J. Biomechanics Vol. 13, pp. 211–218.
Pergamon Press Ltd. 1980. Printed in Great Britain.

0021-9290/80/0301-0211 $02.00/0

ISOTROPY AND ANISOTROPY OF UTERINE MUSCLE DURING LABOR CONTRACTION*

J. MIZRAHI† and Z. KARNI‡
Department of Bio-Medical Engineering, Technion-Israel Institute of Technology, Haifa, Israel
and
W. Z. POLISHUK§
Head, Department of Obstetrics and Gynaecology, The Hadassah University Hospital, Jerusalem, Israel

Abstract – A strain rosette analysis performed on 36 women during their 36–42 weeks of pregnancy at various points over the fundal region, shows that the functional performance of the uterine muscle is *anisotropic* in its character and a kinematic isotropy is a good approximation only during the early stages of labor. The various groups of fibers exhibit different viscoelastic properties, with the longitudinal group showing more resilience than the others. A case which proved an exception was that of an eighth month delivery showing the reverse behavior of strain hardening.

INTRODUCTION

The uterine muscle, the myometrium, is anatomically described as being composed of families of longitudinal and circular muscle fibers (Bumm, 1911) lying in three principal layers (Frank, 1931): (1) the *stratum supravasculare* – adjacent to the peritoneum; (2) the *stratum vasculare* – the middle and thickest layer of the three through which the large blood vessels run, and (3) the *stratum submucosum* – the innermost and thinnest of them all. Were there not any mechanical interaction between the separate groups of muscle fibers, the myometrium could act as an *anisotropic* organ. In other words, if a portion of the muscle was isolated from the rest of the organ and subjected to simple extensions in several different directions, the lateral contractions consequent upon the extensions would have different values. It is preferable here to speak of *relative* extension, that is, the elongation per unit initial length, commonly referred to as the longitudinal strain. Similarly, lateral strain is the lateral contraction per unit initial length. It is only with complete isotropy that lateral strain is independent of the direction of the longitudinal strain.

Isotropy is not an inherent property of the myometrium. For one thing, the anatomical sandwich-like separation of the myometrium into definite layers strongly favors an anisotropic behavior of the muscle. However, due to the intricate interlacing of the fiber bundles through the various layers, the myometrium is likely to show more isotropy than anisotropy. It is therefore the former property which appropriate strain measurements of the organ during its deformation are expected to verify.

To measure isotropy, strain rosettes have to be used. The rosette is an arrangement of four strain gauges in four different directions about a given centroid. The angles between the axes being known, the reading of any three gauges are necessary and sufficient, in the case of perfect isotropy, to permit the prediction of the fourth strain, but the latter is also independently measured so that the computed strain can be checked against that which is measured. The entire rosette is then rotated about its centroid and the whole process is repeated. If the computed values from three arbitrary gauges coincide with the measured values of the fourth, for all orientations of the rosette, complete isotropy is established. This has to be performed for every space point and each time value separately, and the processing of the considerable volume of data obtained is conveniently handled by a computer.

The question of isotropy and anisotropy has also been discussed in relation to cardiac muscle – the myocardium. Unlike the uterus, which at the end of pregnancy can be considered as a thin shell structure (Karni and Polishuk, 1970) in which the thickness is small by comparison with the length and the width of the organ, the myocardium is classified as a thick-walled shell structure. Its isotropy has then to be examined not only over the middle surface but also over the thickness of the muscle. Studies of the architecture of the human ventricular myocardium (Grant, 1953; Lev and Simkins, 1956; Hort, 1960;

---

* *Received* 28 *December* 1978; *in revised form* 16 *August* 1979.

† Present address: Department of Biomechanics, Loewenstein Rehabilitation Hospital, P.O.B. 3, Ra'anana, Israel.

‡ During 1975–1978, Visiting Professor, Department of Biomechanics, College of Osteopathic Medicine, Michigan State University, East Lansing, MI 48824, U.S.A.

§ The late Professor Polishuk, who was a co-supervisor of J. Mizrahi's doctoral thesis, and actively participated in the experimental studies throughout, died in Jerusalem on 29 June, 1976.

Ross *et al.*, 1967) and particularly of the left ventricle (Grant, 1965), showed that the myocardial wall could be regarded as a fiber-wound continuum of interconnecting muscle fibers of a well-defined anisotropic character (Streeter and Basset, 1966; Streeter *et al.*, 1969). Yet, the early thickwall theories for the calculation of the stresses in the wall of the left ventricle still assumed the myocardium to behave as an isotropic, homogeneous material (Ghista and Sandler, 1969; Mirsky, 1969). Later, anisotropic considerations were introduced into the calculations of stress distributions in the canine left ventricle during diastole and systole (Streeter *et al.*, 1970) and for the intact heart (Mirsky, 1970). In none of these studies were strain gauges employed and the calculations were based on assumptions discussed in the texts.

The uterine muscle, in contrast, is more easily accessible for strain measurements. The strain gauges can be applied to the skin above the uterus or directly onto the surface of the myometrium itself during a Caesarian section. In both cases, however, the readings are later evaluated for the mid-surface of the muscle – a common procedure adopted in thin shell models. We shall return to this point later when the results have been examined.

METHODS

The strain gauges used were PEEKEL* electrical resistance high-extension rubber strain gauges type 20S. These have a maximum extensibility of 20% and compressibility of 15%. The active length of a gauge is 13 mm; the gauge factor in static extension is $-0.0136 \pm 2\%$ and the gauge factor in static compression is $+0.0182 \pm 2\%$. The reason for a negative gauge factor in extension is due to the construction of the rubber gauge; the resistance wire undergoes compression when a positive strain is applied.

The rosette consisted of four gauges oriented at angles of 45° apart. For such an arrangement, the strain at a direction designated as zero is connected with the three other directions by means of the simple relation:

$$\varepsilon_o = \varepsilon_{45^\circ} + \varepsilon_{135^\circ} - \varepsilon_{90^\circ}.$$

When the measured values of the strains $\varepsilon_{45^\circ}, \varepsilon_{135^\circ}, \varepsilon_{90^\circ}$ were fed into the computer, they yielded calculated values for ε_o which could be checked against the measured value.

The strain rosettes were connected to a Brüel and Kjaer strain-gauge bridge type 1516, which was capable of direct recording of both the static and the dynamic strains of the deforming bodies. The apparatus contained a 3 kHz oscillator which fed a Wheatstone bridge consisting of pairs of strain gauges, each pair including one active gauge and one dummy gauge for skin temperature compensation.

The pick-up sensitivity of the gauge in extension was 2–3 μm, or converted to strain, 0.01%. The measured strains during labor contractions ranged from 2 to 5% so that the error of the strain record amounted to no more than 0.05% of maximal amplitudes. The relaxation time of the rubber gauges was very short (order of milliseconds) and in the inactive state it kept a steady and stable base line.

The location of the centroids of the rosettes was referred to a model map of the uterus which had been drawn earlier by Karni and Polishuk (1970) and served as a spatial reference system for the measurements. The level of the umbilicus was used as the point from which the gauge distances were measured. Our studies, carried out at the maternity ward of the 'Hadassah' University Hospital, Jerusalem, were made on 36 women in labor at 36–42 weeks of pregnancy. The strain record covered the various stages of labor up to delivery and was only interrupted when the patient had to change position, move or be wheeled away, etc.

During a contraction which usually lasted over a minute, the recorded strain pattern was broken down into 30 quasistatic ordinates (Biot, 1965) with an average time difference of 2–2.5 s between successive ordinates. The letter C denoted the calculated values, and the letter M the measured ones. Thus, if the C and M values coincided, isotropy was established. In the event that the agreement was within the size of the printed letter, only the letter M was used by the computer, to stand for the two.

RESULTS

Two typical strain rosette recordings performed over the anterior left and right sides of the uterus above the umbilicus at the fundal region, are shown in Fig. 1. For both sides, the inclinations of the gauges marked 1 to 4 were, with respect to the meridian, 0°, 45°, 90° and 135° respectively, as indicated on the scheme. The recorded strains cover a little more than one contraction during the first stage of labor. The maximal extension (positive strain) at this stage is of the order of 2%.

Figure 2 shows the computer solution for the left side recording with gauge 4 acting as the reference gauge. The C-points indicate what the readings of gauge 4, calculated from those of gauges 1, 2 and 3, should be if complete isotropy prevails. The M-points are the actual measured values of gauge 4 when smoothed over the high-frequency respiratory oscillations. The overlapping of the two sets merely indicates that during the first stage of labor the myometrium can still be considered as functionally isotropic.

Figure 3 shows the results corresponding to the advanced first stage of labor, for the same anterior left side of the uterus. Here, too, the computed values agree well with the measured ones, at both ends of the contraction wave. However, at the middle section a discrepancy between the two builds up, reaching a peak value of 30%.

---

[*] Automation Peekel, Alblasstraat 1, Rotterdam-8, Holland.

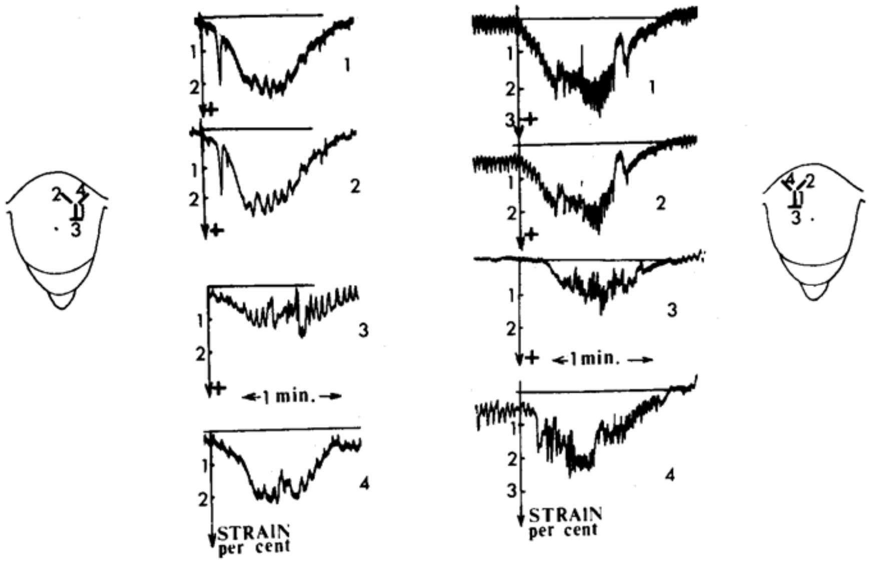

Fig. 1. Strain rosette records.

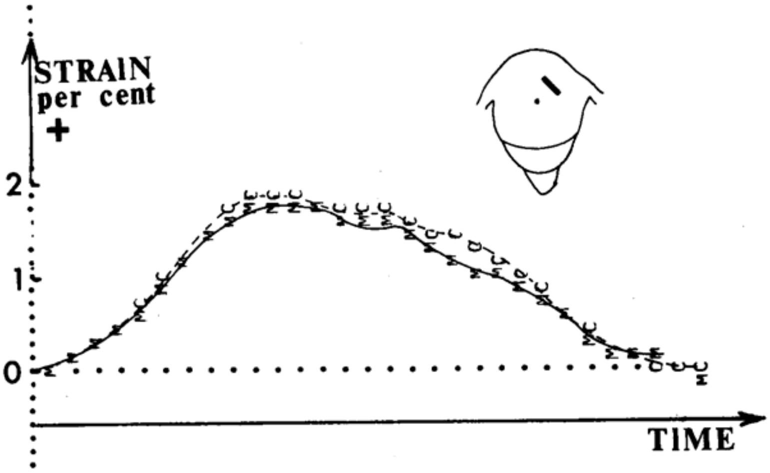

Fig. 2. Measured (solid line) and computed (dashed line) strain during the first stage of labor.

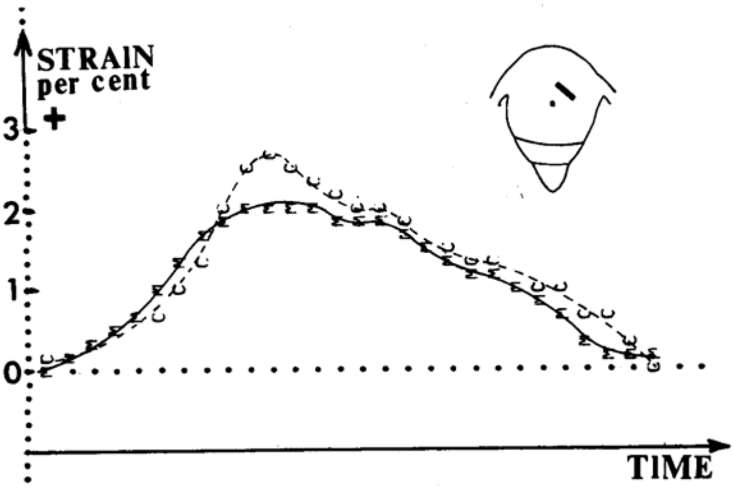

Fig. 3. Measured (solid line) and computed (dashed line) strain during the advanced first stage of labor.

The results shown in Fig. 4 present measured vs computed values of strains for different combinations of the gauges in the rosette. In each case the gauge used as reference is noted alongside the curves. Although shown for the left side of the uterus only, data for the right side were measured and analysed as well. It emerged that for both sides at peak contraction the computed strain for the inclined gauges 2, 3 exceeded the measured strain, whereas for the longitudinal gauge 1 the opposite was true. This pattern repeated itself in a more pronounced fashion during the second stage of labor, as shown in Fig. 5.

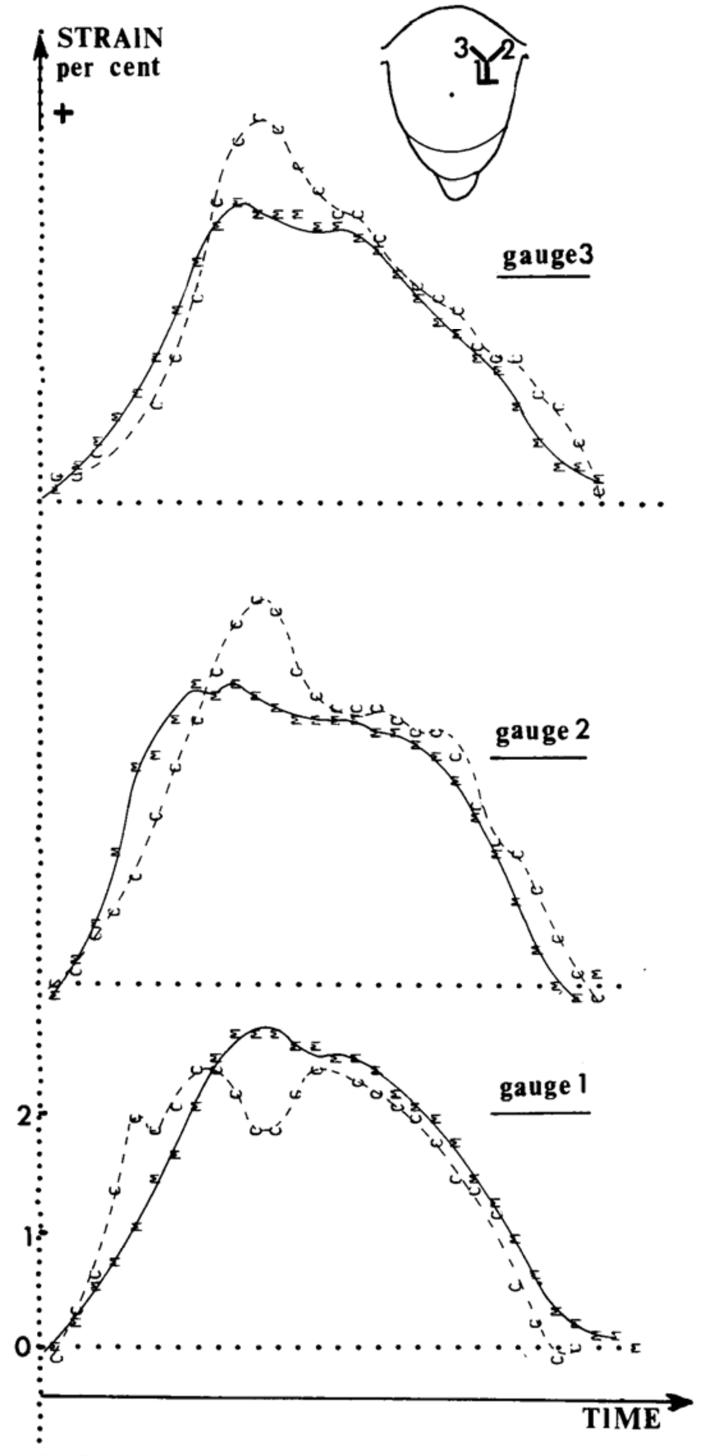

Fig. 4. Measured (solid line) and computed (dashed line) strains for the left side of the uterus during the advanced first stage of labor.

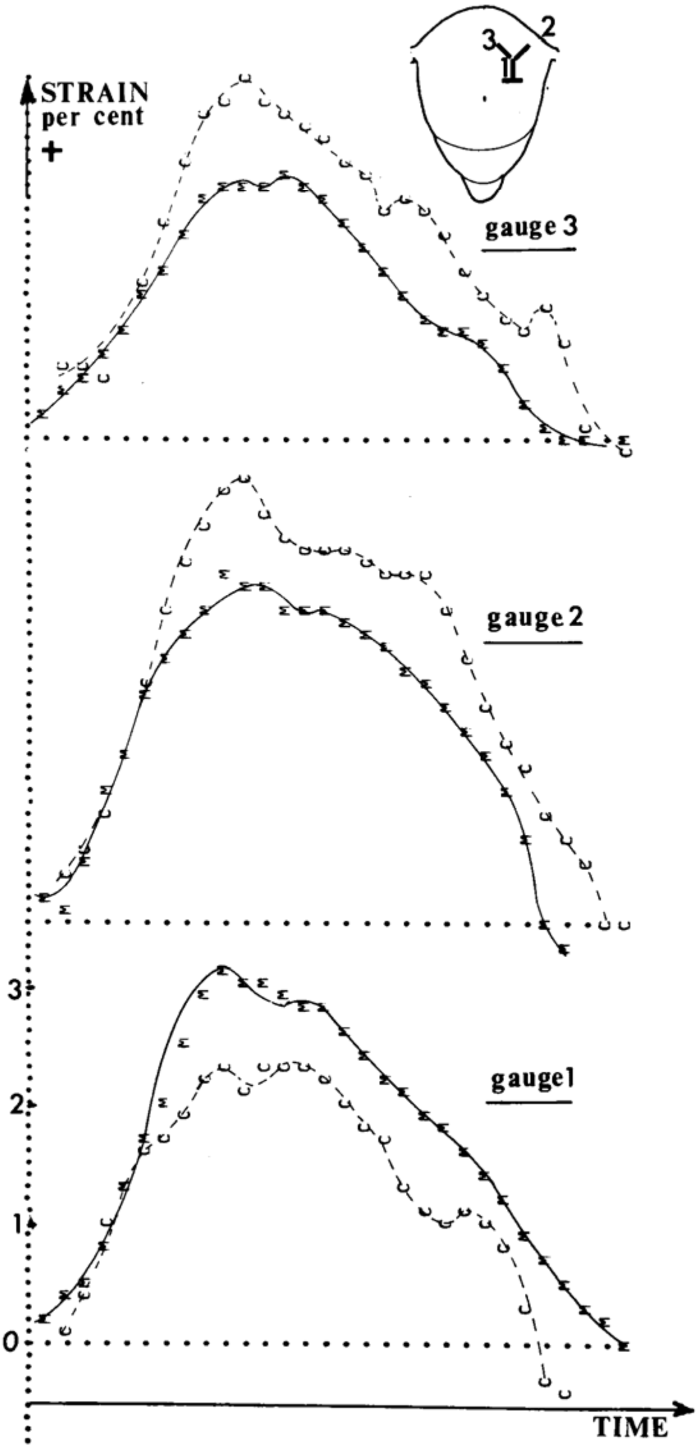

Fig. 5. Measured (solid line) and computed (dashed lines) strains for the left side of the uterus during the second stage of labor.

It is also observed that in this stage there is still good agreement between computed and measured values at the onset of contraction. However, with the build-up of the contraction, the two sets of values diverge and do so maximally at the peak of contraction. Later, during the relaxation of the muscle, the gap narrows but does not disappear entirely even at the end of the contraction. This is typical viscoelastic behavior which characterises the muscular activity towards the last phase of labor.

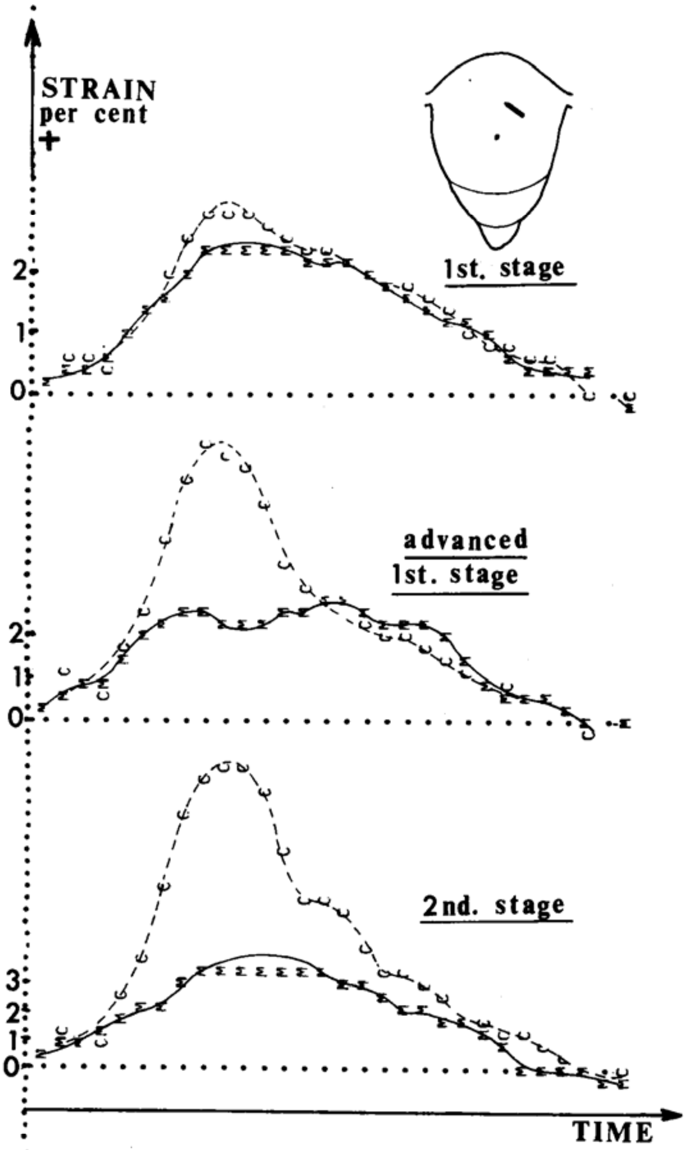

Fig. 6. Average strains, measured (solid lines) and computed (dashed lines), of eight normal cases during the various stages of labor.

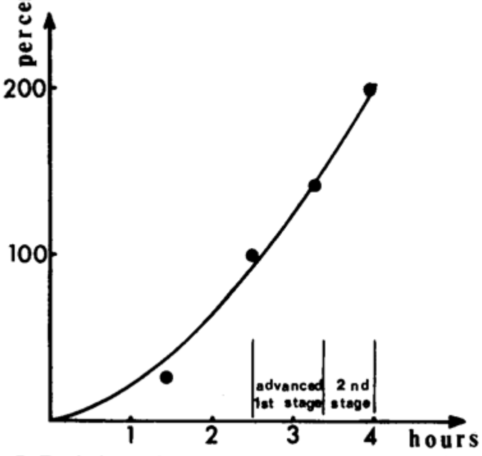

Fig. 7. Deviations of maximal strain values from isotropy during the various stages of labor.

Thus, the deviation from isotropy steadily increases with the progression of labor up to delivery. This is summarized in Fig. 6 where the average results of eight normally progressing labors are plotted for one of the inclined gauges (No. 3 in Fig. 4) acting as the reference gauge during all stages of labor. Plotting the maximum deviations between the measured and calculated strains of Fig. 6, as a percentage, yields Fig. 7, which casts further light on these results. It shows that both the anisotropy as well as its time rate of change (the first derivative) increase monotonically from the onset of labor up to delivery.

A case which proved an exception is shown in Fig. 8. Unlike the others, this patient developed earlier labor contractions during the eighth month of pregnancy and delivery took place 24 h later. Here, the relation

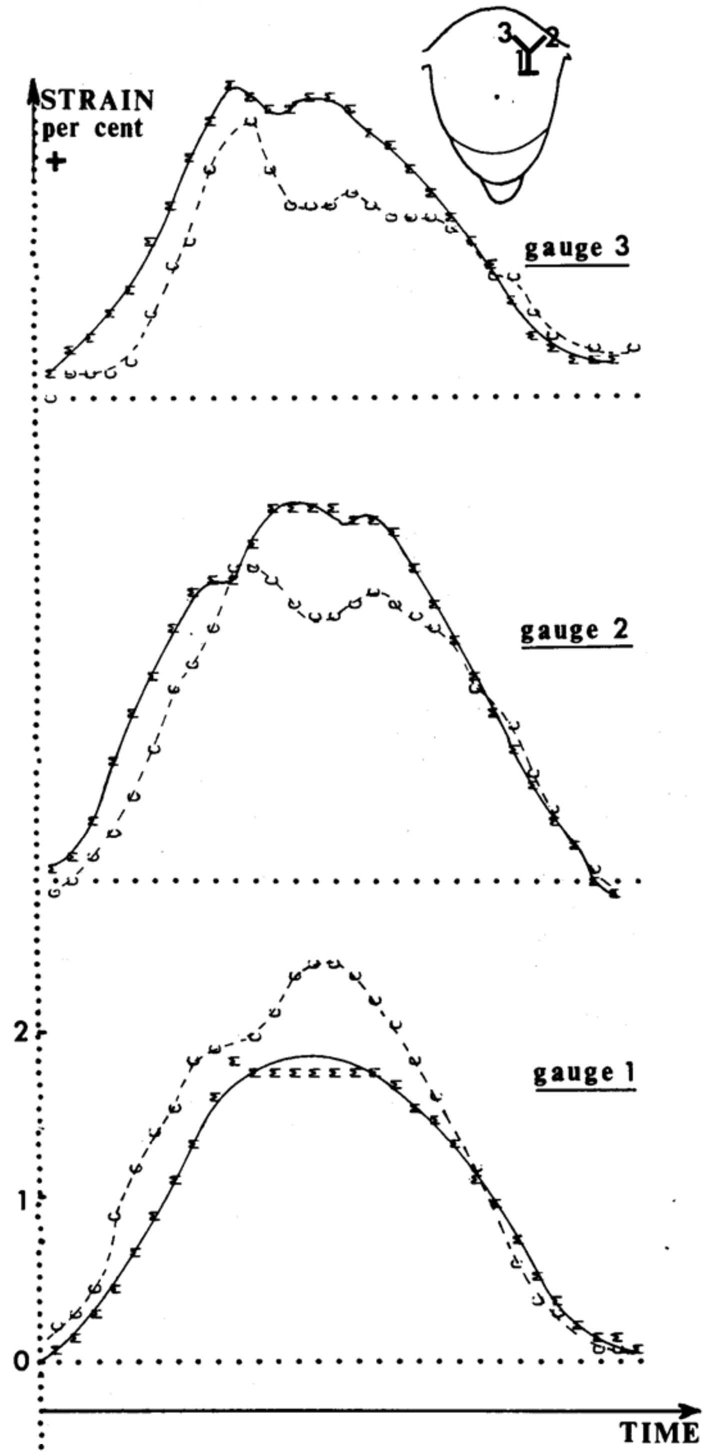

Fig. 8. Measured (solid lines) and computed (dashed lines) strains during premature contractions.

between the measured and the computed strain values showed, in comparison with the previous cases (see Fig. 6), a complete reversal of the pattern. Thus, for gauge 1, the measured values fall below those computed, whereas for gauges 2 and 3 they were above them. Also, the viscoelastic behavior of the muscle fibers showed itself during the *build up* of the contraction in the longitudinal fiber direction (gauge 1), and these fibers became more elastic during the second phase of the contraction. This phenomenon known as "strain hardening" is one in which the elasticity of a material improves with repeated loading and unloading cycles. All this points to the fact that some distinct changes in the material properties of the muscular fibers may take place between the eighth and ninth months of pregnancy.

DISCUSSION

The strain rosette analysis clearly shows that the functional behavior of the uterine muscle is basically *anisotropic* in character. When during the early stages of labor the deformations are still small, the different groups of muscle fibers, due to their interlacing, still act as an ensemble, and to a close approximation isotropy prevails. However, with the advancement of labor, deviations from isotropy build up indicating that each group of fibers becomes more and more functionally independent of the others. They even exhibit different material properties (Pearsall and Roberts, 1978), the longitudinal fibers showing a higher resilience than the circular ones. A pattern of a delayed recovery from deformation during the contractional relaxations is a common feature of the various fiber groups, which is even more pronounced at the final stage of labor. It was noted, however, that in a premature eighth month delivery the opposite was the case.

The study of isotropy and anisotropy of the uterine muscle forms only a part of a comprehensive analysis of uterine kinematics during labor and delivery. This has included the technique of strain uterography and its clinical applications, a mechanical model for the uterus and its kinematic analysis, details of which have been presented elsewhere (Mizrahi *et al.*, 1977; Mizrahi and Karni, 1975; Mizrahi *et al.*, 1978). The numerical solution of the equations and the experimental data analysis, together with the statistical computations of error estimates, standard deviations, and the like were programmed on an IBM 370 computer and an account of this work is given in Mizrahi's thesis (1975).

Particular attention was paid to the relative merits of skin strain measurements above the uterus and contact measurements performed on the muscle itself during a Caesarian section. The purpose of the analysis was to put to the test the fundamental postulate underlying thin shell theory, namely, the Kirchoff–Love postulate. By this assumption, strains measured at different layers in the shell should be in the same proportion as the ratio of the perpendicular distances of these layers from a common middle surface. Based on this assumption, the ratios of the strain amplitudes on the skin and on the muscle could, again, be pre-calculated and compared with the measured ones.

In one of the cases, the data were as follows: for a 9.5 mm thickness of uterine muscle, a 18 mm thickness of tissue above it, and for a radial radius of curvature of 120 mm at the point of measurement, the computed ratio of amplitudes between strains measured at the skin surface and, later directly below it on the muscle itself, should by the Kirchoff–Love postulate, yield a value of 1.16 for the above figures. A statistical *t*-test for 14 contraction waves, seven recorded before the Caesarian and seven during the section with contact strain gauges placed temporarily on the uterine surface, yielded the mean value of 1.15. This represented a difference of 0.9%, which was about half the estimated experimental error, and it was therefore considered sufficient to vindicate the Kirchoff–Love postulate.

Acknowledgement – This research was sponsored in part by the Julius Silver Institute of Bio-Medical Engineering Sciences, Technion-Israel Institute of Technology, Haifa, Israel, under Research Project No. 140-065.

REFERENCES

Biot, M. A. (1965) *Mechanics of Incremental Deformations*, pp. 3–6. Wiley, New York.

Bumm, E. (1911) *Grundiss zum Studium der Geburtshilfe*, pp. 107–112. Bergmann, Wiesbaden.

Frank, R. T. (1931) *Gynaecological and Obstetrical Pathology*. Appleton, New York.

Ghista, D. N. and Sandler, H. (1969) An analytic elastic-viscoelastic model for the shape and the forces of the left ventricle. *J. Biomechanics* **2,** 35–47.

Grant, R. P. (1953) Architectonics of the heart. *Am. Heart J.* **46,** 405–431.

Grant, R. P. (1965) Notes on the muscular architecture of the left ventricle. *Circulation* **32,** 301–308.

Hort, W. (1960) Makroskopische und mikrometrische untersuchungen am myokard verschieden stark gefülter linker kammern. *Virchows Arch. path. Anat. Physiol.* **333,** 523–524.

Karni, Z. and Polishuk, W. Z. (1970) The uterus as a thin shell structure. Research Report SR TSI 70–05, Technion-Israel Institute of Technology, Haifa.

Lev, M. and Simkins, C. S. (1956) Architecture of the human ventricular myocardium. *Lab. Invest.* **5,** 396–409.

Mirsky, I. (1969) Left ventricular stresses in the intact human heart. *Biophys. J.* **9,** 189–208.

Mirsky, I. (1970) Effects of anisotropy and nonhomogeneity on left ventricular stresses in the intact heart. *Bull. math. Biophys.* **32,** 197–213.

Mizrahi, J., Karni, Z. and Polishuk, W. Z. (1977) Strain uterography in labour. *Brit. J. Obstet. Gynaec.* **84,** 930–936.

Mizrahi, J. and Karni, Z. (1975) A mechanical model for uterine muscle activity during labor and delivery. *Israel J. Tech.* **13,** 185–191.

Mizrahi, J., Karni, Z. and Polishuk, W. Z. (1978) A kinematic analysis of uterine deformation during labor. *J. Franklin Inst.* **306** (2), 119–132.

Mizrahi, J. (1975) Deformation analysis of the uterine muscle during labor and delivery. D.Sc Thesis submitted to the Technion-Israel Institute of Technology, Haifa.

Pearsall, G. W. and Roberts, V. L. (1978) Passive mechanical properties of uterine muscle (myometrium) tested *in vitro*. *J. Biomechanics* **11,** 167–176.

Ross, J. Jr., Sonnenblick, E. H., Covell, J. W., Kaiser, G. A. and Spiro, D. (1967) Architecture of the heart in systole and diastole: technique of rapid fixation and analysis of left ventricular geometry. *Circulation Res.* **21,** 409–423.

Streeter, D. D. Jr. and Basset, D. L. (1966) An engineering analysis of myocardial fiber orientation in pig's left ventricle in systole. *Anat. Rec.* **155,** 503–511.

Streeter, D. D. Jr. Spotnitz, H. M., Patel, D. P., Ross, J. Jr. and Sonnenblick, E. H. (1969) Fiber orientation in the canine left ventricle during diastole and systole. *Circulation Res.* **24,** 339–347.

Streeter, D. D. Jr., Vaishnav, R. N., Patel, D. P., Spotnitz, H. M., Ross, J. Jr. and Sonnenblick, E. H. (1970) Stress distribution in the canine left ventricle during diastole and systole. *Biophys. J.* **10,** 345–363.