NECK INJURY PREVENTION BY AUTOMATICALLY POSITIONED HEAD RESTRAINT

M. H. Muser ‡, Ch. Dippel *, F. Walz §

‡ Institute of Biomedical Engineering and Medical Informatics, University of Zürich and Swiss Federal Institute of Technology, Zürich, Switzerland

* Institute for Lightweight Construction, Swiss Federal Institute of Technology

§ Institute for Legal Medicine, University of Zürich

ABSTRACT

Low-Mass Rigid-Belt vehicles have shown a promising protection potential for their occupants in frontal and lateral collisions. The higher vehicle acceleration levels caused by their increased stiffness can be compensated by properly chosen advanced restraint systems and integrated lateral padding.

In rear impacts, however, new means of neck protection are required. Even in conventional cars with properly designed rear end deformation zones, headrests reduce neck injuries only in 20 - 30 % of the cases. Reasons for this fact include inadequate positioning or even insufficient adaptability of the headrest, and inappropriate construction of the seat back.

Due to inadequate or lacking legislation and user negligence current headrests are rarely adjusted properly, although it is known that a carefully designed and individually adapted head-neck restraint could reduce neck injuries considerably.

Automatic position monitoring and adjustment for the head-neck restraint in both the horizontal and vertical axis could alleviate these shortcomings. Such a system, consisting of electronic sensing devices, control circuitry, and electrical translation mechanisms, is implemented in the light vehicle seat currently under development by our Working Group. First experiments with this new approach for neck injury prevention are discussed. The control circuit could also alert the driver from sitting too close to the steering wheel, thereby contributing to an optimal effectiveness of the air bag deployment in frontal collisions.

ADVANCES IN OCCUPANT RESTRAINT TECHNOLOGIES: JOINT AAAM-IRCOBI SPECIAL SESSION

September 22, 1994, Lyon, France

The construction of a car seat is essential for all of its passive safety aspects. In rear impacts, the seat back and the headrest form the occupant restraint. Although many different headrest designs have been implemented by the car makers, major safety problems remain unresolved. Field studies have shown that the headrest is rarely well adjusted [van Kampen 1993], and in some cases the range of adjustment does not cover the entire driving population. Furthermore, usual headrests can only be adjusted in a vertical direction. The horizontal distance between the occupant's head and the headrest is often quite high (around 100 mm on average [Parkin 1993]), and cannot be reduced. For the low mass vehicles being studied by our Working Group, crash conditions are expected to be different from larger cars. In particular, significantly higher mean car acceleration levels (50 g vs. 15 - 20 g in a 50 km/h rigid barrier impact) have to be anticipated because of the small deformation zones, which aggravates the risk of head-neck injuries in rear impacts. In addition to these facts, accident statistics indicate a rising number of rear-end collisions as well as an increase in the corresponding insurance claims [Deutscher 1993]. The existing technical rules cover the headrest problems only superficially. If headrests are installed (which is not mandatory), they must undergo static and dynamic load tests [ECE 1992] for approval. However, regulations regarding the adaptability of headrests or protection criteria taking into account the biomechanics of rear impact head-neck injuries are still missing.

Based on these facts, our Working Group has decided to develop a new safety seat for use in lightweight vehicles. Since the current mechanisms for the individual adaptation of the headrest are often cumbersome and therefore neglected by the users, only an automated system using electronic sensors can guarantee an optimally adjusted and thus better restraint in the head-neck area during rear impacts. The design of a new head-neck restraint, which is horizontally as well as vertically adaptable and offers the capability of an automated operation is presented on the following pages.

BIOMECHANICS OF THE HEAD AND CERVICAL SPINE DURING REAR IMPACT

Biomechanic considerations, in particular the injury mechanisms associated with rear end impacts, represent the basis for the specification of the design parameters of a head-neck restraint system. A number of studies including volunteer tests and measurements of the isolated cervical spine [Backaitis (ed.) 1993] have been devoted to this problem. However, cervical injuries often occur at load levels well below the physical tolerance limits established in these studies. Such lesions[1] are often hard or impossible to localize by diagnostic methods, although they compose a large part of the total number of injuries in traffic accidents. Therefore, it appears to be justified to disregard in a first step these tolerance limits, allthemore as they exhibit a considerable variability, and rather concentrate on the control of the kinematics of the head-neck-thorax system during the rear impact. The course in time of the relative displacements within this system has been subdivided by various authors into the following three phases [Penning 1993] (Figure 1)

1. Immediately after the onset of the acceleration, the head is displaced horizontally backwards, thereby introducing shear forces in the upper vertebrae and deforming the cervical spine into an S-shape.
2. The resulting forces cause an extension of the spine.
3. Depending on the characteristics of the headrest (if any), a rebound of the head sets in, possibly even resulting in a flexion.

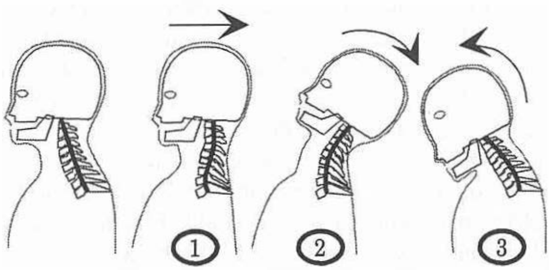

Figure 1: Kinematics of the head-neck-thorax system during a rear end impact (schematically)

It is important that the extent of the translational displacement during the first phase is minimized by the headrest, because many lesions are believed to occur in this phase. This means that the headrest must be positioned vertically at the centre of gravity of the head, and horizontally as close by as possible to the posterior head surface. The relative displacements can be further diminished by using a contoured head-neck restraint, e.g. supporting the neck, too.

The third phase (rebound) is believed to be of minor importance. However, using energy absorbing materials in the construction of the headrest as well as including controlled plastic deformation characteristics in the design of the seat back reduces rebound in any case.

---

[1] Such injuries are often termed 'whiplash'. This term is inappropriate, because it generates a confusion between the actual lesion (for example 'distortion of the cervical spine') and the biomechanical circumstances which caused it [Walz 1994].

DESIGN PRINCIPLES

The design goals for the new head-neck restraint system can now be formulated. As it has been mentioned above, the system is planned to be incorporated in the low mass vehicle seat currently under development at our Working Group. A lightweight construction is therefore mandatory, and higher car accelerations must be taken into account. The low mass vehicle (LMV) is assumed to be built with a hard shell, e.g. there are only minimal deformation zones on all sides of the car [Niederer 1993]. The currently unknown acceleration profile for rear impacts can be assumed to be very similar to the profile already measured in frontal impact crash tests. A mean acceleration of 50 g and a Δv of 33 km/h are used as a worst case situation for the construction calculations. This corresponds to a car with a mass of 1200 kg hitting the LMV (600 kg) with a speed of 50 km/h.

The vertical adjustment range of the headrest must accommodate occupant sizes from the 5th percentile female to the 95th percentile male, as defined by SAE [SAE 1989]. The adjustment is believed to be correct if (on the vertical axis) the geometric centre of the headrest coincides with the centre of gravity of the occupant's head. This requirement is very rarely fulfilled in currently available seats, e.g. the headrest cannot be pulled out far enough or loses its stability when adapted to a 95th percentile male position.

The horizontal adjustment range is harder to define, since no anthropometric data are available on the sitting posture of drivers under realistic traffic conditions. In a field study, Parkin [Parkin 1993] has measured horizontal distances between the back of the driver's head and the centre of the headrest. He found distances ranging between 80 and 240 mm for the 5th and the 95th percentile, respectively (approximated from graph). Since the seating position in the LMV will be more upright than normal (the seat back angle is fixed), this range can be reduced to approximately 100 mm. The horizontal adaptation of the system includes not only the headrest, but also the (contoured) neck support. From a safety standpoint, a configuration where the headrest surface is always in contact with the occupant's head would be optimal (cf. Figure 2). Since this would be irritating for the driver, a distance below 4 cm is planned. In order that the thorax and the head will get into contact with the underlying energy absorbing padding at the same time even if a small distance between head and headrest of some 4 cm is accepted, a thicker comfort padding is used on the seat back than on the head-neck restraint.

If the proper adjustment of the head-neck restraint system cannot be guaranteed, only little is gained in view of injury prevention. One of the reasons why the adjustment of the headrest is often neglected is the unhandy mechanism, which requires the driver to use both hands, e.g. to turn around in the seat, in order to apply the necessary force. Accordingly, all necessary adjustments of the new system will be operated electrically to circumvent this problem. This also facilitates the implementation of self-locking mechanisms, ensuring that the headrest cannot be moved out of the selected position by external forces during the crash.

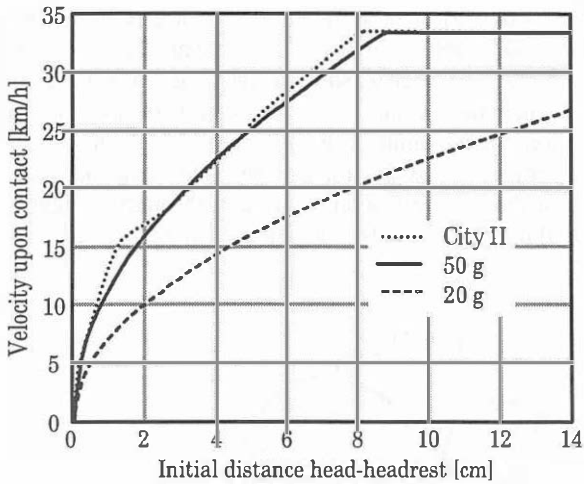

Figure 2: Velocity of the head upon impact vs. initial distance between the head and headrest; for mean vehicle accelerations of a conventional car (20 g), estimated LMV (50 g), and based on a curve measured in a frontal impact test of a Horlacher City II.

The second reason why headrests are maladjusted is that most users do not know what the correct position would be [Deutscher 1993]. An electronic, two-dimensional detection of the occupant's head position is necessary to provide either an appropriate feedback (warning light) to the user or directly drive the adjusting motors. Whether such an automated adjustment would occur only during the start-up phase or continuously control the headrest motion is not yet clear.

MECHANICAL IMPLEMENTATION

The occupant's head, neck, and thorax have to be supported as evenly as possible by the restraint during a rear impact. For this purpose, the adjustable head-neck restraint should be adapted to the contour of the occupant at all points of contact. An obvious solution would be to divide the restraint vertically into closely spaced horizontally moving segments in order to have an optimised contour under all circumstances. This would require not only a complex and expensive mechanism but also a corresponding number of independent sensors, control systems, and motors. A compromise between a good adaptability and a practical construction must therefore be found. A promising solution is to divide the restraint into a head part and a neck-upper thorax part. The head part performs a translational movement, while the neck part rotates around its lower end which is fixed on the back rest (Figure 3). This results in a forward translation of the headrest coupled with a minor downward shift. A mechanism guaranteeing an exactly horizontal movement would be difficult to implement for geometrical reasons. In fact, the downward shift is not very disadvantageous because passengers tend to have their head in a lower position when leaning forward. Since this downward movement of the passenger's head is smaller than the corresponding vertical translation of the headrest, a compensation through a slight backward inclination of the whole head-neck restraint can be introduced.

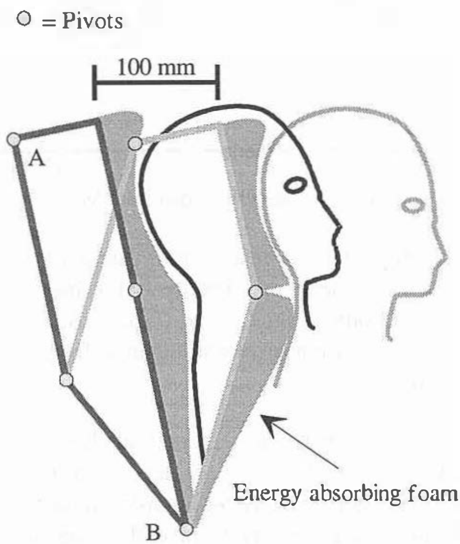

Figure 3: Horizontal head-neck restraint adjustment mechanism. The spindles for the adjustment are mounted between points A and B on both sides of the assembly.

The proposed mechanism is based on a parallelogram which can be adjusted by variation of the length of one of its diagonals. Only one distance sensor and one motor is required. The relationship between the change of length of the diagonal and the resulting horizontal movement of the headrest is not linear, but the deviation from linearity (within the range of operation) is negligible. A functional model of the new system was built to test the adjustment control system and to get a starting point for the optimisation of the geometry.

The longer diagonal of the parallelogram will be loaded by tensile forces in a head impact, whereas the shorter diagonal will bear compressive forces. These compressive forces will be considerably lower due to the geometry. However, the longer diagonal was used for carrying the translation mechanism, because this results in a simpler construction. The adjustment works by means of two Bowden cables connected to a spindle which is driven by a DC electric motor. Thus, the motor can be decoupled from the seat construction, thereby favouring acoustic isolation. An elastic element in the shorter diagonal resets the assembly backwards upon release of the cables. The forces effective in the diagonals and the rest of the structure are a function of the front-to-back size of the construction. For the chosen dimensions the force per wire is equivalent to the force effective on the head multiplied by 2.5 (this value would be -0.64 if the shorter diagonal was used). Accordingly, if the head is decelerated with 80 g, the cables must bear a force of 10 kN each. In reality, those forces will be even higher, since the neck and upper thorax have to be considered, too. However, Bowden cables are not suitable to transmit forces of this magnitude, and furthermore the relatively high elasticity of such a connection would cause more rebound, which is highly undesirable. For the final construction, the Bowden cables will be replaced by flexible shafts which drive spindles mounted directly in the diagonals of the assembly. The shafts transmit the necessary torque for the movement of the headrest only, and in case of a head impact, the spindles will block themselves and no forces are transmitted back to the motor.

During a head impact, the foam padding is the main element responsible for energy absorption. The padding must be shaped adequately and its stiffness must be such that the resulting head accelerations do not exceed the human injury tolerance limits. In the worst case for a lightweight vehicle as mentioned above (rear impact, $\Delta v = 33 km/h$, initial distance between head and headrest = 4 cm), a deformation of the restraint of at least 5 cm is necessary to obtain an average head acceleration below 80 g. Yet, foams can only be compressed by approximately 60 % of their initial size without a significant increase of the deformation force. These considerations lead to a foam padding which is about 8.3 cm thick. Of course, this is only true under the assumption of a perfectly rigid headrest and seat back structure, which is not realistic. If the bending of the seat back and resulting backward motion of the headrest is taken into account, the necessary thickness of the foam padding becomes considerably smaller, depending on the overall seat construction. Nevertheless, the required thickness of the padding constitutes a problem. With increasing thickness it becomes more and more difficult to optimise the padding contour. For example, the gap occurring between the two parts becomes larger whenever the mechanism is in its most forward position. This problem can be solved by placing the foam padding in a more backward position relative to the side struts, where sufficient space is available. However, the side structure must be covered with enough padding too, to prevent injuries to the head if the restraint is not hit in its centre. This leads to a concavely shaped padding that also reduces the risk that during an oblique rear crash the head glances off the headrest. It is also conceivable to implement plastically deforming force limiters in the diagonals of the structure. Those elements could supply an additional amount of energy absorbing capacity for very severe impacts.

The next step planned in the construction will be the optimisation of the padding contour by means of optical registration of the gap between the existing padding and different occupants in various postures.

HEAD POSITION SENSORS

The position of the occupant's head must be sensed in the horizontal as well as in the vertical direction. Since the measurement should be made as unobtrusive as possible, a direct contact of the measurement system with the occupant must be avoided. It is important that the sensing system measures the posterior surface of the head and not, for example, the contour of the occupant's hair. Various contactless sensors, such as electro-optical, ultrasonic, capacitive, and inductive, are readily available for industrial purposes Their accuracy generally exceeds our demands by far (± 5 mm would be sufficient).

HORIZONTAL DISTANCE MEASUREMENT

The distance to be measured for the horizontal adjustment is defined as the length of a horizontal line emerging at the rearmost point of the occupant's head contour and ending on the surface of the headrest. The headrest must already be adjusted vertically when the horizontal measurement starts. All the sensor types mentioned above (except the inductive type) could theoretically be used for the measurement of this parameter. However, optical distance sensors rely on the reflectance of the measurement object. This could lead to problems, since the optical properties of the head are widely varying, and the hair contour instead of the head surface will be measured in most cases. Furthermore, the cost of such sensors is quite high (some 100s of CHF). A solution using a light barrier would be feasible at low cost, but it would not allow a variable distance control. Ultrasonic sensors would be very accurate and suitable for the task, but, apart from their relatively high cost, the sensors available from stock can only measure distances above 100 mm, because there is a dead time after the emission of a burst during which the sensor cannot receive the reflected signal.

The capacitive sensor appears to be the best choice for the task. These sensors are used for the measurement of distances ranging from nanometers to meters, and can be made very accurate. Their 'field of view', e.g. the area in which objects are detected, can be adapted to the measurement problem by appropriate design of the sensor geometry. A prototype of such a sensor has been built and tested in the mock-up of the new head-neck restraint. Its working principle is illustrated in

Figurc 4. A sinusoidal voltage with a frequency of 100 kHz and an peak amplitude of 12 V is applied to a conducting surface (the generator), forming one plate of a capacitor.

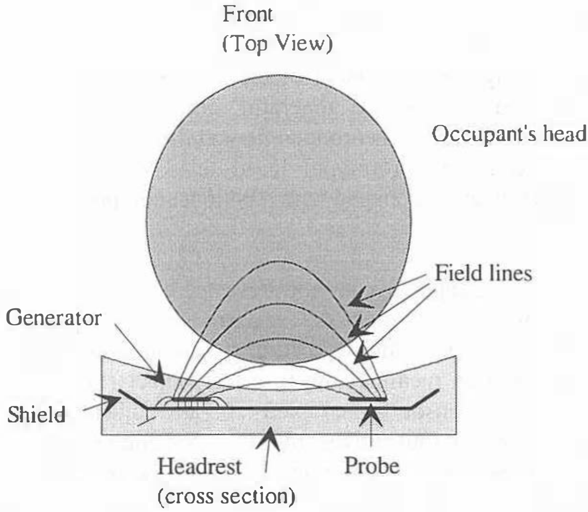

Figure 4: Capacitive head distance sensor, top view, cross-section. The field lines that cross the area of the head would be absorbed and thus would not contribute to the signal detected at the probe. The shield protects the sensor from influences of objects behind and at the sides of the headrest.

The current (in the range of a few µAmpères) between a second plate (the probe) and ground is measured. If an object (e.g. the occupant's head) enters the alternating field built up between the two plates, this current changes, depending on the dielectric properties of the object and its distance to the plates. Since the human body can be assumed to be conducting, the field lines cannot enter the body and the measured current decreases with distance. The generated field is very weak and has a relatively low frequency, therefore any influence on the comfort of the occupant can be excluded. Since the currents involved are also very low, electromagnetic compatibility between the sensor and other electronic devices in the car is also ensured. On the other hand, the possibility that other devices (ignition spikes, cellular phones, stereo equipment) might influence the measurement must be considered. Several methods can be used to minimize these error sources:

- The positioning system itself has a relatively high time constant, given by the inertia of the moving parts and the limited power of the electric motor. Feeding the sensor output voltage through a low pass filter with a cut-off frequency smaller than 1 Hz has no influence on the performance of the system, but eliminates almost all of the high frequency interference.

- Shielding of the sensor on all except the front side is mandatory in any case, since objects approaching the sensor from behind must not have an influence on the measurement.
- Synchronous demodulation of the measured current, e.g. measuring only the component of the current which has exactly the same frequency as the generator, could further reduce the measurement errors. Synchronous demodulation is currently not implemented in the prototype. Road tests will show if such techniques (always associated with additional component cost) are necessary.

In summary, the capacitive sensor presented here seems to be very well suited. It offers low weight (< 1 g), low cost (component cost: 4-5 CHF retail price) and sufficient accuracy. The directional sensitivity of the sensor has been measured using a test object (Figure 5). The horizontal distance sensor is coupled to an adjustable window discriminator whose output drives the DC positioning motor. The headrest can thus be made to continuously follow the head movements of a test person with a relatively high speed (approximately 0.1 m/s). If such a high speed, continuous readjustment makes sense in everyday use has yet to be determined.

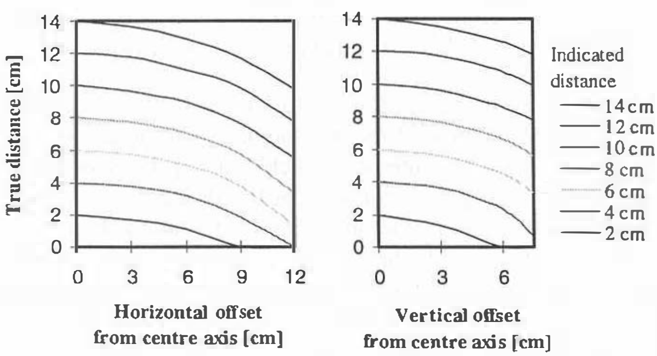

Figure 5: Directional sensitivity of the capacitive sensor. A steeper decline of the sensitivity in the vertical axis can be seen, e.g. the headrest has to be placed correctly on the vertical axis before the horizontal adjustment can be made.

VERTICAL POSITION MEASUREMENT

The measurement necessary for the vertical adjustment of the headrest poses less problems than for the horizontal distance. Since the ideal position of the headrest in the vertical axis is known (centre of headrest = centre of gravity of the head), no quantitative measurement is necessary. Furthermore, the vertical adjustment will be performed only once, at the time of start-up of the motor. A simple threshold measurement is sufficient. Several principles, all implementable with low cost, are proposed:

1. Position measurement of the shoulder belt: in the LMV seat currently being developed, the shoulder belt is fixed on the B-pillar and guided through an opening in the seat back. The guiding device moves together with the headrest in the vertical direction, in order to guarantee an optimal belt geometry for all occupant sizes. This implies that the angle between the shoulder belt and the seat back must be held constant. The vertical movement of headrest and belt guide can thus be controlled directly by a three-position switch that detects whether the belt angle is correct or not. This solution has the disadvantage that the shoulder level of the occupant is taken as a reference, in lieu of the centre of gravity of the head. However, a comparison with anthropometric tables shows that this will lead to a maximum error of only 20 mm for all occupant sizes. Another obvious disadvantage is that the system works only if the safety belt is used.
2. A second capacitive system could be mounted on the roof of the car. Precautions will have to be taken against the two sensors interfering with each other, and the sensor geometry must be different to account for the movement of the whole seat along the horizontal axis.
3. A light barrier, mounted on the top of the headrest, can detect whether the headrest is too low. As mentioned before, such a device detects some point within the contour of the occupant's hair, not the surface of the head. If the headrest is designed appropriately, errors introduced by this might be tolerable. The regulation electronics would in this case be set so that the headrest would rather be positioned too high than too low.

CONCLUSIONS

A full scale mock-up of the new low mass vehicle seat has been built (Figure 6), incorporating the automatically positioned head-neck restraint. Currently, the vertical adjustment mechanics are not implemented. The functionality of the mock-up has been tested with various persons of different sizes. The feasibility of such a system has thus been shown.

Dynamic load tests using a head impact test utility currently under construction will be necessary to prove the crashworthiness of the system. Such tests are planned in the second half of 1994, and will be followed by sled tests as soon as the prototype of the new seat is complete.

Road tests will be needed to find a good strategy for the horizontal adjustment, e.g. a single adjustment at the time of start-up versus a continuous readjustment.

REFERENCES

Backaitis H. (ed.)
Biomechanics of Impact Injury and Injury Tolerances of the Head-Neck Complex
SAE PT-93/43, Warrendale USA 1993

Deutscher Ch.
Bewegungsablauf von Fahrzeuginsassen beim Heckaufprall
Dissertation TU München, München 1993

ECE
ECE R 17 "Einheitliche Bedingungen für die Genehmigung der Kraftfahrzeuge hinsichtlich der Sitze, ihrer Verankerungen und Kopfstützen"
European Union, 1992 (Translation)

Niederer P., Walz F., Kaeser R., Brunner A.
Occupant Safety of Low-Mass Rigid-Belt Vehicles
Proc. 37th Stapp Car Crash conf., SAE 933107, p 1-13, San Antonio 1993

Parkin S. et al.
How Drivers Sit in Cars
Proc. 37th Ann. Conf. AAAM, 11/1993

Penning L.
Acceleration injury of the cervical spine by hypertranslation of the head
Eur. Spine J., 1, 7-19 (1992)

SAE Human Physical Dimensions
SAE J833, U.S.A. 1993

Svensson MY, et al.
A dummy for rear-end collisions
Proc. IRCOBI 1992, Bron France 1992

van Kampen L.T.B
Availability and (proper) Adjustment of Head Restraints in The Netherlands
Proc. IRCOBI 1993, Bron France 1993

Walz F.
Biomechanische Aspekte der HWS-Verletzungen
Der Orthopäde I, 1994