General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

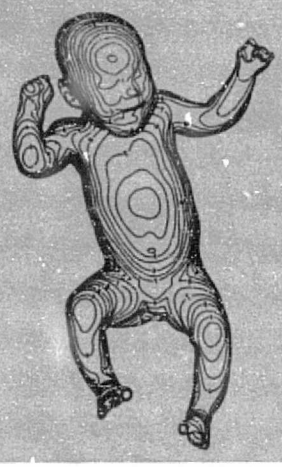
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

NASA CR-
151726



DEVELOPMENT OF BIOSTEREOMETRIC EXPERIMENTS

FINAL REPORT
NAS9-14562

(NASA-CR-151726) DEVELOPMENT OF BIOSTEREOMETRIC EXPERIMENTS Final Report, 1 Jan. - 31 Dec. 1977 (Texas Inst. for Rehabilitation and Research) 73 p HC A04/MF A01 CSCL 06B G3/52
N78-25759
Unclas
21619

JUL 1978
RECEIVED
NASA STI FACILITY

Biostereometrics Laboratory
Texas Institute for Rehabilitation and Research
Baylor College of Medicine
1333 Moursund Ave.
Houston, Texas 77025

DEVELOPMENT OF BIOSTEREOMETRIC EXPERIMENTS

R. E. Herron, Ph.D.
Principal Investigator

Final Report
NAS9-14562

May, 1978

Biostereometrics Laboratory
Texas Institute for Rehabilitation and Research
Baylor College of Medicine
1333 Moursund
Houston, Texas 77030

CONTRACT NO.: NAS9-14562

TITLE: Development of Biostereometric Experiments

Report for period January 1, 1977 to December 31, 1977

Introduction

The primary objective of this project was to:

> "Draw on the expertise of the Biostereometrics Laboratory at the Texas Institute for Rehabilitation and Research to develop joint experiment programs for the upcoming space shuttle missions."

The work reported here related to preparatory studies and joint experiment programs dealing with hardware, software, reliability and interpretative aspects of biostereometrics associated with the space shuttle flight and related applications. Also included is a summary of an inflight experiment proposal for a forthcoming space shuttle mission.

Item 1. A report of the joint development by the Biostereometrics Laboratory, Texas Institute for Rehabilitation and Research and Danko Arlington, Inc. of the Kelsh K-460 Stereometric Camera.

Item 2. A report of a joint experiment by Texas Institute for Rehabilitation and Research and Lovelace Foundation on the comparability of body volume computation by stereophotogrammetry and by underwater weighing.

Item 3. A summary report of an investigation into the constancy of human body volume using a biostereometric method.

Item 4. Discussion of the results of Skylab experiments into changes in body composition due to space flight, based on biostereometric measurements performed by TIRR.

Item 5. Report of quantitative three-dimensional displays developed for biomedical applications.

Item 6. Summary of a proposed inflight study, entitled "Biostereometric Analysis of Body Volume Changes During Sustained Weightlessness," to be performed on board the space shuttle.

Item 1

THE KELSH K-460 STEREOMETRIC CAMERA--A NEW TOOL FOR MEDICINE AND BIOLOGY

J.O. Danko, Jr. and J.R. Cuzzi

Reprinted from

SPIE Vol. 89, Applications of Optics in Medicine and Biology, 1976

(pp. 61-68)

Reprinted from Vol. 89—Applications of Optics in Medicine and Biology
© 1977 by the Society of Photo-Optical Instrumentation Engineers, Box 1146, Palos Verdes Estates, California 90274 USA

THE KELSH K-460 STEREOMETRIC CAMERA – A NEW TOOL FOR MEDICINE AND BIOLOGY

Joseph O. Danko, Jr., President
Kelsh Instrument Division
Danko Arlington, Inc.
4800 East Wabash Avenue
Baltimore, Maryland 21215

Jaime R. Guzzi, Assistant Professor
Texas Institute for Rehabilitation and Research
Baylor College of Medicine
Houston, Texas 77025

Abstract

The use of the close-range technique in biostereometrics has created the need for a simple, precise universal stereometric camera system. The Kelsh K-460 Stereometric Camera has been designed to fill this need. The camera focusing distance of 360mm to infinity covers a broad field of close-range photogrammetry. The design provides for a separate unit for the lens system and interchangeable backs on the camera for the use of single frame film exposure, roll-type film cassettes, or glass plates. The system incorporates the use of the surface contrast optical projector (SCOP) developed at the Biostereometrics Laboratory, Baylor College of Medicine.

I. Background

Much has been written during the past few years about the close-range technique that has been developed at the Biostereometrics Laboratory, Baylor College of Medicine in Houston. Under the direction of Dr. R. E. Herron, stereophotogrammetric methods have been used for human body measurement for both medical and non-medical purposes.[1]

The research at Baylor has been noted with interest by such professional organizations as the American Medical Association, which presented the following definition of biostereometrics in one of its recent journals:

> "Biostereometrics, based on principles of analytic geometry, is the spatial and spatiotemporal analysis of biological form and function. It's main tool is stereophotogrammetry -- the use of stereoscopic equipment and methods in making a record of a three-dimensional object, such as man."[2]

There has also been considerable interest shown in the research by specialists in anthropology, automotive safety, clothing manufacturing, and furniture design.

At Baylor, a surface contrast optical projector (SCOP) has been developed for illuminating the human body shape being photographed. It flashes a contrast texture onto the normally flat skin tones and makes accurate stereocompilation possible.

To capture the complete body shape, two pairs of stereo cameras are usually required. These camera pairs are placed opposite each other, with the body in between. The flash of the surface contrast optical projector system is programmed to expose one camera pair a few micro-seconds before the exposure of the second pair takes place. With the use of grids and measuring tapes near the body, or body member, a photogrammetric control network is established. After development in the darkroom, the negatives of the stereo pairs may be set up in stereoplotters, creating stereo models of the body forms. These models can be scaled and accurately measured in three dimensions.

The measurement of the stereo model is performed by the plotter operator, using an XYZ digitizer. Usually, cross-sections are digitized and stored in a memory system for further analysis. However, techniques have been developed at Baylor which can reveal a wealth of body information from a relatively few carefully selected data points. Topographic maps of the body have been helpful in dramatizing biostereometrics, but in reality, have little practical value.

Many software programs have been developed for extracting a variety of data from the digitized body measurements. The output might be in the form of volume measurement, volume distribution curves, profiles, surface area, or some other parameter, depending on the information required by the user.[3,4]

ORIGINAL PAGE IS
OF POOR QUALITY

II. The Need for a Universal Camera

To further the improvement of the close-range technique at Baylor, a number of experimental camera systems were devised.

One of the early camera systems consisted of two Kelsh plotter projectors mounted on a base frame. Hinged shutters that were operated by solenoids were attached to the Kelsh plotter lenses. A cassette for containing unexposed film was adapted to the cone castings. Stereo photographs were taken through the Hypergon lenses of the Kelsh projectors, while the film was held against a glass pressure plate. The same projectors were used to compile the stereo image in a Kelsh plotter from the film negatives. Also, the same pressure plates that were used in the camera were used for the lower half of the film-glass sandwich in the plotter. This eliminated any errors due to the distortion that would have been caused by the pressure plate.

The same technique was used with Multiplex projectors, photographing the subject and projecting the image through the Multiplex lens system.

A more recent development is the adaptation of non-metric cameras for human body measurement. At Baylor, two Hasselblad superwide cameras with 38mm lenses were mounted on an X-frame and a tripod. The Hasselblads were provided with fiducial marks which were calibrated with the lenses.

The surface contrast optical projector, utilizing a xenon lamp, was mounted on the common plane with the optical axes of the Hasselblad lens pairs. Two pairs of Hasselblads, each with a SCOP attachment, were used for photographing a complete body shape. For the Hasselblad system, glass plates were obtained on special order, coated with a black-and-white panchromatic emulsion.

In 1972, representatives of the Kelsh Division and the Biostereometrics Laboratory discussed the possibility of developing a universal stereometric camera system for biomedical purposes. The team at Baylor had recorded the advantages and disadvantages of the early camera systems that had been used. And they had also drawn up a set of specifications for a universal camera system that would be ideally suited for their purposes. The Kelsh Division was intrigued by this fascinating new field and readily agreed to contribute its knowledge of instrument manufacturing toward the design of the new camera system.

The result of this joint effort is revealed in the Kelsh K-460 Universal Stereometric Camera System that is described in this paper.

III. The Basic Stereo Camera with Xenon Flash

The basic K-460 camera system was designed to benefit from the many advantages of stable base polyester film diapositives (or negatives). Extensive research has proven that there is no significant random deformation in properly printed stable base film diapositives.[5] Unlike glass, film diapositives do not break when dropped, and they may be conveniently stored in file folders. Film is currently being used which can be processed in an X-Ray film processor. Hospitals and other medical centers almost always have an X-Ray processor available. And only a minute or two is needed for the development and drying of a stereo pair in such a unit.

Panchromatic film has been found to be the best type for recording the variety of skin tones when photographing the human body. For the K-460, a 105mm wide panchromatic film was selected for a 105 X 127mm (4" X 5") format.

A photograph of the Kelsh K-460 Universal Stereometric Camera is shown in Figure 1. The Xenon SCOP flash unit (Item 1) is supported in a central post casting (Item 2) which has been in turn mounted on a tripod. An X-frame (item 3) suspends the two camera heads (items 4,5) so that the optical axes of the two lenses are on the same plane as the xenon flash. The camera heads may be moved apart to a base distance of 920mm, which is sufficient for many architectural purposes, and more than adequate for complete human body photography at an optimum focusing distance.

ORIGINAL PAGE IS
OF POOR QUALITY

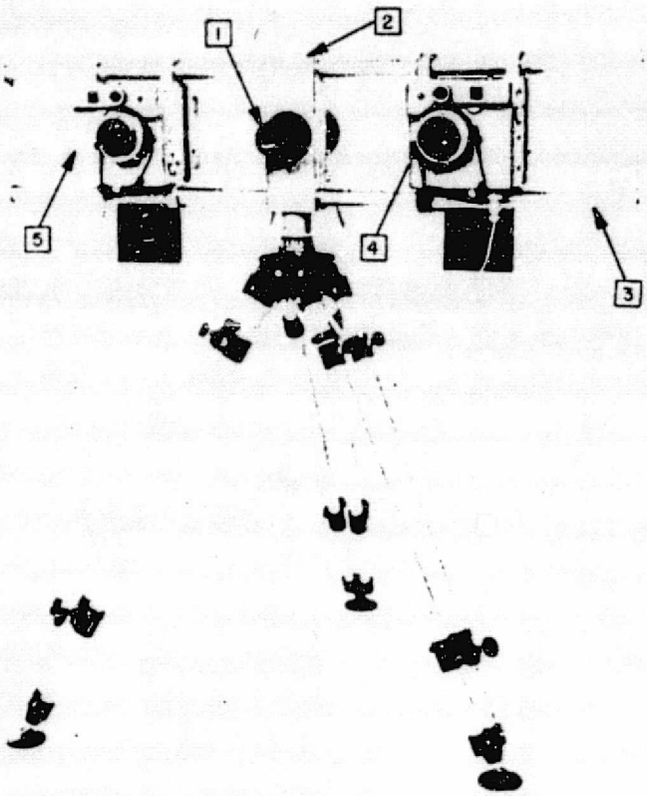
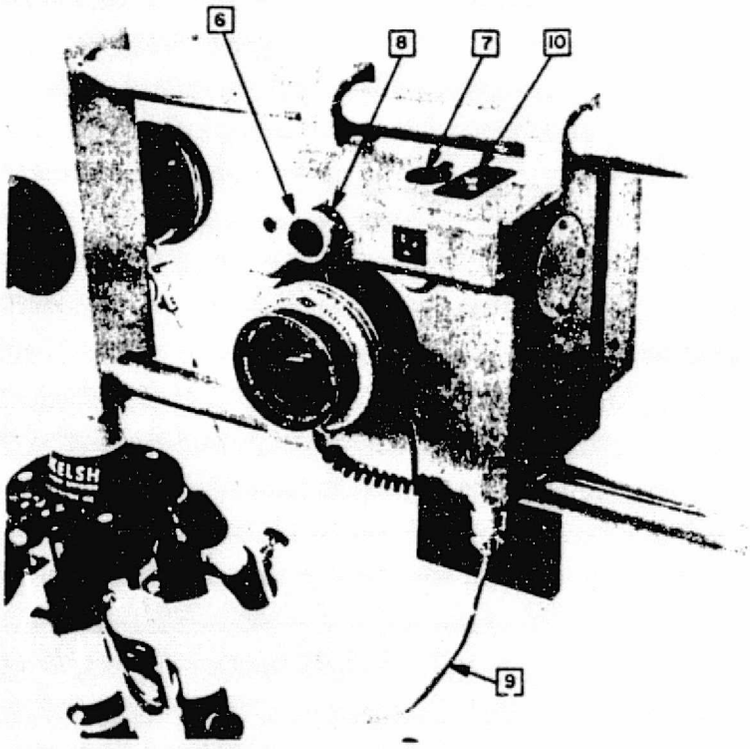


Figure 1. The Kelsh K-460 Universal Stereometric Camera

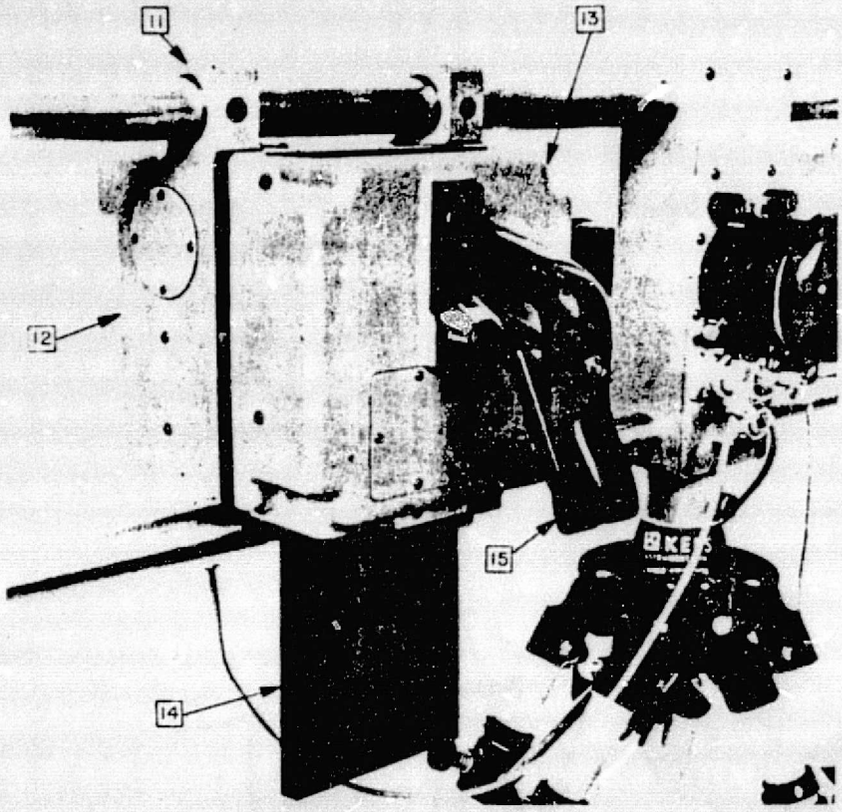


ORIGINAL PAGE IS OF POOR QUALITY

Figure 2. A close view of a camera head

A closer look at one of the camera heads is shown in Figure 2. The camera shown uses a Fujinon wide-angle 90mm focal length lens that has been fitted with an Ilex electronic shutter, for a stop opening from f8 to f32. The focusing distance of the lens may be adjusted from 360mm to infinity by means of the adjusting knob (Item 6). The dial on the top of the camera housing (Item 7) displays the principal distance in millimeters, as well as the optimum front focusing distance settings. A micrometer dial (Item 8) on the adjusting knob allows the principal distance to be set within 0.01mm.

The electrical cable (Item 9) from the camera head to the center post permits the camera to be fired remotely. Most of the electronics for this firing system are housed within the center post casting. The SCOP flash is fired from a remote power supply, by means of X synchronization within the shutter system. A small ruby window (Item 10) in the top of the camera head indicates to the operator if the internal "marker flash" lamp has fired. More will be said about this feature later.



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 3. Rear view of a camera head

Figure 3 shows a rear view of one of the camera heads. Three lugs (Item 11) on the front lens housing (Item 12) support that section of the camera on the X-frame. Attached to the rear of the lens housing is a film housing (Item 13). Projecting from the bottom of the film housing is the lower half of a single film cassette (Item 14) which has been extended to allow a single frame film exposure to be made.

A handle and trigger mechanism (Item 15) has been made a part of the film housing, and controls the action of a pressure pad within the housing. Figure 4 shows the film housing detached from the lens housing. The pressure pad (Item 16) is seen as well as the glass pressure plate (Item 17) which is mounted on the lens housing. The 105mm film is offset from the optical axis of the lens to obtain the smallest camera base possible, and to conserve film for the single-model stereophoto format. Four fiducial marks (Item 18) are located in holes which have been drilled through the optically flat glass plate. These fiducial marks are pinpoints of light which emanate from four fiber optic conductors that have been located to bisect the optical axis of the lens. The light source for the fiducials is located within the lens housing and consists of a small flash lamp assembly. This same "marker flash" illuminates a drum dial inside of the lens housing. By means of an optical system, the principal distance of the camera lens at the time of exposure is flashed from the drum dial to the upper outside corner of the film through the glass plate.

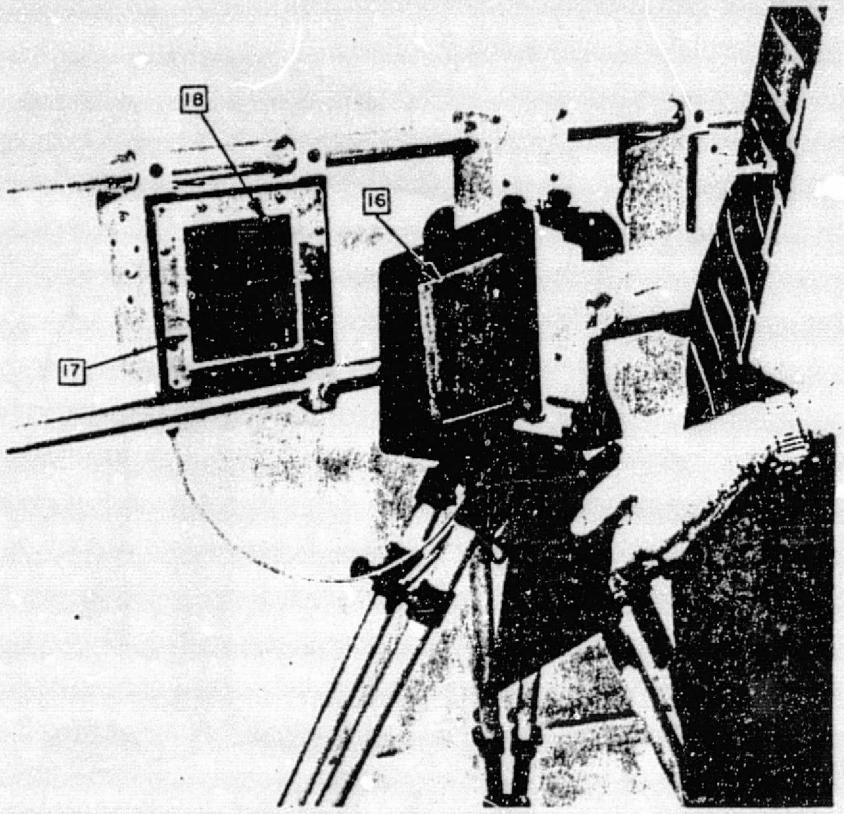


Figure 4. The film housing may be detached from the lens housing

The basic camera system accepts single frame film cassettes which are loaded in the darkroom with 105mm wide cut film. The cassette is slipped into the film housing through a slot in the top of the housing. A cover snaps closed on top of the cassette when it is in place, effectively sealing the film against extraneous light. By pulling the lower half of the cassette down to a stop, the film is positioned so that the pressure pad may be released to hold it flat against the glass plate and the fiducial marks.

After exposure, the cassette is pushed up into the film housing so that the film may be withdrawn with it to be taken to the darkroom for processing.

IV. Optional Accessories for the K-460 Camera

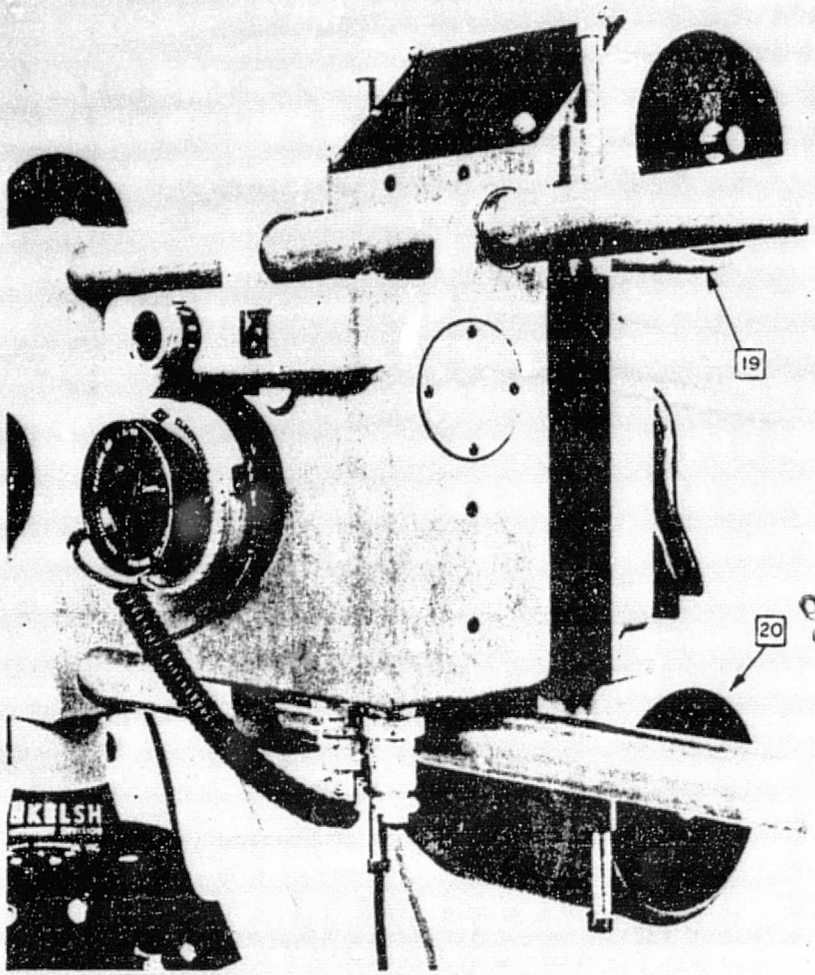
The design of the basic K-460 camera system was planned to permit the evolution of many types of accessory attachments. The lens housing has been made to accept lenses of different focal length and manufacture. And the detachable film housing permits various other film and photographic plate systems to be used.

A set of roll film cassettes has been designed for the K-460 camera. These cassettes may be mounted directly on the basic single-film housing as shown in Figure 5. The upper cassette (Item 19) may be removed from the housing and loaded in the darkroom with a spool of 105 millimeter film which will allow 250 exposures. After loading, this cassette may be brought out of the darkroom and easily refastened to the top of the film housing. A counter dial on the side of the cassette indicates to the operator the number of available exposures.

The lower cassette (Item 20) shown in Figure 5 is for removing a partial or an entire spool of roll film after it has been exposed. A crank on this lower cassette allows the operator to index the film for succeeding exposures. The lower cassette may be detached at any time for taking exposed film into the darkroom for processing.

The glass pressure plate assembly shown in Figure 4 may be detached rather easily from the lens housing. This permits the use of a film housing with a vacuum plate, if required.

Another design option is a housing and cassette for photographic glass plates.



ORIGINAL PAGE IS OF POOR QUALITY

Figure 5. Optional roll film cassettes may be mounted directly on the single film housings

Figure 6 shows the two camera heads mounted on a "table mount" X-frame. When the flash attachment is not required, the table mount permits the two camera lenses to be close enough together to give the operator a 142mm camera base distance. This arrangement is very useful for taking stereophotographs of small inanimate objects.

V. Compiling the Stereo Model from Film Negatives

A special close-range Kelsh plotter system has been designed to restitute the stereo imagery from the K-460 camera. The plotter is called the Kelsh K-480 and uses a modified projector and lens system along with the new correction cam mechanism, making possible the compilation of either pressure plate, vacuum or glass plate photography. Because of the added surface contrast, film negatives may be used directly in the stereoplotter and compiled as readily as diapositives.

The pressure plate system is the simplest way to present film for a negative exposure. The optically flat pressure plate that has been used in the camera is 3.3mm thick. When projecting a stereo image from film in the close-range Kelsh K-480 plotter at camera principal distance, the same thickness of glass is used for the lower half of the film-diapositive (negative) sandwich. The distortion and displacement of image caused by the glass pressure plate are thus cancelled out.

When projecting a stereo image from a film pair at other than camera principal distance, the model is measured using an affine solution, with a factoring for the Z dimension. Lower sandwich plates of a different thickness can then be used in the Kelsh projectors for a proportionate distortion correction.

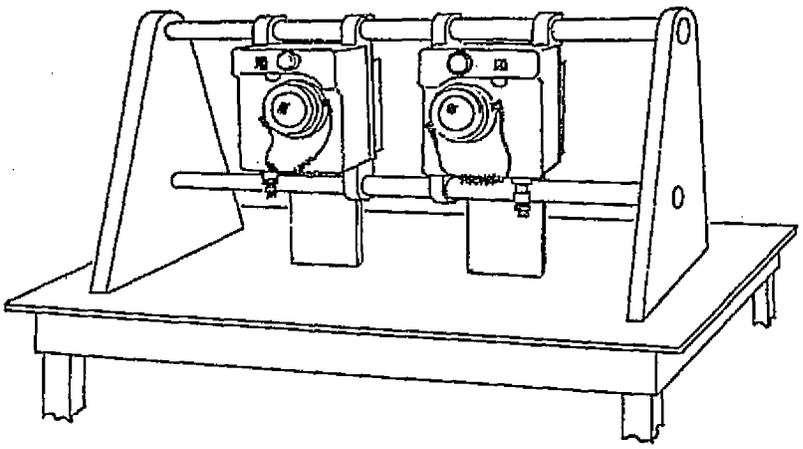


Figure 6. Camera heads mounted on a table frame for stereometric photos of small objects

The new Kelsh correction cam system in the K-480 permits the compilation of film negatives taken with a vacuum system. The cam system corrects for the distortion caused by a 3.3mm (.130") lower glass sandwich plate in the projector.[6]

Optical train plotters can be equipped with special glass correction plates to compensate for the distortion caused by the glass camera pressure plates. The film housing which is furnished with the more elaborate vacuum system permits photography to be taken without a pressure plate, and such photography may be compiled directly on an optical train plotter without the need for the correction plates.

VI. Conclusion

The theme that was kept in mind throughout the design and development of the K-460 camera system was "precision, simplicity, and flexibility". Testing has proven the camera system to be unusually precise for the purpose for which it was designed. The use of stable base polyester film negatives has allowed the basic camera design to be a simple one. And the interchangeability of the film housings as well as the lens system has allowed a wide degree of flexibility.

The camera can also be used for generating surface contours directly on the object or body using moiré interferometry. By projecting a line pattern on the subject using the xenon flash, interferometric records can be readily produced. The K-460 is the first camera system that has been designed to accommodate moiré interferometry in a close-range stereometric camera, which should prove helpful in extending the applications of these two complimentary techniques.

Both the Biostereometrics Laboratory and the Kelsh Division believe that the K-460 stereometric camera system does show promise of fulfilling all of the original design requirements, and feel that the camera could have an exciting future in the field of medicine and biology.

References

1. Herron, R.E.: Biostereometric measurement of body form, in YEARBOOK OF PHYSICAL ANTHROPOLOGY, 1972. American Assn. of Physical Anthropologists, 1973, vol. 16, pp. 80-121.

2. THE JOURNAL of the American Medical Association, March 31, 1975, vol. 231, No. 13, p. 1327.

3. Cuzzi, J.R., Herron, R.E.; et al. "Volume and Surface Areas of Body Parts Using a Photogrammetric Minicomputer System". Proceedings of the Symposium on Close-Range Photogrammetry. American Society of Photogrammetry. University of Illinois, Champaign-Urbana, January 26-29, 1971.

4. Herron, R.E., Cuzzi, J.R.; et al. "Experimental Determination of Mechanical Features of Children and Adults". Final Report DOT-HS-231-2-397, Department of Transportation, February 1974.

5. Young, Major M.E.H., and Ziemann, Dr. H., "An Investigation of Film Diapositive Distortion", a paper presented at the 1971 CIS Convention, Ottawa, Canada.

6. Danko, Joseph O., Jr., "New Kelsh Correction Cams", published in the September 1972 issue of PHOTOGRAMMETRIC ENGINEERING.

Item 2

Body Volume by Stereophotogrammetry and by Weighing Underwater: A Comparative Study

U.C. Luft, R.E. Herron, J.R. Cuzzi, J.E. Hugg and J.A. Loeppky

ORIGINAL PAGE IS
OF POOR QUALITY

INTRODUCTION

The density of the body (mass/volume) is a useful indicator of gross body composition in terms of fat and lean body mass ( ). Whereas the measurement of mass (Wt) is commonplace and can be made with great accuracy, the estimation of body volume (V) is more difficult. Methods based on air displacement ( ) and helium dilution ( ) have not found wide acceptance because of difficulties in temperature and humidity control and the complicated equipment required. Densitometry using Archimedes' principle by underwater weighing is relatively simple and convenient to perform on healthy adults, but it is less suitable for seriously ill patients and small children and is certainly not applicable in the absence of gravity as in space.

A new method for measuring body volume (and its distribution) has recently evolved from work in the field of "biostereometrics--the spatial and spatio-temporal analysis of biological form and function based on principles of analytical geometry." The method, which has been described in previous publications ( ), involves the use of a stereometric sensor, in this case stereophotogrammetry, and specially-developed mathematical procedures. Two stereocameras are arranged as shown in Fig. 1. The resulting stereophotographs, which comprise two "stereopairs," one for the front and another for the rear view, are reduced on a stereoplotting instrument of the type used for compiling contour maps from aerial photographs. The output from the stereoplotter is in the form of digital three-dimensional coordinates of approximately 5,000 points (for the adult male) distributed over the body surface. These data constitute a comprehensive spatial description of the body surface at the moment of recording. The volume of the major body segments and the body as a whole can then be computed mathematically as outlined below.

The following study was conducted in order to compare concurrent determinations of body volume by a stereometric method (V_{St}) and by underwater weighing (V_w) in a group of adult males large enough in number and variety of body size and physique to warrant meaningful statistical analyses.

Methods and Procedures

Measurements were obtained on 40 healthy male volunteers, between 8-9 am and before breakfast, with both methods. In two of the subjects the V_{St} and V_w measurements had to be made two days apart, but their body weight did not differ by more than 100g. Prior to weighing underwater they were weighed dry on a dynamomenter balance (Chatillon Model 470, range 0-150kg) to the closest 100g. Then they entered a tank with water kept at 34°C and after removing as many air bubbles as possible from the skin were seated on a metal frame chair hanging from a balance (Chatillon Model 470, range 0-15kg) suspended by block and tackle. The subject was then immersed up to his chin after putting on a noseclip and the submersion level of the chair marked for subsequent tare readings. Immediately before putting his head under the surface the subject was required to take 5 deep breaths fairly rapidly, to facilitate breath-holding, followed by a maximal inspiration. He then slowly exhaled approximately 2/3 of his vital capacity previously marked off on a spirometer until the operator called "stop". At this point the subject separated from the mouthpiece and submerged his head without further loss or gain of air until a reading was taken on the scales (5-10 sec). Three consecutive measurements were performed in this fashion over a period of as many minutes and the corresponding readings of underwater weight and exhaled air noted together with tare readings and water temperature. The exhaled volume was corrected

for BTPS conditions and subtracted from the individual's total lung capacity as measured previously by a nitrogen wash-out method ( ). Body volume net (V_w) and density (D) were calculated by the following equations:

$$(1) \qquad V_W = \frac{Ma-(M_W + RV \cdot D_W)}{D_W}$$

$$(2) \qquad D = \frac{M_a \cdot D_W}{M_a - (M_W + RV \cdot D_W)}$$

where M_a = weight in air, M_W = weight under water, RV = residual air in the lungs and D_W = density of water at measured temperature. The average of the three measurements was taken for each subject.

In order to ensure that the gas volume in the lungs during the subsequent stereophotogrammetry was as close as possible to that during the underwater weighing, the subject took a maximal inspiration and exhaled slowly to the same volume marked on the spirometer during underwater weighing before holding his breath for the photographs.

Stereometric Derivation of Body Volume

In the stereometric procedure, body volume is computed as follows. The body is first broken down into five major segments--head and trunk, left arm, right arm, left leg and right leg. The stereoplotter-generated coordinates defining a set of serial cross sections of each segment constitute the raw data.

Each cross section is treated as a harmonic variation of the radius extending from the mathematical center of gravity of the cross section to the surface of the skin (Fig. 2). The curve which expresses the relationship of of the radius (ρ) to the angle (α) which it subtends is defined by the form:

ORIGINAL PAGE IS
OF POOR QUALITY

$$(a) \qquad \rho = a_0 + \sum_{i=1}^{n} (a_i \cos i\alpha) - \sum_{i=1}^{n} b_i \sin i\alpha,$$

where: ρ = the radius,

α = the angle subtended from the selected origin,

i = the number of a term in the equation,

a and b = coefficients which define the relation of the angle to the radius, and

n = maximum value of i.

This classical form, which defines any harmonic variation with the proper values for n, has drawbacks which can be overcome by first changing the variable of the trigonometric terms to simpler forms as in the following equation which can be considered as a polar coordinate version:

$$(b) \qquad \rho = a_1 + \sum_{i=1}^{n} (a_{2i} \cos^{i-1}\alpha \sin\alpha + a_{2i+1} \cos^{i}\alpha).$$

From the above, we derive the orthogonal version for fitting purposes:

$$(c) \qquad \rho = a_1 + \sum_{i=1}^{n} \rho^{-1} x^{i-1} (a_{2i}\, y + a_{2i+1}\, x),$$

where: $\rho = \sqrt{x^2 + y^2}$.

The area of each cross section is then computed by a polar integration of the curve defined by equation b. In normal integration, the infinitessimal increment is a rectangle whose smallest base lies on the axis of integration. For polar integration, the infinitessimal increment is a triangle whose smallest base lies on the curve and the opposite vertex on the origin of polar coordinates.

The volume is derived in much the same way as the area of a cross section, except there is no need to define a harmonic variation. Therefore we use an overlapped, spanned, parabolic interpolation of the cross sectional areas vs

the vertical axis or height. The total body volume is given by the orthogonal integration of the spans between the first and last cross sections. Thus, the body volume is the area under the curve and the curve itself represents the volume distribution from head to foot (Fig. 3). Partial volumes can be computed between any two cross sections by considering their values as the limits of the integration.

Results

The data presented in Table 1 show that the subject population covered a wide range in age, body size and density. The net volume found by immersion does not include the volume of gas in the lungs, which is part of the volume obtained by stereophotogrammetry. Thus lung volume must be added to the net volume to be able to compare the gross volume by both methods as shown in the last two columns in Table 1. Without exception the V_{St} values were higher than the V_W and the mean difference was 2.884 liters or 3.8% of the mean for V_W. The difference was statistically highly significant ($p<.001$). On the other hand a regression and correlation analysis of the data revealed an almost perfect correlation:

$$V_W = -1.7946 + 0.9859V_{St} \quad (3)$$

$$r = 0.9987 \quad SEE = 0.706 \text{ liters}$$

The standard error of estimate is 0.95% of the mean value for V_W.

Discussion

The high correlation found between the results of the two methods and the relatively small standard error of estimate for the regression implies that both methods have high degree of precision. However the highly significant

difference between the mean values raises the question: which of the two methods is more accurate in estimating the true body volume. A strong argument in favor of the immersion method is that the values obtained for body density with it give results more compatible with theoretical calculations in the literature ( ) and with direct chemical analyses of tissues in animals ( ) and man ( ). The mean density using the net volume derived by underwater weighing of our 40 subjects is D_W = 1.058kg/liter while using V_{St} less the mean lung volume (3.050 liters) D_{St} is 1.014 kg/liter. According to the equation proposed by Keys and Brözek (1953) to estimate the fat fraction (Ff) of the body from density (D):

$$(4) \qquad Ff = \frac{4.201}{D} - 3.813$$

The mean value for Ff using D = 1.058 from underwater weighing is 0.158, while the same calculation with D = 1.014 kg/liter obtained from V_{St} corrected for lung volume gives an Ff = 0.330, more than double the amount of fat. The latter would suggest that the majority of our subjects were obese, which was not the case. Actually only two of them (Table 1, No. 16 and 28) were unusually fat.

The consistency and precision of the stereometric method and the fact that the discrepancy between it and the immersion method is apparently not due to a random error but to a systematic one, could justify the use of the regression equation (eq. 3) established by this study to adjust future measurements by the stereometric method to values that would be obtained by underwater weighing on the same subjects.

The systematic overestimation of body volume by the present stereometric method is probably due to the limited coverage of the dual stereocameras, which does not take account of such hidden concavities as the armpits and the

perineal region, among others. There are other possible sources of discrepancy, but it is outside the purview of the present study to evaluate them definitively.

An attemptwas made to determine whether or not the difference between the two methods was related in any way to the physical characteristics of the subjects, by computing correlations between the difference ($V_{St} - V_w$) and the four parameters of body build shown in Table 2. Neither gross weight, density nor body volume had a significant correlation with the difference, but there was a highly significant, positive correlation between the latter and the subjects stature, suggesting that the taller the subject, the greater the discrepancy between the two methods. Considering the relatively small range of variation in height as compared to weight and volume among the subjects (Table 1), it is notable that the correlation with height is the highest.

Since height apparently affects the magnitude of the systematic error of the dual stereocamera method it was included as the second independent variable in a regression equation to predict $y = V_W$ (liters) from $x = V_{St}$ (liters) and $z = Ht$ (cm):

$$y = 6.0833 + 1.0007x - 0.0508z \qquad (5)$$

$$r = 0.9989 \qquad SEE = 0.634 \text{ liters}$$

With this regression the correlation coefficient (r) is slightly better and the standard error of estimate less than in equation (3). Using either equation (3) or (5) stereometric determinations of body volume with the technique described above can be adjusted to approximate values by underwater weighing for the estimation of body density (eq. 2) under circumstances where the latter method is either inconvenient or not applicable.

An advantage of the stereometric method is the additional information it provides regarding how the body volume is distributed among the component body parts. The volume distribution curve is a simple and mathematically elegant means of displaying the total body volume. This parameter has already proved useful in aerospace, growth, nutritional, orthopedic and other biomedical studies and it would seem to hold promise for adding a new facet to applied physiological research.

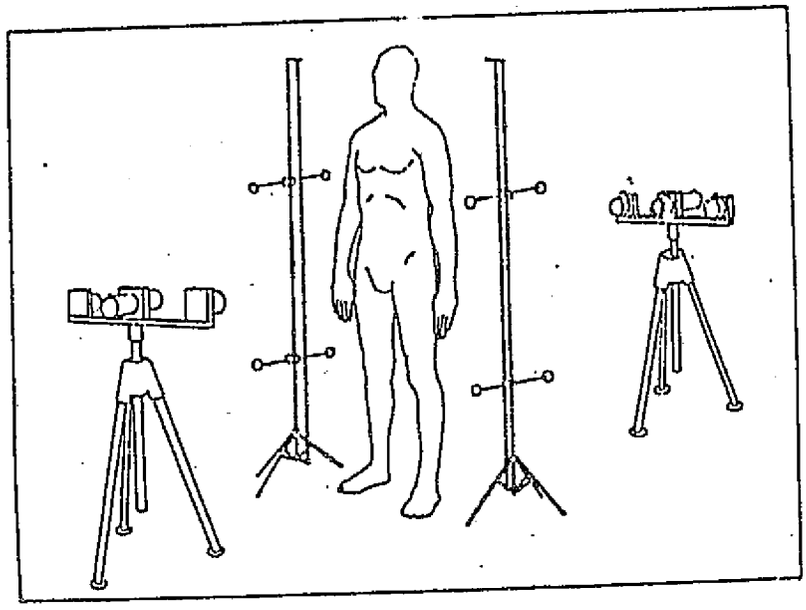


FIGURE 1

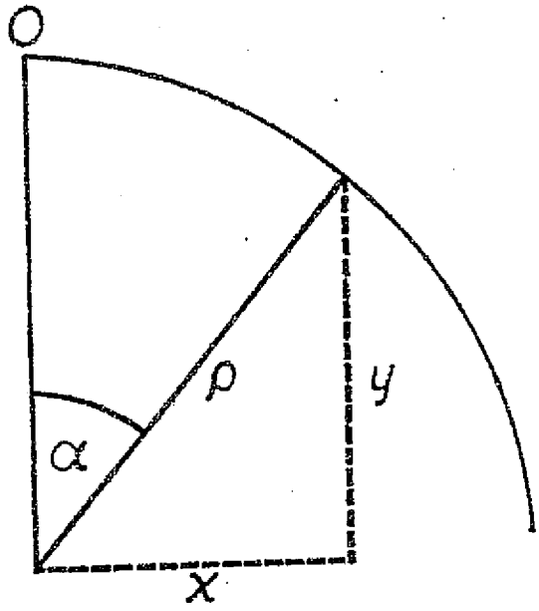


FIGURE 2

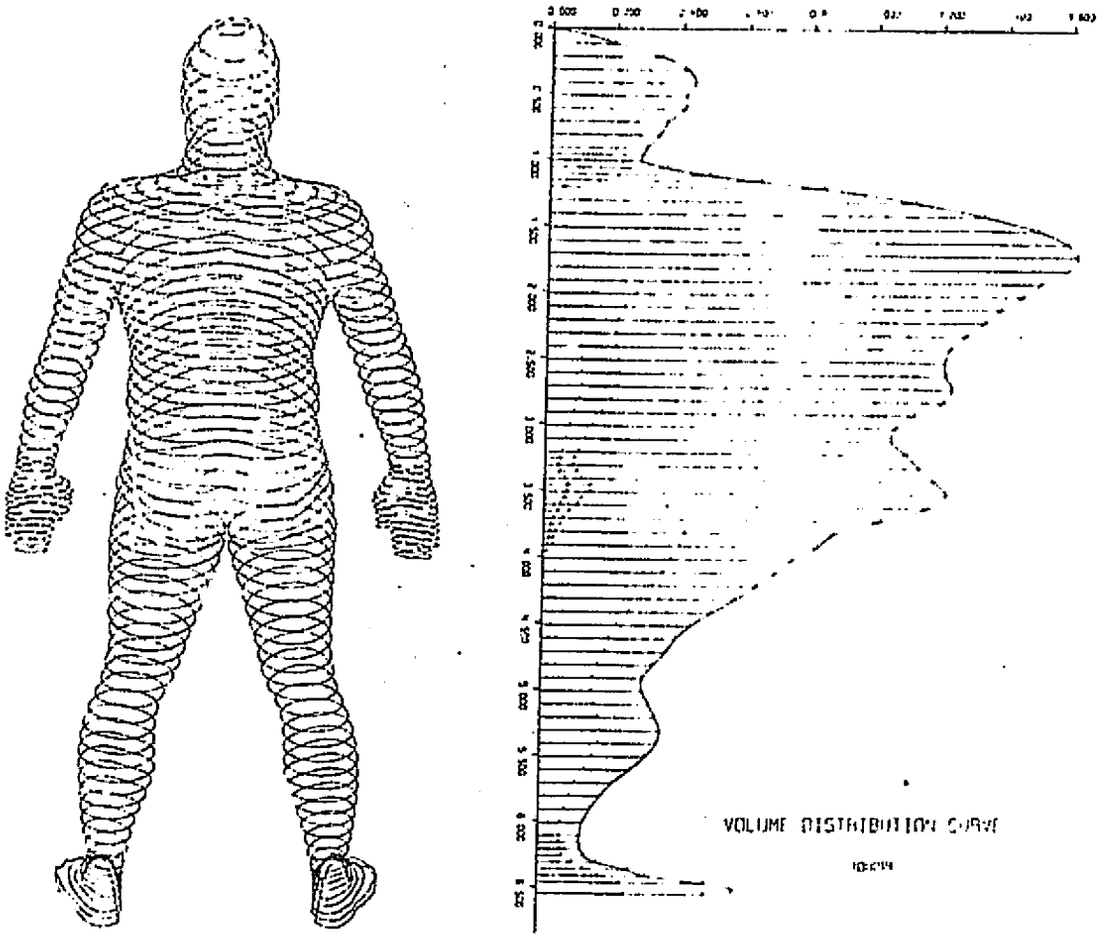


FIGURE 3

ORIGINAL PAGE IS
OF POOR QUALITY

Item 3

THE COMPONENTS OF VARIABILITY IN VOLUMETRIC DISTRIBUTION DETERMINATION BY STEREOPHOTOGRAMMETRY

A Dissertation

by

DANIEL BAKER SHEFFER

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirement for the degree of

DOCTOR OF PHILOSOPHY

August 1976

Chapter V and Table 1
(pp. 56-59 and p. 38)

CHAPTER V

SUMMARY, CONCLUSION AND RECOMMENDATIONS

Summary

The underlying need for this investigation was the lack of information regarding constancy of body volume. The purpose was to determine the contribution of selected components of total variability in biostereometric measurement of the distribution of body volume in human subjects. The objectives of this study were to: (1) determine the contribution of measurement error variation in volume distribution calculation using stereophotogrammetry, and (2) determine the contribution of intra-individual variation in volume distribution calculation using stereophotogrammetry.

Collection of data for this study entailed the use of stereophotogrammetry for determination of the biostereometric measurement of the volume distribution. The subjects in the investigation were six male volunteers between the ages of 20 to 30 years. The stereophotogrammetric technique of data acquisition provided simultaneous recording of the front and rear stereopairs of each subject. Two sets of modified Hasselblad stereometric cameras linked by electro-mechanical shutter releases and synchronized with flash projectors were utilized.

Each subject reported to the Human Performance Laboratory at Texas A&M University for eight consecutive days at a prescribed time between the hours of 6:00 and 8:00 a.m. for the photogrammetric measurement. At each testing session, the subject wore a non-elastic type of

athletic supporter that did not compress the waist and buttocks areas. The subject had certain anatomical landmarks identified throughout the study so that his body could be analytically dissected for segmental evaluation. A standardized pose was assumed by each individual that allowed the maximum amount of his surface to be exposed to the cameras. The pose also was easily replicated so that variation in volume distribution due to differences in stance would be reduced. The pulmonary vital capacity of each subject was predetermined using a Collins respirometer. At each testing session the subject was required to hold one half of his vital capacity during the photographic exposure in an effort to reduce volume deviation due to lung volume changes.

Following the data acquisition, the photographic plates were developed and enlarged for the data reduction process. The data were reduced by a skilled technician on a Kern PG-2 stereoplotting instrument at the Biostereometrics Laboratory, Baylor College of Medicine. The purpose of the data reduction was to obtain a series of Cartesian coordinates that represented points lying on the surface of a precisely scaled stereomodel of the subject's body. The coordinates for the surface points were read in parallel cross-sections approximately 5.08 centimeters apart and perpendicular to the long axis of the body. The coordinates of each cross-section were recorded beginning at the head of the subject and continued lower until the entire subject was read. The reduction output was automatically entered on data processing cards which provided the suitable input to a digital computer programmed to calculate the body volume distribution.

The resultant volume distribution output was examined for variation over an eight day period in the total body, the right leg and a ten centimeter segment of the right leg. The within-subject variation in the repeated determination was partitioned into measurement error variation and intra-individual variation as described in a model by Henry (28). The lack of a treatment variable common to all subjects in this study prevented the computation of a meaningful inter-individual component, a part of the total variation model.

In an effort to obtain an estimation of the measurement error variability, the volume of a steel cylinder was calculated using a geometrical equation and compared to a series of three volume determinations by stereophotogrammetry. The resultant comparison yielded a range of volume deviation from +1.02 to +1.71 percent, with an average error of +1.39 percent.

The volume distribution for each subject was examined separately so that an indication of intra-individual variability over repeated measures could be determined. Total body volumes of the six subjects ranged in deviations of -1.28 to +1.13 percent. In view of the possible measurement errors, the changes in total body volume could be considered as stable over the eight day period. Examination of the patterns of deviation from day to day demonstrated that the manner in which the subjects varied was not similar in respect to one another. The right leg volume deviation yielded similar results as the total body variation. The range of deviations was somewhat greater, -1.82 to +1.68 percent for three of the subjects. However, these variations remained within the limits of possible measurement error variation

and the right leg could be considered stable in its volume from day to day. Again, as seen in the total body variation, the manner in which the subjects varied from day to day over the eight day period was not similar.

The greatest amount of intra-individual variability was found in the ten centimeter segment measured in the right leg of four subjects. The volume deviations ranged from -4.43 to +2.96 percent for these subjects, which indicated there were changes in the right leg segment that were not due to measurement error alone, but could be attributed to actual segmental variation within the subjects. Subject 4 demonstrated slight variation in the leg segment. This finding was consistent for Subject 4 whose total body and right leg volume remained stable over the eight days.

Conclusions

Based on the results of this study, it was concluded that total body volume and right leg volume remain stable over an eight day testing period. It was also concluded that the volume of a ten centimeter leg segment does vary from day to day. It was further concluded that by utilizing the biostereometric technique of stereophotogrammetry, it is possible to measure the volume distribution of human subjects not feasible by the standard anthropometric techniques.

Recommendations

The following recommendations are based on the findings of this study:

Table 1

Eight day deviation in total body volume for male subjects

Subject		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Mean	S.D.
1.	Volume[a]	91093.8	90486.0	91296.3	91900.0	91497.3	92327.8	91848.9	92019.7	91552.5	± 558.2
	Deviation (%)	(-.55)	(-1.16)	(-.28)	(+.38)	(-.06)	(+.84)	(+.32)	(+.51)		(±.61)
2	Volume	72740.2	72800.6	72293.9	73078.5	73347.2	72810.5	73776.0	73039.4	72985.8	± 413.9
	Deviation (%)	(-.34)	(-.25)	(-.95)	(+.13)	(+.49)	(-.24)	(+1.08)	(+.07)		(±.56)
3	Volume	92512.6	92677.4	91690.1	93251.8	93470.8	92275.7	93936.7	93246.7	92882.7	± 679.6
	Deviation (%)	(-.39)	(-.22)	(-1.28)	(+.39)	(+.63)	(-.65)	(+1.13)	(+.39)		(±.72)
4	Volume	104259.6	102985.6	102706.2	103038.6	102660.0	103110.3	103697.4	103926.7	103298.1	± 551.9
	Deviation (%)	(+.93)	(-.30)	(-.57)	(-.25)	(-.61)	(-.18)	(+.39)	(+.61)		(±.53)
5	Volume	74359.4	74294.1	73736.8	74551.5	75151.7	75097.4	75002.2	74542.2	74591.9	± 449.3
	Deviation (%)	(-.31)	(-.40)	(-1.15)	(-.05)	(+.75)	(+.68)	(+.55)	(-.07)		(±.60)
6	Volume	83767.0	83502.4	84477.9	84241.9	84042.3	83480.0	83452.3	84400.4	83920 5	± 398.6
	Deviation (%)	(-.18)	(-.50)	(+.66)	(+ 38)	(+ 14)	(- 52)	(-.56)	(+.57)		(±.47)

[a]Volumes are in cubic centimeters

Item 4

THE EFFECTS OF PROLONGED SPACEFLIGHT ON HUMAN BODY COMPOSITION

BY

MICHAEL W. WHITTLE

Submitted for the Degree of

Doctor of Philosophy

University of Surrey, March 1978

Chapters 7 and 8
(pp. 90-104)

CHAPTER 7

DISCUSSION OF RESULTS

7.1 Changes in Body Composition due to Spaceflight

The Skylab experiments have provided the first clear insight into the changes in body composition which occur when man is exposed to the weightless environment of spaceflight. Changes were observed in all 4 of the major body compartments - water, cell solids, fat and bone mineral.

7.1.1 Water

The results obtained from the Skylab experiments support the hypothesis that there is a net loss of water from the body during the first 1-2 days in orbit, which is followed by a stabilisation of the total body water at a reduced value (section 3.2.2). Berry (1975) postulated that the loss of water was brought about by the Henry-Gauer reflex (Henry et al 1956), in which the stimulation of atrial stretch receptors induces a diuresis, by the supression of production of antidiuretic hormone (ADH). However, Leach and Rambaut (1977) observed that no diuresis took place, and that the net loss of water appeared to be caused by a supression of thirst. The physiological mechanism responsible for the reduction in total body water has not yet been explained.

The magnitude of the inflight water loss was estimated in several different ways, probably the most accurate of which was from the change in body mass. The loss in body mass early in the flight was 1.55 kg, whereas the gain in mass immediately following splashdown was 1.2 - 1.4 kg (section 6.6.1). The discrepancy between these estimates may be explained by the suggestion of Thornton and Ord (1977) that part of the early inflight loss in mass was caused by anorexia, due to 'space sickness' (section 3.2.1), and not by the mechanism which maintains the inflight total body water at a reduced level. Leach and Rambaut (1977) estimated the early inflight net loss of water to be 1800 ml, based on water balance data (section 6.6.3), but they pointed out that the data were so scattered that they did little more than indicate that a net loss of water <u>had</u> taken place.

The difference in the measured total body water between the beginning and end of the flight included not only the early inflight reduction in body water, but also the loss of water which would have accompanied any reduction in cellular mass, such as that due to the partial muscle atrophy thought to occur in flight (section 7.1.2). Tracer dilution measurements gave a 1.18 kg mean change in total body water over the course of the flight (Table 6-9), which is less than the estimated 1.2 - 1.4 kg early inflight water loss, and makes no allowance for a further loss of water due

to partial muscle atrophy. However, the standard deviation of the measurement of total body water is about 2% of the body weight, or about 1.4 kg (Table 2-2, page 24), and it is possible that the loss of total body water was underestimated. It is certainly difficult to reconcile a cellular water content of 75% (Allen et al 1959b) with the observed loss of 0.71 kg cell solids and 1.18 kg water (Table 6-9), unless it is assumed that either the cell solids were overestimated, or the water underestimated, or both. Estimates of the loss in total body water derived from the regression equations for total body volume and body weight were 1.4 kg and 1.8 kg respectively (section 6.5.4), but although these values are the expected order of magnitude, they were obtained very indirectly, and can not be regarded as at all accurate.

Taking all the data together, it seems unlikely that the mean change in total body water over the course of the flight was more than about 1.6 - 1.8 kg. There can be no doubt that some partial muscle atrophy took place during the flights (section 7.1.2), but if it is accepted that 1.2 - 1.4 kg of the water loss was due to the acute adaptation to zero gravity, the loss of water from muscle atrophy could not have exceeded 0.6 kg, corresponding to a mean loss of muscle mass of under 0.8 kg. This estimate is in accord with the estimated mean loss of 0.52 kg muscle from the legs, by biostereometric analysis (Table 6-9), but is in sharp contrast with the much higher estimates of cellular loss by other methods. It is possible that the water lost in the acute adaptation to zero gravity was somewhat less than the 1.2 - 1.4 kg estimated, and that part of the increase in weight during the first few days postflight was due to an increase in fat or muscle tissue, rather than to a simple 'rehydration', but without further studies there is no way to resolve this question.

Summarising the observations on the changes in body water, the Skylab results support the hypothesis that the body loses water during the first 1-2 days in orbit, as an adaptation to zero gravity. The loss of water appears to be mediated by a supression of thirst, rather than by a diuresis, as previously speculated. The mean loss has been estimated at 1.2 - 1.4 kg. The mean loss in body mass during the first 6 days inflight was 1.55 kg, probably made up of a combination of this loss of water, and a further loss of water, and possibly fat, resulting from the anorexia caused by 'space sickness' (section 3.2.1) during the first 3 days in orbit. Later in the flight there was almost certainly a further loss of water associated with the partial atrophy of skeletal muscles, due to relative disuse (section 7.1.2). The magnitude of this loss cannot be estimated with any precision,

ORIGINAL PAGE IS OF POOR QUALITY

but is unlikely to have exceeded 0.8 kg, and was more probably in the range 0.4 – 0.6 kg.

7.1.2 Cell Solids

The most direct information on the change in cell solids over the course of the Skylab flights was provided by the exchangeable potassium (Table 6-9), the mean loss being 0.71 kg. About 0.1 kg of this loss was undoubtably associated with the 0.2 – 0.3 kg loss of red cells reported by Johnson et al (1974) and described in section 3.3. The remaining loss of cell solids was presumably due to the partial atrophy of skeletal muscle, due to relative disuse in the absence of gravity. Several studies have demonstrated a reduction in the girth of the thigh or calf muscles following spaceflight (e.g. Berry, 1973b), and a progressive reduction in calf girth was observed in the Skylab astronauts over the course of the SL-4 flight (Johnson et al 1977). However, in such determinations it is impossible to distinguish between changes in girth due to changes in muscle mass, and those due to changes in fat or fluid. Evidence for muscle atrophy was provided by the high correlation between the change in leg volume and exercise (Table 6-10), and by the observation of a marked reduction in leg strength postflight (Thornton and Rummel, 1977).

Table 6-14 gave estimates for the change in cellular mass over the course of the mission, calculated from the exchangeable potassium, the nitrogen and potassium balances, and the biostereometric analysis. The latter differed from the other measurements in that it was an estimate of the change in muscle mass in the legs, rather than cellular mass in the whole body, although it is probable that the changes in leg muscle formed the greater part of the total change in cellular mass.

The most notable feature of Table 6-14 is that the values in columns (2) and (3) appear to be far too high. The Skylab mineral balance experiment was troubled by very erratic data, which the author believes was due to the investigators being unable to exercise sufficient control over the conduct of the experiment. It is simply impossible to believe, for example, that subject CR lost 4.71 grams of nitrogen and 10.99 milliequivalents of potassium per day over the course of the flight (Table 6-13), to give estimates for the cellular loss of 12.52 and 9.23 kg (Table 6-14), compared with a total loss of body weight of only 0.18 kg. It is the opinion of the author that the mineral balance results for potassium and nitrogen are incorrect, and they will not be considered further. It is to be hoped, however, that further analysis of these results may eventually produce some useful conclusions.

The estimated change in cellular mass from total body potassium (Table 6-14, column 1) is considerably higher than the estimated change in muscle mass in the legs by biostereometric analysis (column 4). Between 0.2 and 0.3 kg of the reduction in cellular mass may be explained by the loss of red blood cells, leaving a mean loss of about 2 kg from other tissues. As stated in section 7.1.1, it seems likely that this is an overestimate of the cellular loss. This is not surprising, since the measurement of cellular mass from total body potassium is relatively inaccurate, with a standard deviation of about 3% of the body weight, or 2.1 kg (Table 2-2).

It is impossible to assess the accuracy of the biostereometric estimates of leg muscle change (Table 6-14, column 4). The estimates are the order of magnitude suggested by considerations of total body water (section 7.1.1), but they show only partial agreement with the postflight measurements of leg strength by Thornton and Rummel (1977). The latter noted that the SL-2 and SL-3 crews showed a greater loss of strength from the legs than the SL-4 crew, and also noted that subject CN showed less change than the other two SL-2 crewmen, all of which agreed with the observed changes in muscle mass. However, they noted little difference in leg strength between the SL-2 and SL-3 crews, whereas the estimated loss of muscle mass was much greater in the SL-2 crew. Two factors complicate this type of analysis - firstly, while it is to be expected that there will be a general agreement between strength and muscle mass, it is unlikely that the two will always correspond, and secondly, the inflight exercise programme was complicated by the use of several different devices. Thornton and Rummel stated that the SL-2 crew used only the bicycle ergometer, whereas the SL-3 crew used also exercise springs, and a device called the Mk 1 exerciser, which provided isotonic exercise for various muscle groups. The SL-4 crew used all of these devices, and also a 'treadmill', in which the subject walked on a slippery surface, with elastic cords over the shoulders to simulate the force of gravity. The treadmill exercised primarily the calf muscles, which showed fatigue in a few minutes, in contrast with the bicycle, which could be used for prolonged periods, with fatigue occuring first in the thigh (Astrand and Rodahl, 1970). The regression equations for the change in leg volume (Table 6-11) supported the suggestion that the bicycle ergometer provided greater exercise for the thigh than for the calf, in that they predicted that an exercise level of 100 watt-min/day/kg LBM was necessary to prevent muscle atrophy from the calf, whereas a level of only 81 watt-min/day/kg LBM was necessary to maintain the thigh muscles at their preflight volume.

In summary, it is impossible to give an accurate estimate for the changes in cell solids over the course of the Skylab flights. The reported 0.2 - 0.3 kg reduction in the red cell mass over the course of the flights (Johnson et al 1974) accounts for a loss of about 0.1 kg cell solids. It is probable that the remaining changes in cell solids were associated with changes in muscle mass, although changes in tissues other than red blood cells and muscles cannot be ruled out. Estimates of the changes in cell solids derived from the mineral balance experiment were extremely high, and almost certainly in error. The change in total body potassium gave an estimated mean loss of 0.71 kg cell solids, equivalent to a cellular loss of about 2.3 kg. Such a loss is not supported by the changes in total body water, and it is probably an overestimate. Biostereometric analysis provided estimates for the change in muscle mass in the legs of -1.43 kg to +0.10 kg, with a mean value of -0.52 kg. Such values appear to be the correct order of magnitude, but it is impossible to assess their accuracy, and they do not account for any changes in parts of the body other than the legs.

7.1.3 Fat

The changes in body fat over the course of the Skylab flights were examined in two ways - by attempting to determine the changes occuring in all of the body compartments (Table 6-9), and by relating the caloric intake of the subjects to their changes in total body volume (Table 6-12). There was, unfortunately, only a weak correlation between these two estimates ($r = 0.69$, significant at the 5% level), although they agreed that subject CR gained fat during his time in orbit, and that 7 of the others lost fat, the results disagreeing for subject P. Table 6-9 gave a mean loss of 1.20 kg for the 9 subjects, whereas the biostereometric analysis estimated the mean loss to be only 0.58 kg.

The estimates given in Table 6-9 were based on the measurements of total body water, exchangeable potassium, and body volume. Each of these measurements has an estimated standard deviation of about 2% of the body weight (Table 2-2). Adding variances, and ignoring the relatively small inaccuracies involved in the measurement of body weight, the standard deviation for the estimation of body fat was 3½%. The standard deviation for the postflight change in body fat, given in Table 6-9, was 1.40 kg, or about 2% of the body weight. This figure included both measurement errors and true subject-to-subject variation. The measurement was, therefore, rather more accurate than the 3½% estimated above. However, the latter figure applied to absolute determinations of body fat, and it is probable that the accuracy for repeat measurements in the same subject would have

been better than this.

The estimation of change in body fat from caloric intake is prone to two types of error - the errors of the biostereometric volume determination, probably with a standard deviation of about 2%, and the errors introduced by the assumption that all the subjects would have the same ratio of caloric needs to lean body mass. Even if all the subjects had the same basal metabolic rate (per kilogram LBM), there were considerable differences between them in the amount of exercise taken (Table 6-2). This could have been expected to produce differences in caloric requirements from one subject to another, and hence to produce a spread in the values for the caloric 'NEEDS', derived in section 6.5.2. 1000 watt-minutes of exercise (60 kilojoules) represent an energy consumption of 57 kilocalories, assuming a 25% efficiency for bicycling (Astrand and Rodahl, 1970). The greatest difference in inflight exercise (between subject K and subject GB) was 67.2 watt-min/day/kg LBM, which is equivalent to a caloric difference of 3.8 kcal/day/kg LBM. Thus the mean inflight caloric requirement of 49 kcal/day/kg LBM, derived in section 6.5.2, is subject to individual variation, although it seems likely that the range 47-51 kcal/day/kg LBM would apply to the majority of the subjects. On this basis, the accuracy of determining the change in body fat from the caloric intake is unlikely to be better than 1 S.D. = 1.4 kg, or about 2% of the body weight. Thornton and Rummel (1977) estimated the caloric 'NEEDS' to be 51.6 kcal/day/kg LBM, based on the inflight change in body mass (section 6.6.1), a value which agrees fairly well with the present estimate.

One aspect which should be discussed is whether the loss of fat observed in at least 7 of the astronauts was due to a lack of appetite, or to dietary restrictions. With the exception of subject W, who told the author that he had deliberately under-eaten, as he thought he was overweight, there can be no doubt that the loss of fat was due to the strict enforcement of the pre-planned diet, in support of the mineral balance experiment. Except for subject W, all the astronauts on the SL-2 and SL-3 missions complained of hunger, after the first few days in flight. The diets had been planned to contain about 300 kcal/day less than the astronauts usually ate, following the recommendations of Vanderveen and Allen (1972), although a further 300 kilocalories were available, for use if required, in the form of items such as sweets and bicuits, which contained no nitrogen or minerals. These items proved unpopular, however, and from the midpoint of the SL-3 flight the controls had to be relaxed, to permit additional items of more conventional foods to be eaten. The SL-4 crew did not complain of hunger, having been permitted a much greater food intake, and as a

ORIGINAL PAGE IS OF POOR QUALITY

result at least crewman CR returned to earth with an increased body fat. There is thus little doubt that the loss of body fat is not an inevitable result of spaceflight, and the planners of future long term missions must aim to provide around 49 kcal/day/kg LBM for the crewmen.

Summarising the findings relating to changes in body fat, two methods were used to examine this body compartment in the Skylab astronauts. One was based on the total body water, potassium and body volume, and the other on the relationship between caloric intake and the postflight change in body volume. Both methods had an estimated standard deviation of between one and two kilograms. The mean change in body fat by the first method was a loss of 1.20 kg, and by the second method a loss of 0.58 kg. The correlation between the two sets of results was poor, probably because the changes observed were similar in magnitude to the standard deviations of the two methods. Nonetheless, the methods agreed to the extent that one subject gained fat during his flight, and another 7 subjects lost fat, the results disagreeing on the remaining subject. The high correlation between caloric intake and change in body volume strongly suggests that a caloric intake of between 47 and 51 kcal/day/kg LBM is necessary to prevent the loss of body fat over the course of a flight.

7.1.4 Bone Mineral

Two experiments provided information on the change in bone mineral over the course of the Skylab flights - bone densitometry and mineral balance. Table 6-17 summarises the results of both experiments.

Measurements of control subjects in the bone densitometry experiment gave standard deviations of up to 1.2% for the radius, 1.8% for the ulna, and 1.6% for the os calcis (Vogel and Whittle, 1974). Postflight changes of less than two standard deviations were regarded as insignificant, and using this criterion the only significant changes observed in the Skylab crewmen were losses of density from the os calcis of 7.4%, 4.5% and 7.9%, from subjects CR, GD and P, respectively.

As stated in section 7.1.2, the results from the mineral balance experiment were erratic and difficult to interpret. In the case of calcium, the faecal excretion was extremely variable, and the balance calculations gave no consistent pattern. In contrast, the urinary calcium was relatively stable from day to day, and showed a consistent pattern inflight, increasing over the course of 3 - 4 weeks to between 1.5 and 2.7 times the preflight value (mean 1.9), at which level it stabilised for the remainder of the flight.

If the urinary excretion in the last column of Table 6-17 had persisted for the whole of the flights, the subjects would have lost between 3 and 15 g calcium while in orbit, equivalent to between 8 and 37 g bone mineral. In practice, however, the loss would have been less than this, as the calcium excretion built up to its final level over the course of 3 - 4 weeks. Although such calculations are very approximate, they tally with the results of the bone densitometry experiment, in that the highest losses of calcium were observed in subjects GR and P, followed by subject GB.

In Table 6-9, the subjects were estimated preflight to posess between 3.19 and 4.81 kg of bone mineral. The estimated losses of up to 37 g thus represent at most only about 1% of the total. The investigator for the bone densitometry experiment, Dr. J.M. Vogel, told the author that in prolonged immobilisation the densities of the distal radius and ulna tend to reflect the total body calcium, whereas the os calcis loses density much more rapidly. The failure to observe a change in the density of the distal radius and ulna is thus in line with the very modest estimated loss in total body bone mineral. It is not known whether the loss in density of the os calcis is a magnified reflection of a change in total body calcium, or whether it is primarily a local phenomenon, due to the removal of stress from this particular bone.

One interesting observation is that subject CR did not show a loss of density from the os calcis, when his estimated urinary calcium loss was only 23% less than that of subject GB, who had a 4.5% loss of density. Dr. W.E. Thornton, who was responsible for the inflight exercise programme, told the author that subject CR was the only astronaut to perform 'toe springs' inflight, an exercise performed on the treadmill (section 7.1.2) in which the heels were repeatedly lifted off the walking surface by contraction of the calf muscles. This exercise could be expected to produce a considerable shear stress in the os calcis, and also some compressive stress as the heel impacts back onto the walking surface, and it is interesting to speculate that this subject may have thereby prevented a significant loss of calcium from this bone. However, there was no general correlation between the inflight exercise (Table 6-2) and either the urinary calcium excretion or the change in density of the os calcis.

Whedon et al (1977) anticipated no serious difficulties due to calcium loss on flights of 6-9 months, but they regarded the development of protective measures as essential for flights of any greater duration. This subject is further considered in Chapter 9.

Summarising the observations on bone mineral, the urinary calcium increased during the first 3 - 4 weeks of the flight, to an average of nearly double its preflight value, thereafter remaining at that level for the rest of the flight. The loss of calcium varied considerably from one subject to another, the mean loss being 155 mg/day during the 4th week of the flight. The total loss of calcium, estimated from the urinary excretion and the time in orbit, was in the range 3 - 15 g, equivalent to 8 - 37 g bone mineral, or less than 1% of the body total. Bone densitometry showed no measurable loss of density from the radius and ulna, an observation which is consistent with a loss of bone mineral of less than 2 - 3% of the body total. 3 subjects, however, had significant losses of density from the os calcis; they also had the highest inflight losses of calcium, estimated from the excretion data. It is possible that exercise taken inflight may have modified the change in density in the os calcis, in at least one subject.

7.2 Postflight Recovery of Body Composition

Only limited information is available on the changes in body composition which occured after the astronauts returned to earth. However, it is possible to deduce the general pattern of the postflight changes from such data as exist.

The mean body weight increased rapidly for the first 3 days postflight, after which it stabilised (Figure 3-1, page 32). This pattern is consistent with an increase in total body water to replace that which was lost early in the flight (section 7.1.1), although the change appears to have been slower, taking about 48 hours, in contrast to the inflight loss of water, which was almost complete in 24 hours. The postflight increase in body water was apparently brought about mainly through an increase in fluid intake (Leach and Rambaut, 1977). The author observed that all the astronauts were very thirsty following their flights, and it seems likely that both the inflight loss of water, and its postflight replacement, were brought about by an alteration in thirst. It is not known how an alteration in gravity is able to modify the thirst mechanism, and there is a clear need for further research to explain this observation. The postflight replacement of body water was confirmed by the observation that the total body water of all the subjects had returned to approximately preflight values by the next time it was measured, around R+14 (Dr. Carolyn Leach - personal communication).

Very little information exists on the changes in either cell solids or fat during the postflight period. A gradual replacement of cell solids is suggested by the observation that about two thirds of the postflight

deficit in exchangeable potassium had been replaced by R+14 (Dr. Carolyn Leach - personal communication). All of the astronauts slowly increased their body weight during the postflight period (see appendix), indicating an increase in fat, or muscle, or both of these.

The changes in regional body volume (Table 6-5, Figures 6-1 and 6-2; pages 74-76), indicated a general increase in the volume of all regions of the body during the postflight period, fairly rapidly during the first 4 days, and thereafter more slowly. There were insufficient measurements, however, to establish the exact time course of the changes. It was originally intended to make measurements on the SL-4 crew at R+31, but unfortunately administrative difficulties prevented this. The R+68 measurements of the SL-4 crew showed considerable increases in the volume of the buttocks and thighs, strongly suggesting an increase in body fat over this period, an observation which is supported by the fact that their mean weight at this time was 2.8 kg higher than preflight. It is unfortunately impossible to distinguish between the gains in volume due to fat, and those due to muscle, so although it seems likely that any muscle mass lost during the flight would have been replaced during the postflight period, this cannot be confirmed. If, as suggested in section 4.8, future work is able to establish the patterns of regional volume change associated with alterations in fat and muscle, it might well be possible to distinguish between the changes in fat and muscle on the Skylab data.

No estimates of lean body mass were made during the late postflight period, because the biostereometric analysis, and the measurements of total body water and exchangeable potassium, were made several days apart.

The red cell mass returned to its preflight level 30 - 60 days after the flight, recovery being slowest following the shortest flight, and quickest following the longest one, an observation which has yet to be explained (Johnson et al 1974).

The bone densitometry experiment revealed a very slow recovery in the density of the os calcis during the postflight period. Subject GR had regained his bone mineral by R+87, whereas subjects GB and P had not fully returned to preflight levels by the last occasion on which they were measured, R+95 (Vogel and Whittle, 1974). These observations suggest that it took longer to replace the bone mineral than it did to lose it. The urinary calcium was monitored for 18 days postflight, during which time it fell steadily, reaching the preflight level after 12 - 18 days. It is to be presumed that calcium retension took place during the postflight period, to replace the inflight losses, but apart from the increases in

ORIGINAL PAGE IS OF POOR QUALITY

density of the os calcis, reported above, there is no evidence to support this assumption.

In summary, all of the changes which occured in flight apparently reversed during the postflight period. There is very little information available, however, on the postflight changes in muscle or fat. Both water and bone mineral were probably replaced more slowly than they had been lost in flight. The red cell mass was restored to preflight values in 30 - 60 days. There is no evidence to suggest that any of the astronauts suffered a permanent change in body composition as a result of his time in space.

7.3 Techniques for the Measurement of Body Composition

The present study is probably the first in which water, cell solids and fat have been measured simultaneously in a group of individuals, thereby covering 3 of the 4 body 'compartments' suggested in Table 2-2. It is regrettable that the fourth compartment, bone mineral, was not also measured, but it is understandable that the NASA management should err on the side of caution, when considering the radiation dose involved in neutron activation analysis.

When the lean body mass (LBM) was calculated from the total body water, exchangeable potassium and body density, both singly and in combination, surprising variability was observed (Table 6-6). The results strongly suggested that the widely accepted formulae for estimating the LBM from these variables were incorrect. In particular, the total body water gave slightly high estimates for the LBM, and the exchangeable potassium very low ones, when compared with all the other estimates. It cannot be ruled out, however, that the discrepancies were due to differences between the astronauts' body composition and that of the 'normal' population, possibly as a result of their high physical fitness.

Despite the uncertainties in its measurement, the LBM is a good basis for 'normalising' data, in order to compare results between individuals (Behnke, 1953; von Dobeln, 1956). Without such normalisation, the analysis of the present results, with respect to diet and exercise, would not have been possible. When used in this way, it is likely that errors of 2-3 kg in the LBM are of little consequence, and the common practice of estimating it from either the total body water or potassium is acceptable. When studying body fat, however, it is considered that these two methods are insufficiently accurate, and one of two other approaches should be used: 1) To estimate LBM from body density, the volume determination being made by underwater weighing (Behnke et al 1942) or volumetry (Allen, 1965). While biostereometric analysis, after further development, will almost

certainly be acceptable for this purpose, the results given in Table 6-6 suggest that, at present, the method is not accurate enough.

2) To estimate LBM by the 'combined estimate' method described in section 5.3.5, by measuring total body water, total body potassium, and body volume. In the present study the biostereometric method was used to estimate body volume, as no other method was possible, but again the accuracy, as it exists at the moment, is probably a little lower than desirable. For the most accurate estimate of LBM, it would also be advantageous to measure the bone mineral, by neutron activation analysis, although this is probably unnecessary except in special cases. The body contains 3-5 kg of bone mineral (Table 6-9), and an error of 20% in its estimation would amount to only about 1% of the body weight, which is comparable with the accuracy with which the other body 'compartments' can be measured (Table 2-2).

When studying loss of weight, whether from spaceflight or from other causes, a knowledge of the density of the tissue lost would make it possible to say whether the loss consisted of fat, water, tissue solids, or a mixture of these. Unfortunately, none of the present techniques is sufficiently accurate for this purpose. Dr. P.C. Rambaut, one of the investigators for the biostereometric study of the Apollo 16 astronauts (Berry and Smith, 1972), told the author that the results of this experiment were not published in full, because the calculated density of the tissue lost was outside the physiological range. The reason for this is that the changes occuring could not be measured with sufficient accuracy, since they were similar in magnitude to the standard deviation of the measurement technique. For example, an error of 1 litre in the volume determination, which could be expected even from a technique with a standard deviation as low as 1%, would represent a 33% error in determining the density for a tissue loss of 3 kg.

It seems unlikely that methods of measuring gross body composition will, in the forseeable fututre, reach the accuracy required to determine the tissues involved in changes of weight of the order of a few kilograms. However, two approaches appear promising for such investigations:

1) The use of a carefully conducted metabolic balance technique, such as that a Deitrick et al (1948). This procedure was attempted on Skylab, but the results were very variable, as discussed in section 7.1.2. The metabolic balance technique is much better at detecting changes in bone mineral and cell solids, which are reflected in changes in the calcium and nitrogen balances, respectively, than for studying either water or fat, as it is generally impractical to measure either the insensible water loss or the expenditure of metabolic energy.

2) The use of the biostereometric technique to determine the change in volume of different regions of the body. Although more background studies are needed, the results obtained in the present study suggest that changes in the different 'compartments' of the body are associated with characteristic patterns of regional volume change, and that knowledge of these could be used to determine the tissue changes in a given subject.

It thus appears that the biostereometric technique is potentially a very powerful tool for the study of body composition, and its ability to measure regional body volumes, rather than being simply a by-product of the measurement of total body volume, may prove to be its most useful attribute.

CHAPTER 8

CONCLUSIONS

1. The 9 Skylab astronauts returned from their spaceflights weighing less than they did at the time of launch, the mean loss being 3.03 kg, with a range from 0.18 to 5.17 kg. This weight loss was similar to that observed on earlier American and Russian flights. The change in body weight is thought to have resulted from changes taking place in all 4 of the major body compartments - water, fat, cell solids and bone mineral.

2. Water was lost from the body during the first 1-2 days in orbit, probably by a considerable reduction in fluid intake, in the presence of a slightly reduced urine volume, in response to the movement of blood into the central venous pool. The estimated loss, in a crewman of average size, was 1.2 - 1.4 kg. It was replaced in 2-3 days following return to earth. The thirst mechanism is thought to have played a key role in bringing about the changes in total body water, although the mechanism is unexplained.

3. At least 7 of the 9 astronauts lost body fat, probably due to the combined effort of anorexia early in the flight, and inadequate caloric intake later, due to strict dietary control. The greatest estimated loss of fat was 2.73 kg, and the mean loss was 0.58 kg.

4. There was a high correlation between the inflight caloric intake and the change in total body volume. From this relationship it was deduced that a caloric intake of 47-51 kcal/day/kg lean body mass would be necessary to prevent the loss of fat while in orbit.

5. Changes in cell solids were thought principally to be due to the loss of red blood cells and muscle tissue. The loss of red blood cells amounted to 0.2 - 0.3 kg, the loss becoming smaller as the mission length increased. The mechanism for the loss has not been fully explained, although it may be associated with the haemoconcentration which accompanied the inflight reduction in total body water.

6. Changes in muscle were measured with less certainty, but it is probable that all but one of the Skylab astronauts lost muscle from the legs, the greatest estimated loss being 1.43 kg, and the mean loss 0.52 kg. It is possible that muscle was also lost from parts of the body other than the legs.

7. There was a high correlation between the inflight level of exercise on the bicycle ergometer, and the change in volume of the legs. From this it was calculated that an inflight excerise of 80-100 watt-min/day/kg lean body mass would be necessary to prevent atrophy of the leg muscles. It is possible, however, that some of the other exercise devices used may have been more important than the bicycle ergometer in limiting the extent of the muscle atrophy.

8. Although contributing little to the change in body weight, losses of bone mineral of up to 1% occured in the Skylab astronauts. Local losses of bone density of up to 8% were observed in the os calcis of 3 subjects. The loss of bone mineral could be expected to produce a significant weakening of certain bones after 6-9 months.

9. Biostereometric analysis, using stereophotogrammetry, was used to measure the total and regional body volumes of the Skylab astronauts. The estimated standard deviation for the volume measurement was 2%, although there is a systematic difference between the results from this method and those from underwater weighing. Certain improvements in the method, and a series of studies on the effects of diet and exercise on regional body volume, could make this method one of the most accurate and versatile for the study of body composition.

10. In contrast to other methods of studying body composition, the stereoscopic photographs of the Skylab astronauts form a permanent archival record of their preflight and postflight body form, which can be re-examined at any future date, either to answer new questions, or to take advantage of improvements in analytical technique.

Item 5

THREE-DIMENSIONAL DISPLAYS IN BIOSTEREOMETRICS

R. E. Herron

Reprinted from

SPIE Vol. 120, Three-Dimensional Imaging, 1977

THREE-DIMENSIONAL DISPLAYS IN BIOSTEREOMETRICS

R. E. Herron
Fleming Department of Rehabilitation
Baylor College of Medicine
1333 Moursund
Houston, Texas 77030

Abstract

In biostereometrics, which is a modern approach to the study of biological form and function based on three- and, often, four-dimensional measurement of living organisms and their constituent parts, three-dimensional displays already serve many useful functions. These can be classified into two main categories, where the three-dimensional display is used: (1) as a substitute for the object itself or (2) to highlight spatial or spatio-temporal features of particular interest. In the former category, the ability to "freeze" the form of a living organism and to analyze the resulting photo-optical analog *ad infinitum* without fear of object movement is a major advantage over conventional direct measurement methods. Applications which fall into the second category are particularly valuable for conceptual and educational purposes. Such applications are expected to grow as clinicians, biomedical scientists, biologists and others become more familiar with the potentials of biostereometrics and suitable graphic display capabilities become more widely available.

Biostereometrics is a modern approach to the study of biological form and function based on three- and, often, four-dimensional measurement of living organisms and their constituent parts. In this exciting new field, three-dimensional displays already serve many useful functions. For present purposes, we can classify these functions into two main categories where the three-dimensional display is used: (1) as a substitute for the object itself or (2) to highlight spatial or spatio-temporal features of particular interest.

To appreciate the importance of these roles it is necessary to understand some of the difficulties associated with measuring the form of a living organism. For example, there is the fact that living organisms are dynamic, which means that they change their form from moment to moment. Thus, during the time it takes to make just one direct contact measurement, the organism may significantly alter its form (e.g., by breathing or postural changes) so that the measurement becomes less meaningful or even useless. However, the capacity to create a photo-optical three-dimensional "replica" of an organism at a particular instant in its life cycle eliminates the above problem. In effect, the form of the living organism is frozen and permanently recorded on a set of stereophotographic plates or, perhaps, as a hologram. The resulting photo-optical analog can then be substituted for the organism itself and analyzed *ad infinitum* without fear of object movement.

There are other benefits from this approach which bear mentioning. For example, let us consider the case of an orthopedic surgeon evaluating the outcome of a surgical procedure to correct a spinal deformity. By replacing the patient with a three-dimensional photo-optical display, the evaluation process can be made more comfortable for the patient and more comprehensive and effective for the

surgeon. Three-dimensional displays can serve a similar function in plastic reconstructive surgery, growth studies and other biomedical fields where detailed structural analyses are required.

Another example from orthopedics illustrates the second main role served by three-dimensional displays in biostereometrics. Here the display is used to highlight the spinal curvature in a record of upper body geometry. Using stereometric data (XYZ coordinates) as input and software developed by my colleague, Professor Jaime Cuzzi, a computer graphics terminal is used to display the spinal curvature using different three-dimensional perspectives.

In the short time available today, it is impossible to review in detail the wide range of functions served by three-dimensional displays of biostereometrics. A few examples from recent studies (Fig. 1-12) must suffice. All of the examples illustrated below fall into one or both of the two main categories mentioned earlier, but in each case the function is quite distinctive. After reviewing these wide-ranging applications, it should not be difficult to appreciate the significance of three-dimensional measurement and display in biology and medicine. Although recent developments in holography and CT scanning have helped stimulate greater interest in three-dimensional displays in the biomedical sciences, the exploitation of such displays in biostereometrics, (where the focus is on measurement and analysis rather than the perpetration of "eye-balling" procedures) is just beginning.

Sample Three-Dimensional Displays from Biostereometrics

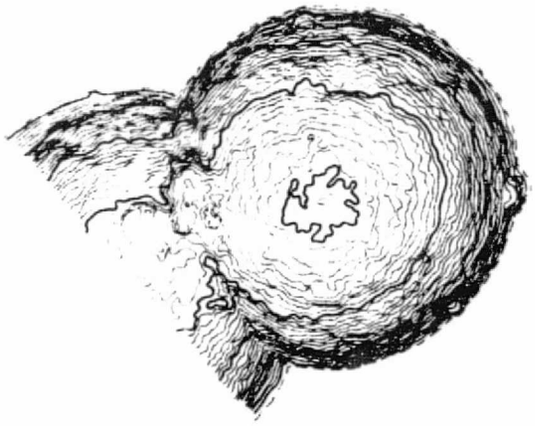


Figure 1

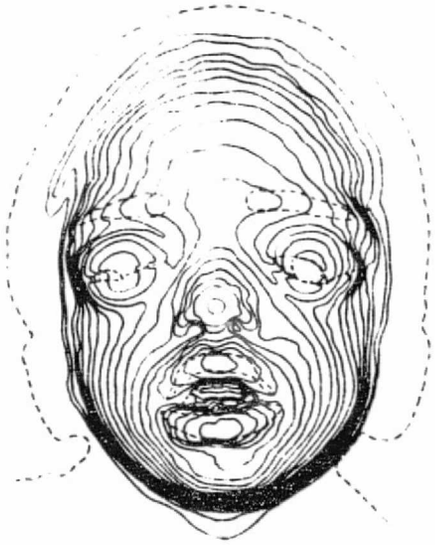


Figure 2

Figure 1 Contour map of two-celled mouse embryo.

Figure 2 Contour map of facial deformity (hypertelorism).

Figure 3

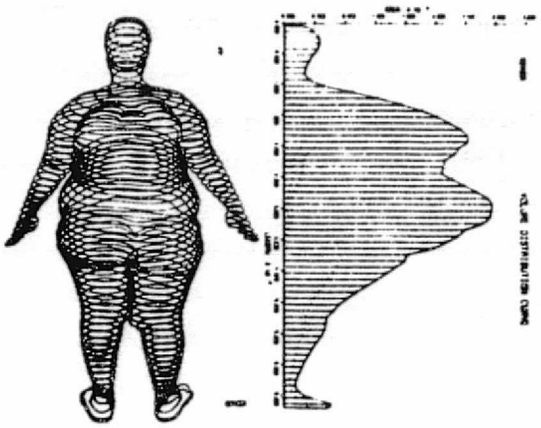


Figure 4

VOLUME DISTRIBUTION OF TISSUES IN LOWER LIMB SEGMENT

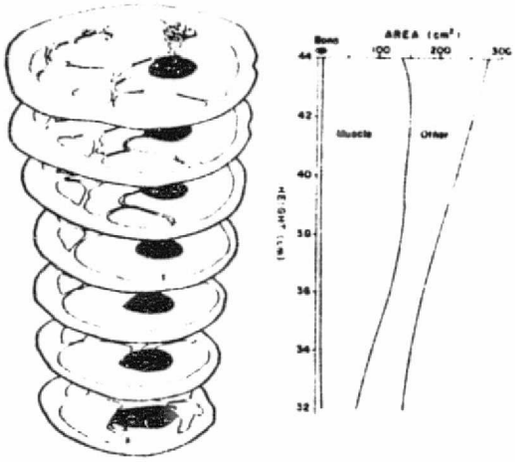


Figure 5

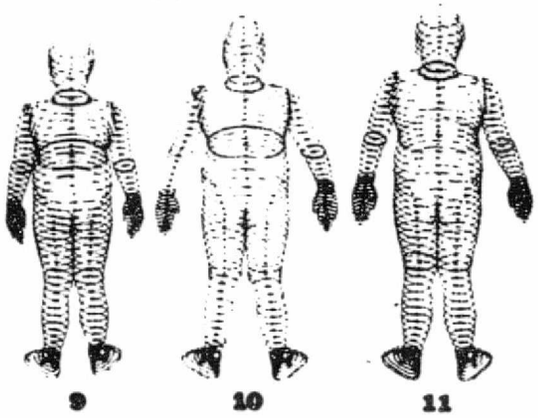


Figure 6

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 3 Cross-sectional plot (left of body form from CRT display. "Computerized moiré" plot (right) obtained by superimposing fine grid over the cross-sectional plot.

Figure 4 Cross-sectional plot and volume distribution curve (cross-sectional area v vertical elevation) of patient prior to treatment for obesity.

Figure 5 Serial cross-sections of limb segment alongside graph showing volume distribution of muscle in relation to other tissues.

Figure 6 Stereometric records of an individual's body form at ages 9,10 and 11 years.

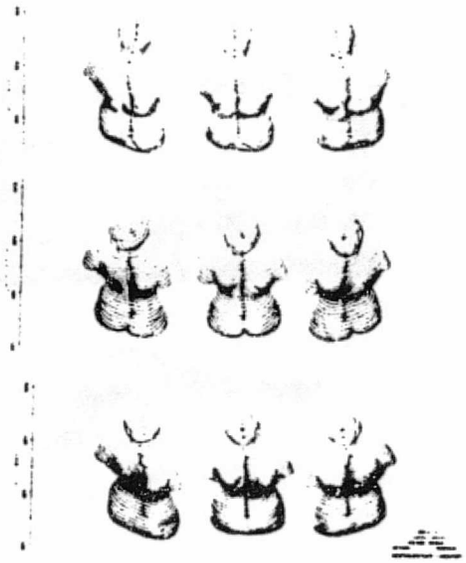


Figure 7

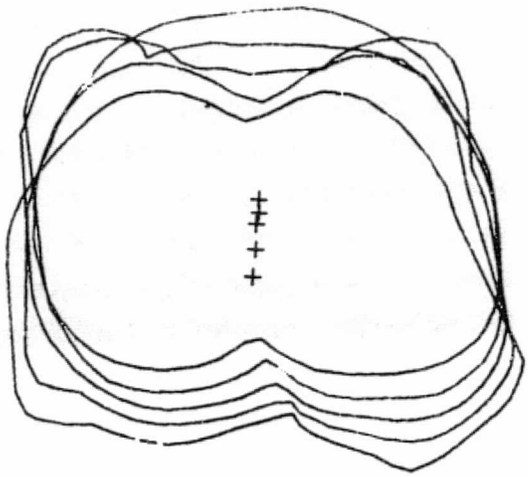


Figure 8

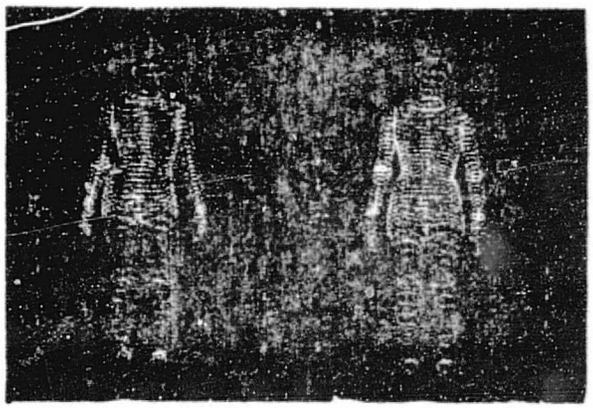


Figure 9

ORIGINAL PAGE IS
OF POOR QUALITY

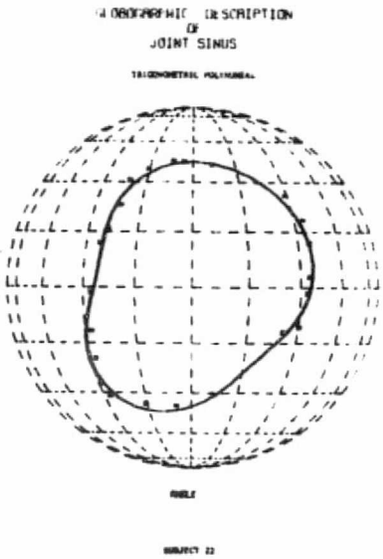


Figure 10

Figure 7 Cross-sectional plots from different perspectives showing the trunk of a patient with spinal deformity.

Figure 8 Selected cross-sections (looking down through the trunk) illustrating important features of trunk geometry. The plus signs indicate the mathematical or isometric centers of the individual cross sections.

Figure 9 Cross-sectional plots of patient with spinal deformity (scoliosis) recorded immediately prior to and six months after surgical correction.

Figure 10 Globographic display of maximum joint (ankle) range of movement. The trace represents the 3-D trajectory of the distal segment of the joint.

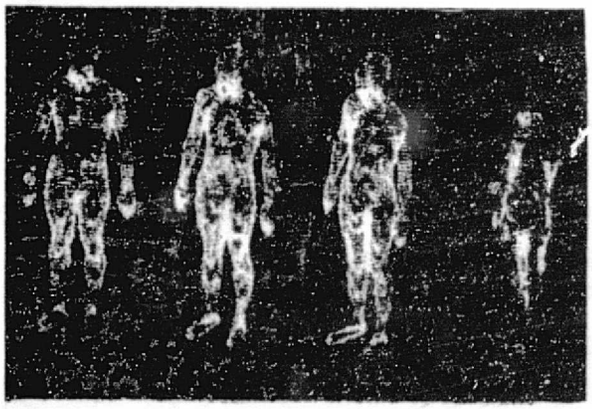


Figure 11

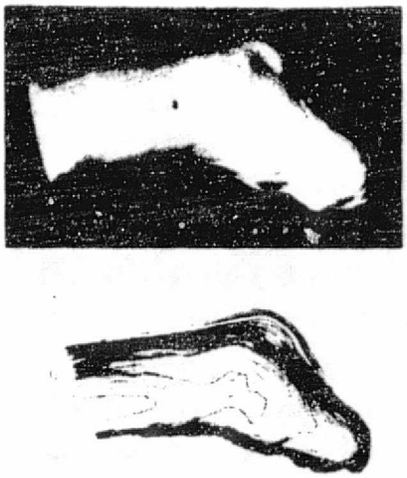


Figure 12

Figure 11 Series of rotated cross-sectional plots of body form with computer-controlled superimposed moiré contours.

Figure 12 Solid 3-D plastic model (above) carved with computer-controlled (N/C) carving device from contour data (below).

Item 5

CONTINUING DEVELOPMENT OF BIOSTEREOMETRIC TECHNIQUES FOR IN-FLIGHT BODY VOLUME STUDIES

R. E. Herron, Ph.D., Professor
Department of Rehabilitation
Director, Biostereometrics Laboratory

Texas Institute for Rehabilitation and Research
Baylor College of Medicine
1333 Moursund
Houston, Texas 77030
713-797-1440

R. E. Herron, Ph.D.
Principal Investigator

For Period:

March 1, 1975 to February 28, 1978

William A. Spencer, M.D.
Professor and Chairman
Department of Rehabilitation

Nicholas C. Hott
Business Manager

Date of Submission: January 31, 1977

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE OF CONTENTS

	Page
TITLE PAGE	1
I. INVESTIGATION AND TECHNICAL PLAN	2
A. Investigation and Technical Plan	2
1. Summary	2
2. Objectives and Significant Aspects	3
3. Investigative Approach	5
B. NASA Instrument Fact Sheet	17
C. Data Reduction and Analysis	18
D. Results Expected	18
E. Payload Specialist Support	18
F. Flight Operational Requirements	18
G. Post-Flight Requirements	19
II. MANAGEMENT PLAN AND COST PLAN	19
A. Management Plan	19
B. Cost Plan	20
APPENDIX	

Title: Biostereometric Analysis of Body Volume Changes During Sustained Weightlessness

Principal Investigator: Robert Ernest Herron, Ph.D., Texas Institute for Rehabilitation and Research, Baylor College of Medicine
1333 Moursund Avenue
Houston, Texas 77030 Telephone: 713/464-5154

Co-Investigators: Jaime R. Cuzzi, B.S., Texas Institute for Rehabilitation and Research, Baylor College of Medicine

Michael J. Whittle, M.Sc., M.B., B.S., Texas Institute for Rehabilitation and Research, Baylor College of Medicine (to be appointed; current affiliation, RAF Institute of Aviation Medicine, Farnborough, Hampshire, England)

Consultant Ulrich C. Luft, M.D., Ph.D., Lovelace Foundation for Medical Education and Research, 5200 Gibson Blvd., S.E., Alburquerque, New Mexico 87108

I. INVESTIGATION AND TECHNICAL PLAN

A. Investigation and Technical Plan.

1. Summary. Biostereometric measurement of body form using a specially designed stereometric camera system has been successfully used to determine changes in regional and total body volume in the crew of Apollo 16 and three Skylab missions. These measurements were, however, restricted to the pre- and post-flight 1 gravity environment, leaving a large gap in our knowledge about body volume changes which occurred in zero gravity. Future shuttle flights will afford an excellent opportunity to study in great detail the body volume changes which occur in flight. The biostereometric experiment conducted on SMS-II (January 1976, LBJ Space Center) demonstrated the feasibility of making such inflight measurements in a shuttle environment. The available space proved more than adequate and the responsible payload specialist found the equipment simple to operate and the time demand (20 minutes per day) modest, considering the uniqueness, comprehensiveness, and utility of the data. Only minor modifications of the procedure are anticipated for zero gravity shuttle operation.

The significance of the body volume changes recorded before and after long-term space missions have been discussed at some length in our previous Skylab related reports. However, the lack of inflight body volume data has precluded more definitive evaluation of fluid shifts and other modifications in body volume distribution which are central to a better understanding of the physiological mechanisms of human space adaptation.

The proposed inflight measurement of body volume changes using the rapid, portable, non-contact biostereometric camera unit (developed and validated over the last seven years with NASA support) will provide valuable data related to important cardiovascular, nutritional and neuromuscular research questions about human adaptation to zero gravity.

2. Objectives and Significant Aspects. Preflight and postflight measurement of body volume and regional volume distribution in Skylab astronauts revealed changes in the quantities of fluid, muscle and fat in their bodies. All nine astronauts demonstrated regional changes in volume distribution which could be related to changes in total body water, muscle mass, and fat deposits. The change in water resulted from a redistribution of fluid in response to zero gravity. Changes in muscle mass resulted from an alteration in patterns of muscle activity in the absence of gravity and changes in fat resulted from discrepancies between the individual's caloric needs and his food consumption.

The volumetric analysis in these studies was based on biostereometrics, a relatively new science which is emerging as a powerful tool in the biomedical sciences. The hardware consisted of a set of two stereometric cameras developed with NASA support at the Biostereometrics Laboratory at the Texas Institute for Rehabilitation and Research, Baylor College of Medicine.

From the front and rear view stereoscopic photographs taken of each crew member, pre- and post-flight, three-dimensional coordinates of numerous points on the body surface were derived using a stereoplotter; these data, in turn, provided the input to a computer which was programmed to yield the volume of segments of the body and the body as a whole. These data have proved to be of great value as a means of gaining insights into the effects of space flight on human physiology which were impossible using any other method. The records obtained in connection with the Skylab missions constitute an archival documentation of the entire body geometry of each astronaut before and after his flight. Analysis of the data is continuing and as new questions arise the body models can be re-examined to satisfy those needs.

Although we have learned a great deal about the effects of space flight on body volume and volume distribution through the Skylab studies, we are still lacking any comparable data concerning the body volume and volume distribution changes which occur during the mission. Therefore, the main purpose of the present study is to measure and evaluate changes in body volume and volume distribution in flight. The results will be examined in relation to current theories about the mechanisms of short-term and long-term human adaptation to sustained weightlessness, with special emphasis on the cardiovascular and nutritional implications for human space operations.

To put it briefly, biostereometrics is the spatial and spatial temporal analysis of biological form and function based on principles of analytic geometry. When applied to humans, it constitutes a modern approach to anthropometry and plethysmography. A suitable stereometric sensor (in this case a pair of stereometric cameras) is used to locate the three-dimensional coordinates of points distributed over the body surface. The coordinates serve as input to a digital computer which is programmed to yield permutations of numerical or analog (physical or graphical) outputs as the application requires. A series of studies conducted under the sponsorship of NASA, Air Force, Army, DOT-NHTSA, SRS, and other government agencies, has led to the development of a solid scientific foundation for the field. Recent, double-blind studies have shown remarkably high correlations between the biostereometric measurement of body volume

and the traditional hydrostatic weighing method (Luft & Herron, 1976). However, the portability and non-contact features of the biostereometric approach confer obvious practical advantages for the measurement of inflight body volume changes.

The data reduction procedures are based on well established principles of engineering instrumentation and mathematics, which have been developed and tested over many years in the earth sciences, most notably in cartography and surveying. Special hardware and software developed at the Biostereometrics Laboratory has been used effectively in over 30 investigations during the last 10 years. Further details of these studies are contained in a number of articles and project reports (see Appendix).

The current status of our research concerning the effects of sustained weightlessness on human body volume was the subject of a recent article by Whittle, Herron, Cuzzi, and Keys (1976). The working hypothesis underlying this research is illustrated in Fig. 1.

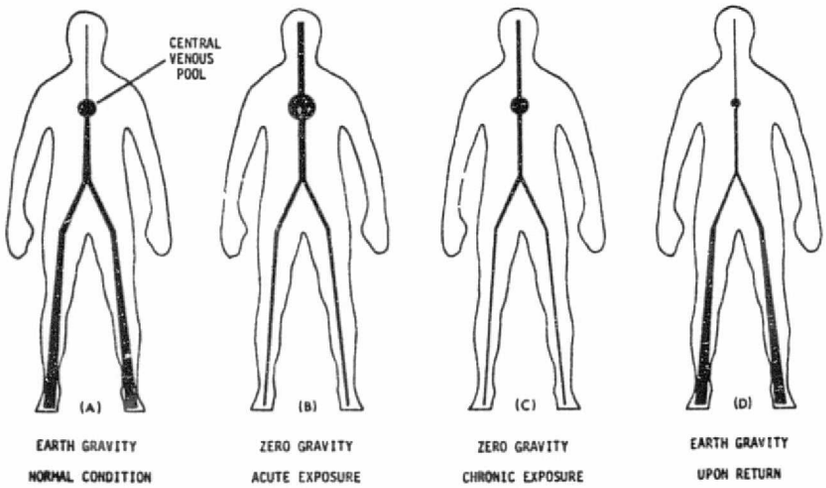


Figure 1. Response of the circulating blood volume to zero gravity.

3. Investigation Approach.

a. Concept of the Investigation.

The sustained weightlessness experienced during space flight has two main influences on the body: it removes the normal hydrostatic pressure gradient from head to foot and it makes postural control and locomotion less demanding than under terrestrial (1 gravity) living conditions. The ensuing physiological effects are not yet completely understood, but a working hypothesis which has gained wide currency goes as follows. The adaptation begins when weightlessness causes a reduction in weight of the long columns of blood in the body. This reduces pooling of blood in the extremities and concentrates greater amounts in the chest regions. There is then a change in the ratio of blood to air in the lungs. Increased amounts of blood return to the right side of the heart. This increases the volume in the right atrium and initiates a reflex stimulus (the Henry-Gauer reflex) to the pituitary gland. This reflex causes a reduction in secretion of antidiuretic hormone; more urine is excreted. As urine flow increases, the adrenal gland is stimulated to increase the level of aldosterone, another hormone, probably due to the renin-angiotensin mechanism. Aldosterone causes the kidneys to retain sodium. But there is no observed system that causes the kidneys to retain potassium. Thus potassium is lost. The body has now entered a phase of electrolyte fluid imbalance. It is seeking to establish a new blood volume level that the reflexes indicate it needs. In addition to potassium losses, the lack of gravity also causes decreases in calcium, magnesium, chloride, nitrogen and phosphorus in the bones and muscles.

Figure 1 (A-D) illustrates the hypothesized response of the circulating blood volume to zero gravity in more detail, based on our pre- and post-flight volumetric analysis of the nine Skylab astronauts.

Figure 1(A) shows the normal pooling of blood in the lower limbs due to gravity. On acute exposure to zero gravity the venous tone in the lower limbs displaces blood into the upper part of the body, and causes an increase in the volume of the central venous pool, shown in Figure 1(B). A negative fluid balance exists for 2-3 days, probably mediated by the Henry-Gauer reflex, and the central venous pool returns to its previous volume, in the presence of a diminished intravascular and extracellular fluid volume, Figure 1(C). Upon return to a gravitational field, as in Figure 1(D), pooling of blood in the lower limbs again occurs, with a reduced central venous pool and a marked tendency to orthostatic hypotension. Retention of fluid occurs, and the pattern of Figure 1(A) is restored in 3-4 days. The fluid changes resulting from space flight are thus a "stepwise" loss of fluid in the 2-3 days immediately following orbital insertion, and a stepwise replacement of that fluid in the 3-4 days following return.

A related hypothesis concerns the effects of sustained weightlessness on body composition. In zero gravity muscular activity is not required to maintain the posture of the body, as it is on earth, except when the crewman is attempting to perform a task requiring his position to be stable. Movement about the spacecraft requires very little muscular activity, normally being accomplished by pushing off in the required direction with the hands, and catching hold once the destination is reached. The total amount of muscular activity would thus be expected to be decreased, with a change in emphasis taking place, the arms being used more than the legs. The reduction in total energy expenditure should result in a diminished caloric requirement, and unless food intake were similarly reduced, an increase in body fat would be expected.

Stereometric measurement of body form (before and after extended space missions such as Skylab) has proved to be a convenient and objective means of obtaining unique information about total body volume and how it is distributed among the major body segments before and after periods of sustained weightlessness. The Skylab biostereometric experiments referred to above and documented in several reports have already yielded archival physiological data on the effects of sustained weightlessness on total body volume and volume distribution which was impracticable to obtain using more traditional biomedical procedures. Examination of these pre- and post-flight data is continuing (Whittle et al., 1976), but it is already apparent that inflight stereometric measurement of body volume parameters would further advance our understanding of the mechanisms involved in short-term and, ultimately, in long-term human adaptation to sustained weightlessness. More specifically, it would permit us to document the chronology and extent of regional body volume changes due to fluid shifts and any other plausible short-term adaptive responses.

There may be other scientific bonuses from recording the total body geometry at regular intervals during shuttle OFT missions, but the present proposal focuses on a protocol for documenting inflight body volume changes, which could shed further light on the cardiovascular mechanisms associated with human adaptation to sustained weightlessness.

A simulation of the proposed shuttle experiment was carried out in January 1976 at the NASA/Johnson Space Center, as part of the seven day Spacelab Mission Simulation II. The simulation demonstrated that integration of daily stereometric measurements of body volume into a "mixed" life science payload should present no great difficulties. All three crew members praised the efficacy and efficiency of the biostereometric procedure and urged that it be given serious consideration for inflight application in future shuttle missions.

b. Methods and Procedures.

Biostereometrics is the spatial and spatio-temporal analysis of biological form and function based on principles of analytic geometry. In a mathematical sense, the surface of a body part or the body as a whole is comprised of an infinite number of points located in three-dimensional space. By locating a well chosen set of these points in three-dimensions, we can quantify the form in an unambiguous, comprehensive way. These data can then provide the input to a computer which is programmed to yield such numerical and graphical outputs as volume, volume distribution, surface area, and cross-sectional profiles.

Data acquisition. Two specially designed stereometric cameras are used to photograph the front and back of the subject simultaneously (Fig. 2). A strobe projector, centrally mounted on each camera, projects a randomized array of lines onto the body, giving the otherwise monochromatic skin surface greater contrast (Fig. 3) which aids the extraction of coordinate data using a semi-automatic stereoplotter (Fig. 4).

The subject stands between two object space control units (attached to the equipment racks in the shuttle mockup as shown in Fig. 5).

A standard pose is used to minimize the effect of postural variations. The subject places both feet on "footprint" patterns to achieve suitable leg separation, and the arms are held alongside the body with flattened palms toward the rear, at approximately one thumb's distance from the thighs. The subject is nude except for a brief garment (e.g., an athletic supporter) and a skull cap, which compresses the hair.

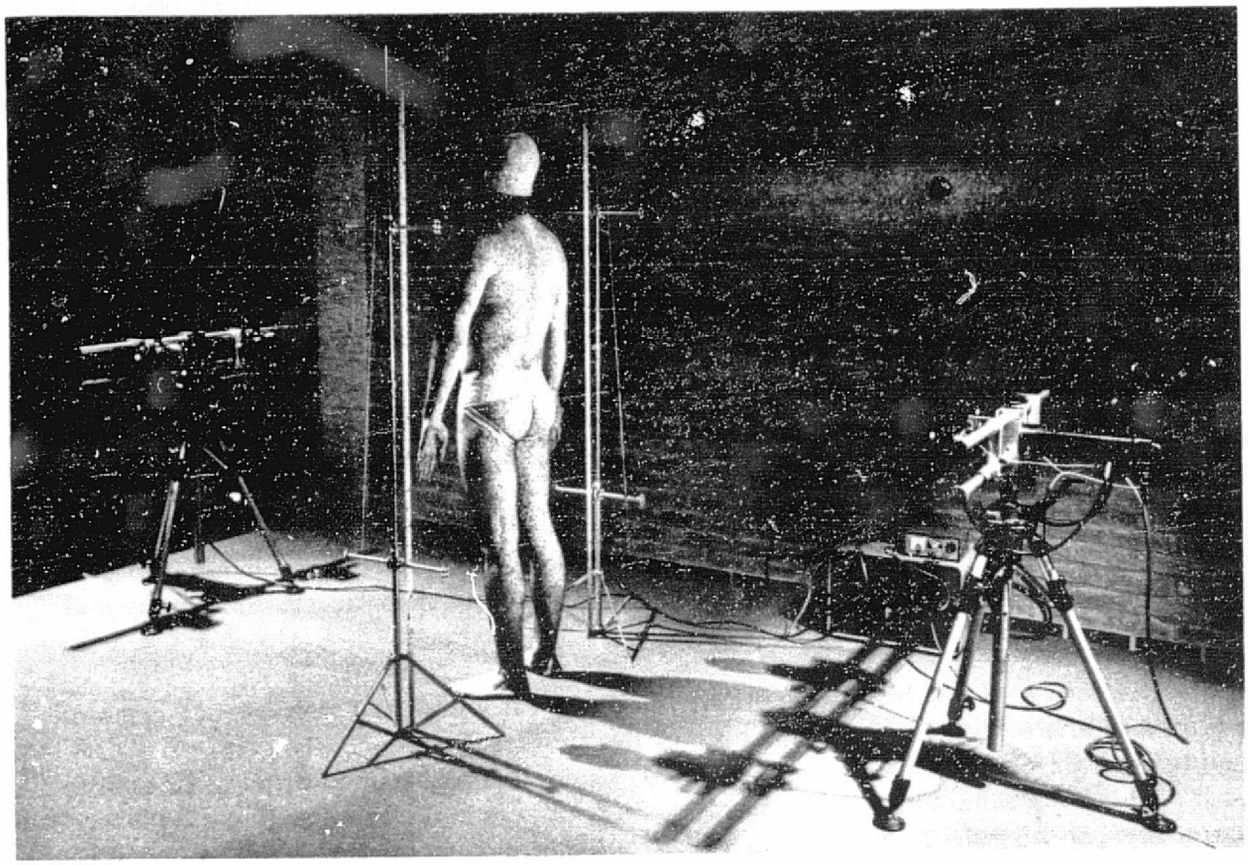


Fig. 2 Whole body volume stereometric camera arrangement

ORIGINAL PAGE IS
OF POOR QUALITY

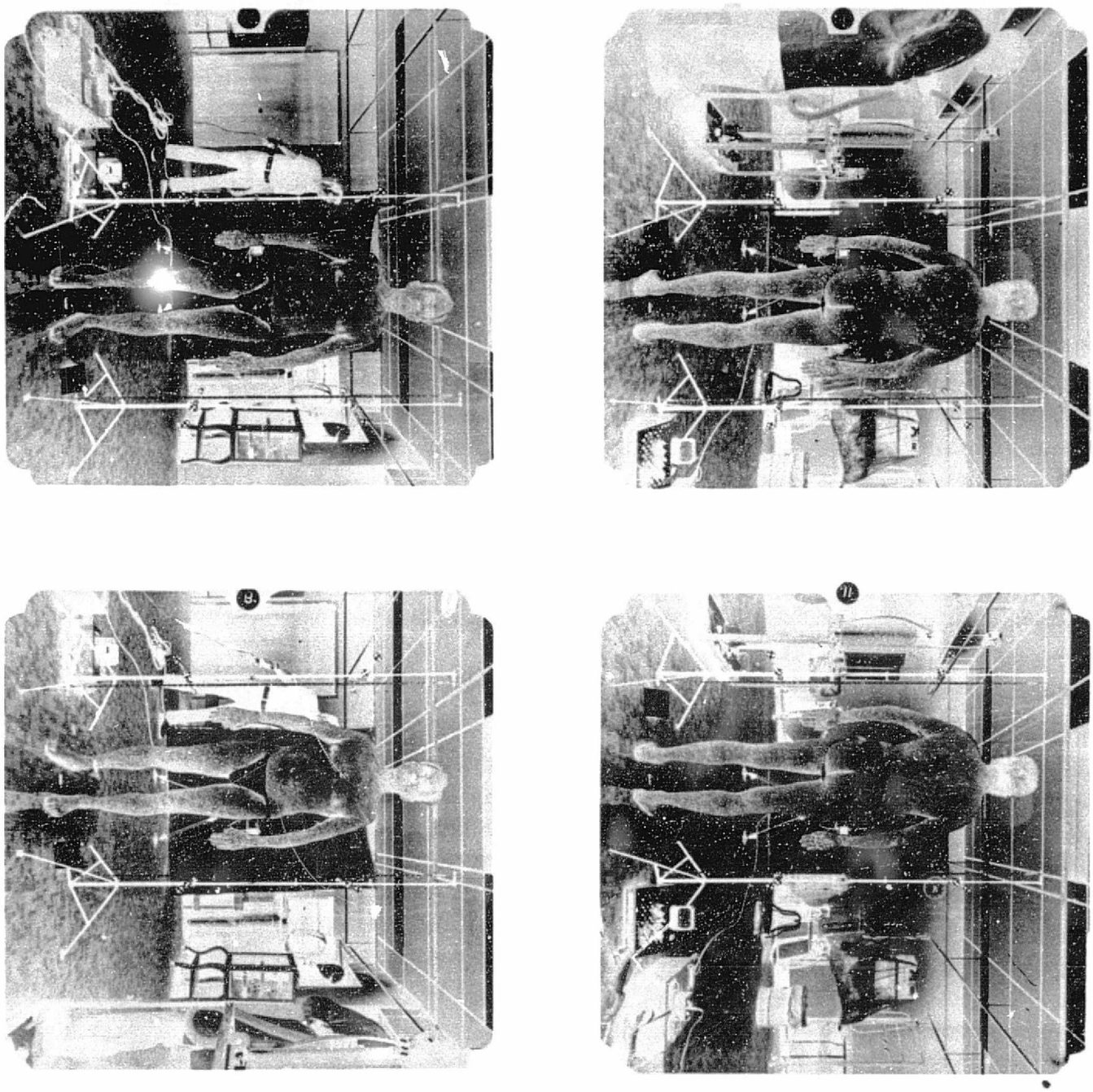


Fig. 3 Front and rear-view stereopairs showing effects of projected contrast on body surface

ORIGINAL PAGE IS
OF POOR QUALITY

PAGE IS
QUALITY

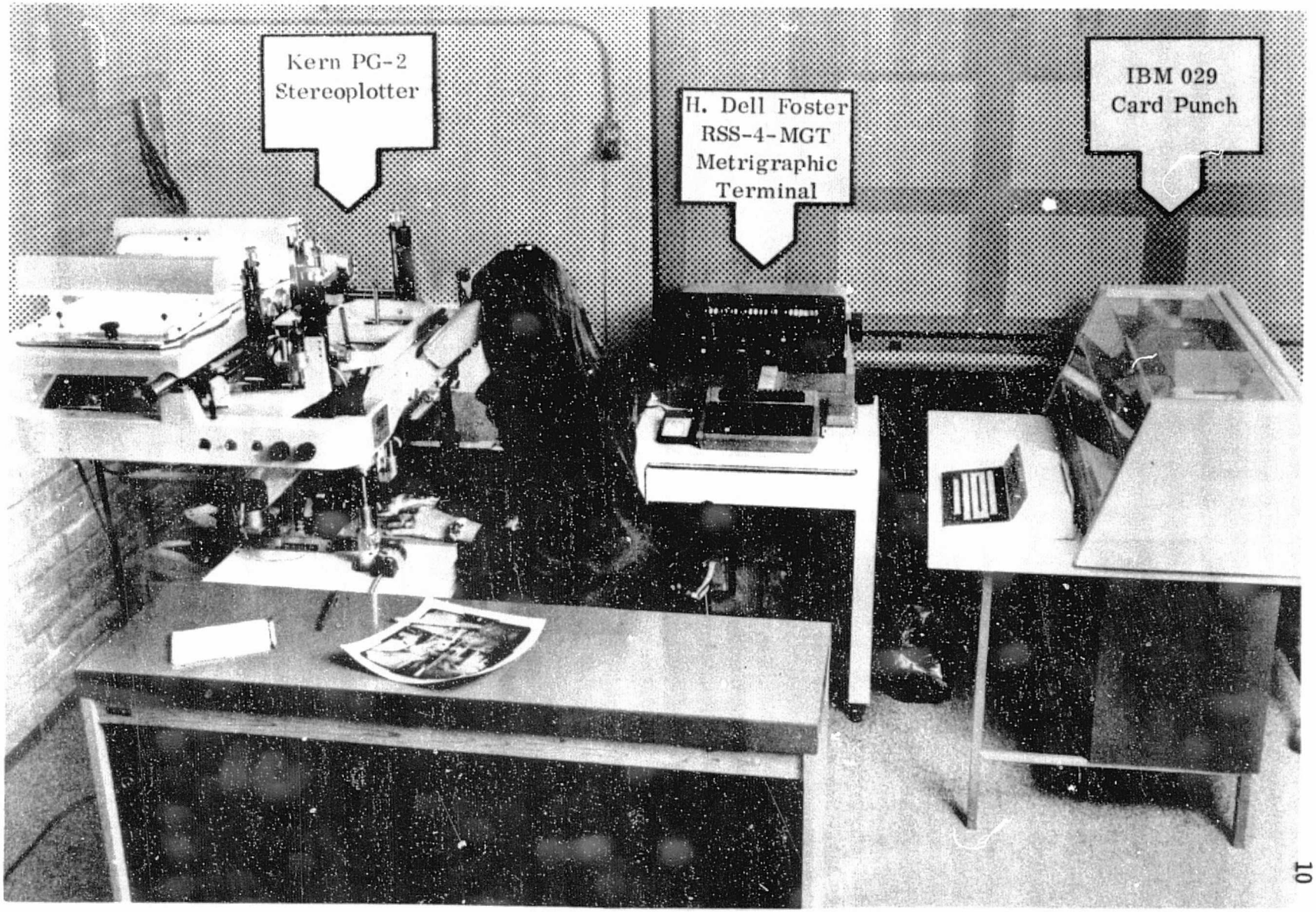


Fig. 4 Semi-automatic stereoplotter data reduction unit

ORIGINAL PAGE IS
OF POOR QUALITY

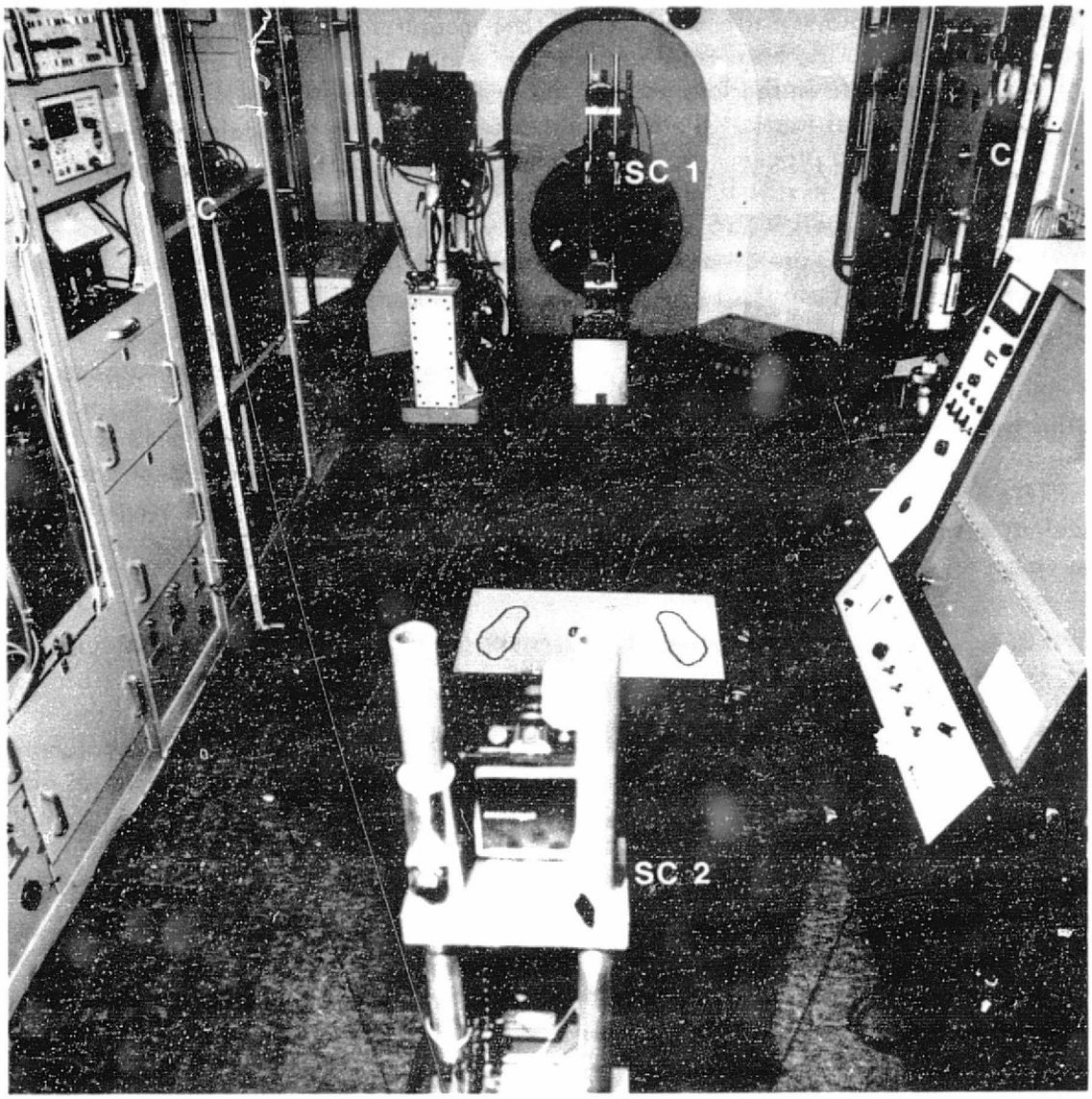


Fig. 5 Stereometric camera set-up in SIM-II shuttle mockup

Plotting and digitization. The photographs are taken on 6.3 cm square glass plates, which are later enlarged to 25.4 cm square on thick-polyester base aerographic duplicating film, using a specially built fixed-focus enlarger. The enlarged photographs are placed in a KERN P-2 stereoplotter which is interfaced via a metrigraphic terminal to a card punch tape storage device. The plotter is aligned for each stereopair to a vertical plane defined by 2 steel tape measures which form part of the object space control units. The horizontal and vertical scales in this plane are derived from the steel tapes. The scale in the long axis of the system is derived from 4 rods of known length mounted near the steel tapes. The front and back stereopairs are scaled independently. Plotting of the subject proceeds from the highest point of the head for the front stereopair, plotting each level from side to side, and working downwards. The interval between successive plotting levels is 2.5 cm as defined by the markings on the vertical steel tapes. The same levels are used in plotting the rear view stereopair, thereby assuring a consistent level for both front and rear views of the body.

Initial data processing. The card deck or tape is processed using a computer program which calculates the scale factors, converts the raw coordinates into centimeters, matches the data for front and back views, and transfers to magnetic storage a level-by-level coordinate description of the entire body form. Cross-sections of each level (Fig. 6) are then plotted using an x-y plotter interfaced to the computer. Other graphical outputs, e.g., frontal and profile views (Fig. 7) are produced using available computer software.

Analysis of data. A computer program is used to calculate the cross-sectional area of the body at each plotted level. Areas which were invisible to the cameras are interpolated and curve-fitting techniques are used to derive the cross-sectional area at 1 mm intervals over the head and trunk, and both arms and legs. The volume of a body segment under examination is calculated by integrating the cross-sectional areas between the previously determined landmarks. This information is presented graphically as a volume distribution curve (cross-sectional area versus height above the floor); as in Fig. 8, where the area under the curve is the total body volume, which can be partitioned into various component segmental volumes, Fig. 9.

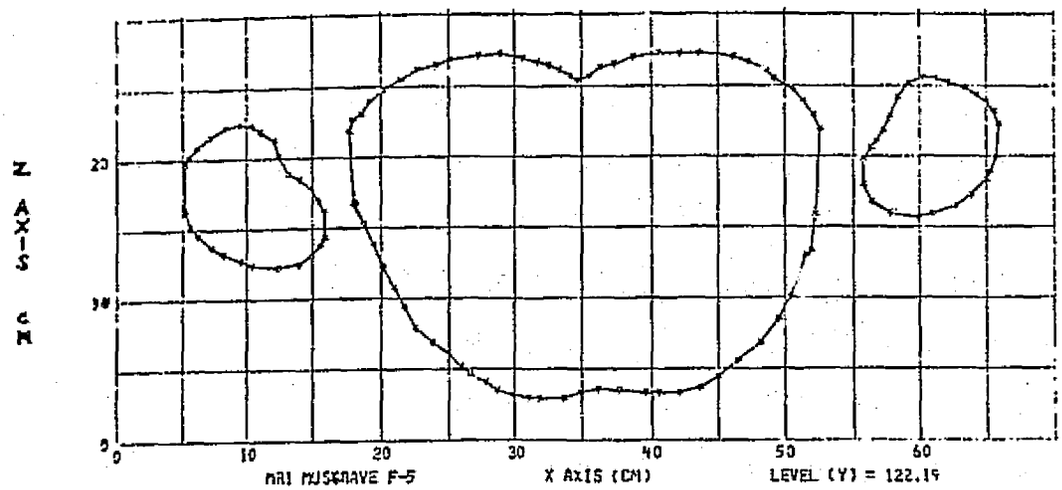


Fig. 6 Cross-section of arms and trunk

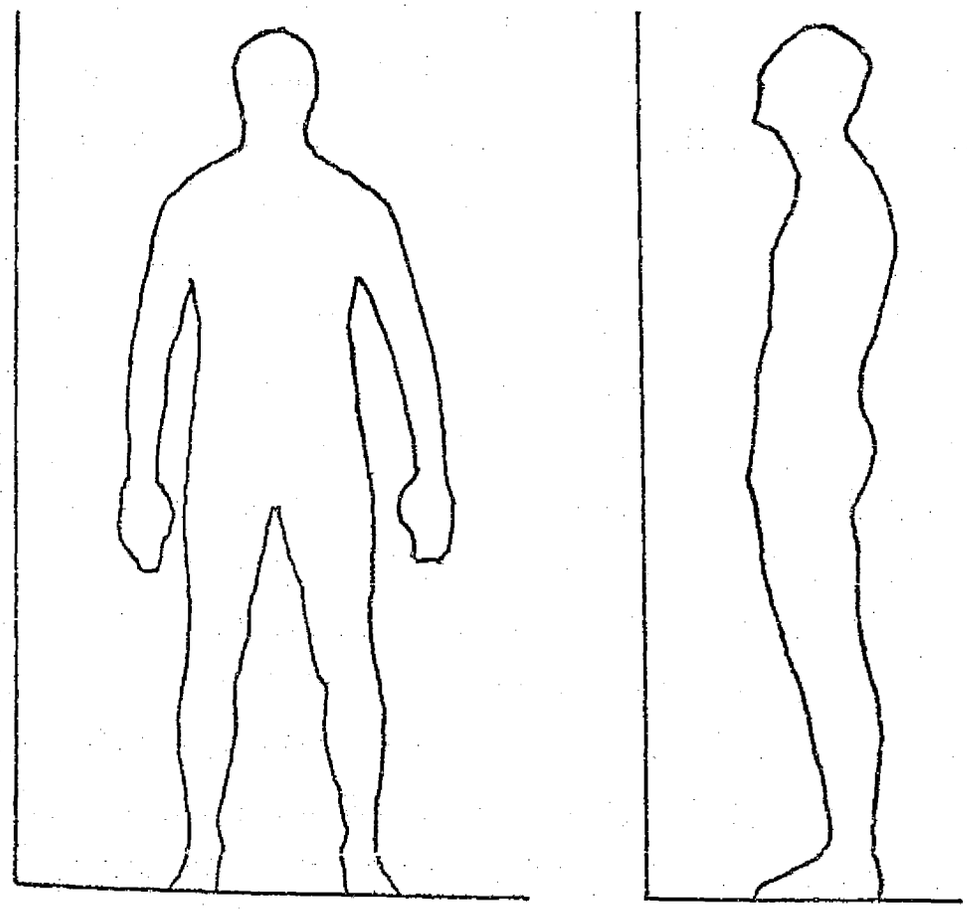
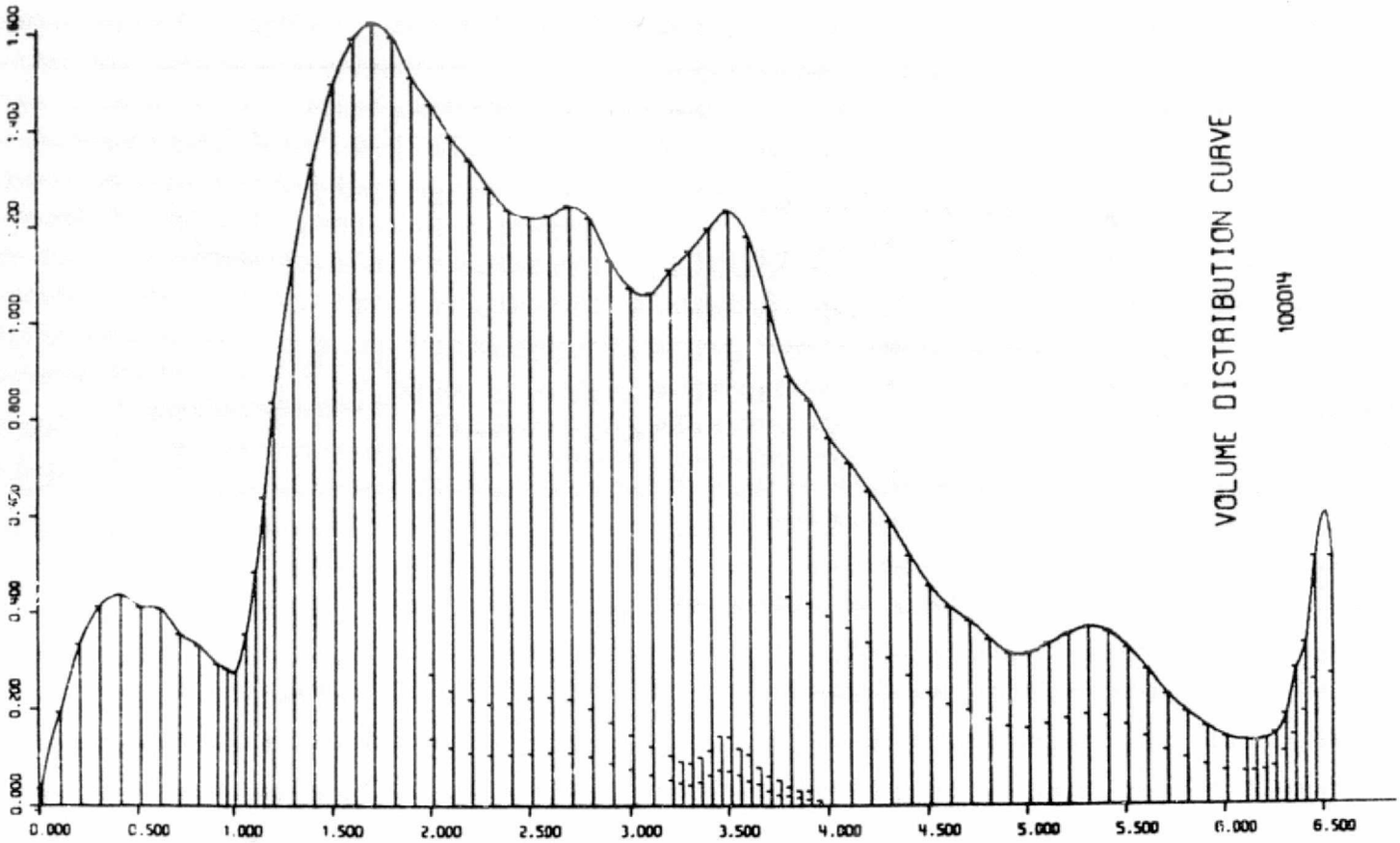


Fig. 7 Computer generated frontal and profile views



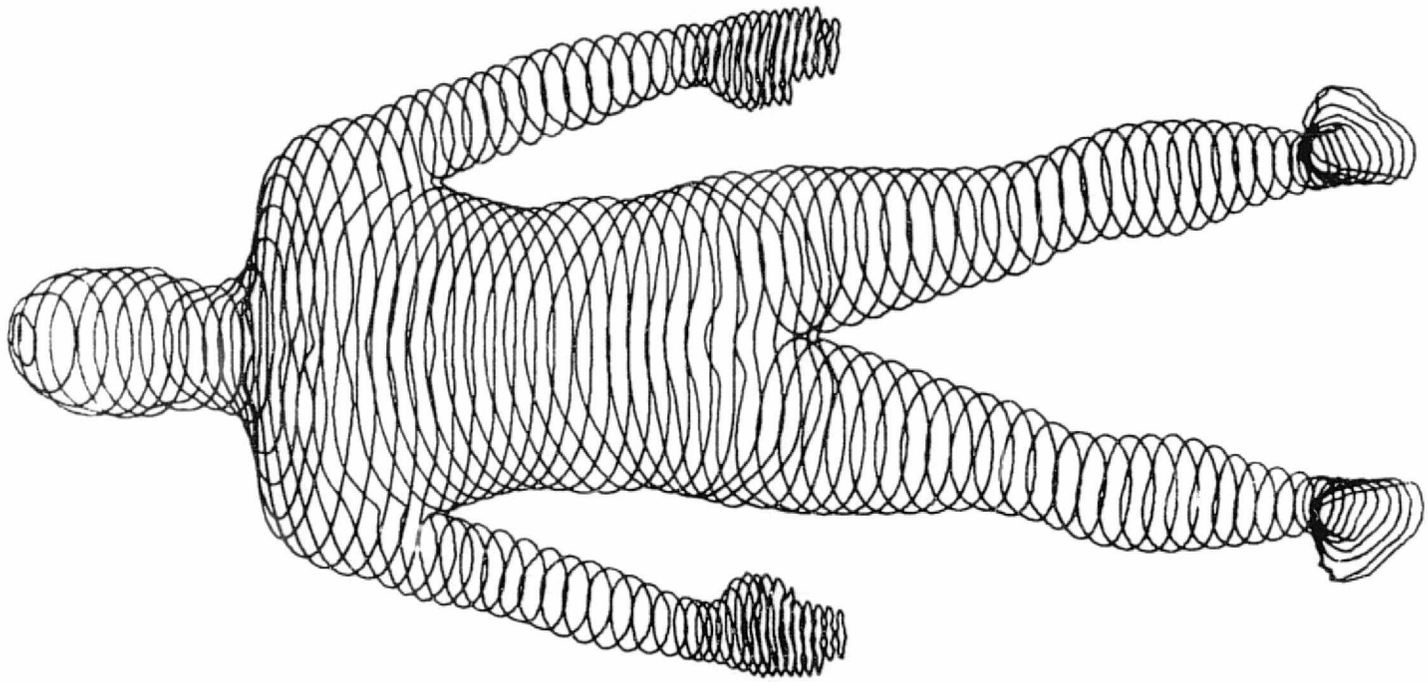


Fig. 8

By plotting the area of each horizontal cross section against height, a body volume distribution curve is obtained so that regional changes in body volume can be readily measured. Each horizontal line in the right-hand graph represents the area of the corresponding cross section in the left-hand plot. Both illustrations are drawn automatically from the 3-D coordinate data describing the body geometry.

ORIGINAL PAGE IS
OF POOR QUALITY

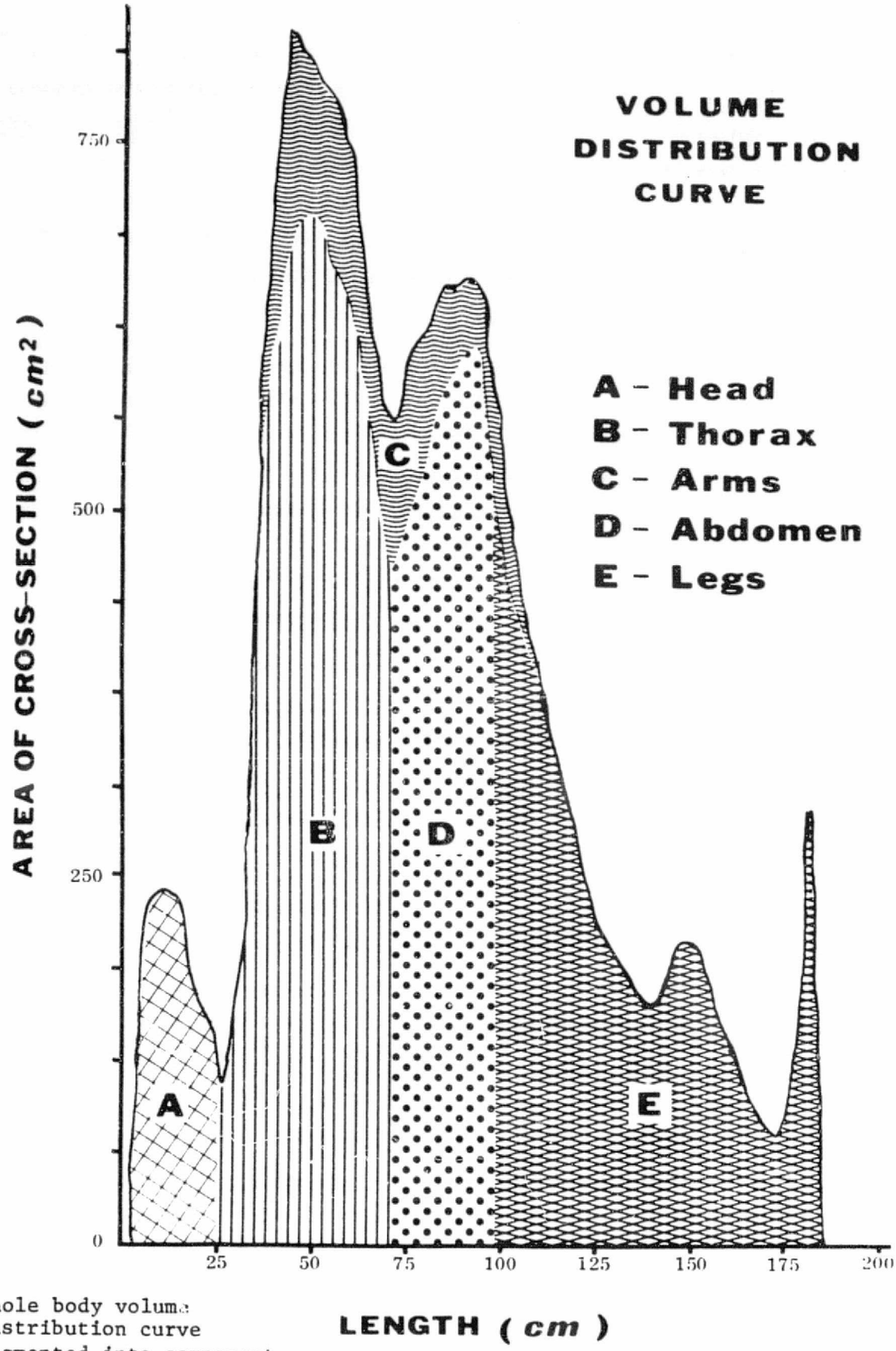


Fig. 9 Whole body volume distribution curve segmented into component volumes

c. Ideally the measurements to be made on the OFT crew should involve preflight, inflight and postflight recordings. Preflight measurements will be made at least twice (under suitably standardized metabolic conditions and as close to launch as feasible) to establish baseline values for body volume and volume distribution. The inflight recording will be made daily, prior to starting the day's activities, as in the SIM/II experiment.

The ranges of numerical values to be expected are subject to some speculation, since changes in body volume and volume distribution have never been measured before under true zero gravity conditions.

The aggregate changes in total body volume should be somewhat less than those found in the Skylab experiments. However, inflight volume distribution curves should reveal for the first time, the degree and extent of limb and trunk volume changes due to fluid shifts associated with a true zero gravity environment.

The first postflight recording would be made as soon as possible after recovery with at least one further measurement at approximately R+7, but preferably also at R+14.

d. Payload Specialist's Tasks.

The tasks performed by the payload specialist are outlined below for a 1 gravity environment such as prevailed during the SIM/II experiment. Obviously, the performance specifications will differ somewhat under the zero gravity conditions of the OFT. However, necessary changes in procedure should be minimal and the physical demands should be reduced. Ground support should not be required--during the SIM/II experiment only a minor problem developed and this was solved by the payload specialist using an onboard trouble-shooting guide (a more complete report of the SIM/II experiment, including the payload specialist's observations, is attached).

For inflight recording, the equipment is set up the previous evening by the payload specialist and made ready to operate as the crew begins their morning activities. The measurements are taken at the same time each day to minimize changes in body form due to extraneous uncontrolled variables. The daily time requirement of approximately 20 minutes can be broken down as follows:

Set up*	5 min
Measurements	2-3 min/subject
Take Down and Storage	4 min

*The set up and take down is accomplished entirely by the designated payload specialist, so that demands on the crew as a whole are minimal.

e. Previous Research in Area of Proposal

Since 1970, the Biostereometrics Laboratory at the Texas Institute for Rehabilitation and Research has worked closely with NASA and NASA-sponsored contractors (Technology, Inc. and Lovelace Foundation) to develop capabilities for biostereometric analysis of human body and limb volume changes associated with manned space flight.

During the last two years (March 1975-February 1977) the TIRR laboratory has provided scientific and technical guidance, hardware and software, and data reduction services (stereoplotting) for several NASA-sponsored body volume studies. These include: (i) Baylor Bedrest Study Phase I, (ii) Baylor Bedrest Study Phase II, (iii) Lovelace-TIRR Comparative Study I (10 subjects), (iv) Lovelace-TIRR Comparative Study II (30 subjects) and (v) SMS II (January 1976).

Summary reports and extracts from articles describing the above investigations are attached.

The protocol for the proposed in-flight shuttle experiment has been applied successfully in over 30 ground-based studies including Apollo 16, three Skylab missions, and the other NASA projects listed above. The prime obstacles for in-flight shuttle use appear to be few. They relate mainly to the making of necessary (but minor) procedural modifications to fit the inflight zero gravity conditions. The camera system adapted readily to the limited storage and space facility of the SIM/II shuttle mockup. Further requirements in packaging and orientation will be made as required to fit the OFT situation.

f. Specific Research Tasks

The specific research tasks to be undertaken during the first year of the proposal are:

(i). A definitive experimental plan for future in-flight body volume studies will be prepared.

(ii). Minor refinements will be made to an in-flight biostereometric system which was used successfully on the SMS II (January 1976) experiment at NASA-LBJ.

(iii). Biostereometrics research and development in such areas as aerospace physiology, nutrition, human engineering (e.g., body mass distribution for maneuverability studies) and computer graphics will be coordinated to maximize the benefits to NASA, rehabilitation medicine and related biomedical fields.

B. NASA Instrument Fact Sheet

Please see Additional Notes.

ORIGINAL PAGE IS
OF POOR QUALITY

C. Data Reduction and Analysis.

The data reduction procedures have been outlined above. They follow the same line of inquiry used to study the nature and extent of body volume and volume distribution changes as in our previous NASA experiments. Details of the method and format for the analytic procedures are contained also in our previous NASA experiment reports (Herron et al., 1971, 1972; Whittle et al., 1974, 1976).

A preliminary report of the findings will be submitted at R+30, a more complete report at R+90, and a final report at R+180. These documents will be presented to the technical monitor at NASA-LBJ Space Center.

D. Results Expected.

The anticipated results were outlined under Item IA2 above. Further discussion of the hypothesized effects of zero gravity on body volume and volume distribution is included in the attached reports of our previous Skylab investigations (Whittle et al., 1974, 1976).

E. Payload Specialist Support.

The tasks to be performed by the payload specialist are described in Item IA3d above. Approximately three training sessions of two hours each will be desirable; this proved effective for the SIM/II mission, although some reduction in training time will be acceptable, if absolutely necessary. Further details are given in the Appendix.

F. Flight Operational Requirements.

The operational requirements which do not directly involve the flight crew would be minimal. In the unlikely event of a problem arising which the payload specialist could not resolve, voice communication with a technical specialist at NASA-LBJ would be desirable.

G. Post-Flight Requirements.

The photographic glass plates will be stored in a specially protected container although the usual precautions against excessive radiation of the exposed imagery should be observed. The exposed plates would be removed as soon as possible after landing for data reduction and analysis. The stereometric camera equipment would be recovered from its stored location at a convenient opportunity following the mission.

II. MANAGEMENT PLAN AND COST PLAN

A. Management Plan.

The scientific management of the experiment will be under the direction of the principal investigator. Scientific and technical support will be provided by the co-investigators, the consultant, and associated scientific/technical personnel at the Biostereometrics Laboratory and NASA-LBJ Space Center.

In our previous NASA studies we have used onsite (LBJ Space Center) scientific and technical support from the Life Sciences Directorate with Dr. Paul Rambaut serving as our main contact person. We expect to continue this relationship and to develop a more refined plan of interaction as the recent changes in NASA-LBJ Life Science Directorate responsibilities become more firmly established.

Life Sciences Directorate
Rep.: Paul Rambaut, D.Sc.

Principal Investigator
R. E. Herron, Ph.D.

Consultant
Ulrich C. Luft, M.D.

Cost Management
N. Hott, TIRR Bus. Man.

Co-Investigator
J. R. Cuzzi, B.S.

Co-Investigator
M. W. Whittle, M.D.

Biostereometrics Laboratory
Technical Staff

NASA Biomedical and
Technical Support Staff

Fig. 10. Shuttle Biostereometric Experiment Management Organization.