 20 cm, it should have been recorded as 20.00 cm, since lengths can be estimated by means of this instrument, to about 0.01 cm. When the measurement is written as 20 cm it indicates that the value is known to be somewhere between 19.5 cm and 20.5 cm, whereas the value is actually known to be between 19.995 cm and 20.005 cm.

By referring again to the 20.64 cm measurement, the possible error in this measurement is ± 0.005 cm and was recorded as being nearer to 20.64 than to 20.63 or 20.65. Hence, the error is less than one part in two thousand.

Now suppose the diameter of the cylinder is measured with the same instrument and recorded as 2.25 cm. This number has only three significant figures, and hence is known to only one part in a little more than two hundred. From this we see that the number of decimal places does not indicate the precision of the measurement.

Now suppose we wish to find the volume of this cylinder as given by the relation

$V = \pi r^2 h$. The radius $r = 1.125$ cm, four significant figures being retained because the original number has been reduced by the process of dividing by 2, thus giving rise to a larger percentage error from deviations in the third significant figure. The accuracy of the original measurement will determine when it is best to include an additional figure in such cases.

If we underline the doubtful figures in the number representing r and find r^2, the multiplication is as shown below.

<pre>
        1.1<u>25</u>   20.6<u>4</u>
      ×1.1<u>25</u>   × 1.2<u>7</u>
     ──────────   ──────────
         5<u>625</u>   1<u>4448</u>
         2<u>250</u>   41<u>28</u>
        11<u>25</u>   206<u>4</u>
       11<u>25</u>   ──────────
     ──────────   26.<u>2128</u>
      1.2<u>65625</u>
</pre>

The result is shown to be 1.265625; but if the doubtful figures are carried through the process of multiplication and only one of them kept in the final result, the result of r^2 is recorded as 1.2<u>7</u>.

If the first 6 in the result is doubtful, the other four figures are worthless in the result and should be discarded. In like manner the product $r^2 h$ has a value of 26.<u>2</u> when we include only one doubtful figure. It should be noted that this final product contains no more significant figures than does the factor having the fewest significant figures, namely, 1.27, which has three.

The next step is to multiply by π, the value of which that you have most probably been using is 3.1416. This multiplication is being left as an exercise for the student under the supervision of the instructor and supplemented by his discussion.

First multiply the result of $r^2 h$ as given above by 3.1416, showing all the steps in the multiplication and indicating the doubtful figures, and record the final result so as to retain only one doubtful figure. Now multiply the value of $r^2 h$ by 3.14 and record the final result as containing one doubtful figure. How do the two results compare? What rule would you suggest concerning the number of digits to use for π in multiplication processes such as this? If the diameter of a certain circle is 9.8<u>1</u> cm, with only one doubtful figure, what should be used as the value of π in obtaining the circumference of the circle? Check the validity of your answer by multiplying 9.8<u>1</u> by 3.14, then by 3.142, and finally by 3.1416. If you keep only one doubtful figure in the final result, how many significant figures of π are required, and how many significant figures are in your answer? Note that 9.81 is almost as large as 10.00, a number having four significant figures. Hence, one must carry enough digits in π to avoid introducing more uncertainty into the answer.

Now take the diameter of the cylinder as 3.2<u>8</u> cm instead of 2.2<u>5</u> cm and calculate