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16. Abstract

Regionalization of specialized perinatal care is a fully viable and progressing concept. The two major components of regionalized care are the level III care facility and the air transport service. In descending importance, the medical transport team, the pilot and aircraft, and related technology and equipment are the three most important components of the transport service. Although significant reductions in perinatal morbidity and mortality have already resulted from development of regional care, additional progress is possible and desirable. Areas of possible improvement are: earlier precrisis diagnosis of maternal and/or fetal risk at level I care; supplementary training of medical transport personnel in perinatal aspects of Aviation Medicine, Physiology, and Safety; technology of preflight stabilization of the pregnant mother or the neonate; adjunct medical training of transport pilots; exclusive use of multiengine, fixed-wing, all-weather aircraft; and technology of in-flight life support and monitoring equipment and methods.

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List of Abbreviations

HRPW	High-risk pregnant woman
HRN	High-risk neonate
CD	Communications and dispatch
RN	Registered nurse
mph	Miles per hour
RT	Respiratory Therapist
EMT	Emergency Medical Technician
$P_{I_{O_2}}$	Partial pressure of inspired oxygen
Pa_{O_2}	Partial pressure of arterial oxygen
$F_{I_{O_2}}$	Fraction of inspired oxygen
tc	Transcutaneous
ICN	Intensive care nursery
HbO_2	Oxyhemoglobin saturation
Pa_{CO_2}	Partial pressure of arterial carbon dioxide
pH	Negative log of hydrogen ion activity
NTE	Neutral thermal environment
RDS	Respiratory disease syndrome
L/S	Lecithin/sphingomyelin ratio
BP	Blood pressure
bpm	Beats per minute
HR	Heart rate
CPAP	Continuous positive airway pressure
MAP	Mean arterial pressure
dB	Decibel
CNS	Central nervous system
torr	Millimeters of mercury
F	Fahrenheit
C	Celsius

EVALUATION OF CARDIOPULMONARY FACTORS CRITICAL TO SUCCESSFUL EMERGENCY PERINATAL AIR TRANSPORT

I. INTRODUCTION.

The perinatal period generally encompasses the last trimester of pregnancy through the first 28 days of neonatal life. The primary foci of perinatal concern are the high-risk pregnant woman (HRPW) and the high-risk neonate (HRN).

Perinatal maternal mortality per 100,000 live births has decreased from 582.1 in 1935 to 47.0 in 1955, and 12.3 in 1976 (53). Neonatal mortality (less than 28 days of age) per 1,000 live births has decreased from 20.5 in 1950 to 18.7 in 1960, and 10.9 in 1976 (53). These decreased mortality rates have been mainly ascribed to the emergence and development of specialized perinatal care facilities (level III care) (10,13,28,33,64,67). Most major urban medical centers now contain expertly staffed and fully equipped level III perinatal facilities.

The medical personnel and equipment of most rural clinics and hospitals (level I care) are adequate for obstetrical delivery of a normal full-term fetus from a normal woman. If antenatal risk is first detected at a level III facility, then level III care is immediately available with the best chance for an optimum outcome. However, if antenatal risk is first discovered at a level I facility, then rapid, safe transport is the logical link to optimum care in a level II or III facility. If neonatal risk is first detected after birth in a level I facility, then rapid transport to a level II or III facility is similarly indicated. A substantial percentage of HRN's will continue to be born at level I facilities because HRN's are not always detectable before birth (8,45,61,63).

II. REGIONALIZATION OF PERINATAL CARE.

To accomplish the most efficient utilization of levels II and III perinatal facilities within any given geographic area, the concept of regionalization of services has been applied. The functional hub of any regional system is its communications and dispatch (CD) center. The CD center integrates all functions of the regional system. It is staffed 24 h a day, 365 days a year. It keeps daily records of all available bed space in intensive care units of all levels II and III facilities within the region. It assigns each request to an appropriate level II or III facility. It dispatches medical transport teams to the referral hospitals to provide the needed degree of intensive care en route to the assigned receiving facility. It coordinates all ground and air transport. The goal of regionalized care is to provide each HRPW and HRN with the level of care consistent with their respective medical conditions.

The concept of regionalized perinatal care has been endorsed by the American Medical Association, the American College of Obstetricians and Gynecologists,

the American Academy of Pediatrics, and the American Academy of Family Physicians (29). Perinatal care has also been regionalized in the major military medical centers and integrated with the aeromedical evacuation system of the United States Air Force (56). Substantial decreases in mortality rates have already been ascribed to regionalization of perinatal care (10,13,33,61).

An important component of regionalized care is its integrated system of transportation. Transport is accomplished by surface and airborne vehicles. About 80 percent of all transports involve surface vehicles such as ambulances and vans, and about 20 percent involve air transport by helicopters or fixed-wing aircraft. This report is primarily focused on perinatal air transport, and on potential effects of the airborne environment on cardiopulmonary functions in the HRPW and HRN. Source materials include recent scientific publications, and firsthand oral information and publications from 23 physicians and registered nurses (RN's) having 174 cumulative years of "hands on" experience in perinatal air transport. The oral information was obtained by individual telephone conferences. All telephone conferees are listed in Appendix I.

The main purpose of this study is to integrate all of the updated information into a comprehensive status report for possible use in formulating appropriate guidelines for the aviation medicine community in the area of perinatal emergency air transport.

III. OPERATIONAL RADII OF TRANSPORT MODES.

The geographic hub of any perinatal region usually consists of one or more level III perinatal facilities. The CD center usually operates out of one of the level III facilities. Vehicular transport modes depend on local conditions such as terrain, population density, weather patterns, and availability of surface or air carriers (33). Within a radius of about 50 miles from the geographic hub, specially equipped and manned ambulances and vans constitute the main mode of transport. Because of its small area, high population density, and high concentration of level III centers, any metropolitan perinatal transport service (e.g., New York City or Chicago) operates quite efficiently with the main use of surface vehicles (33). In the more densely populated eastern half of the United States, level III facilities very often overlap within radii of 50 to 100 miles. Because transport time is very often a critical survival factor, the 50-mile radius is the approximate cutoff distance for surface transport in densely populated urban areas. The 50-mile radius is generally equated to a one-way travel time of about 1 h.

When a perinatal care region is obliged to extend its coverage to a radius of about 150 miles, then surface transport is usually too slow for emergency conditions. When available, the helicopter has been used frequently in the 50- to 150-mile radius. There are several major patient-related disadvantages to helicopter use (12,40,57). These will be covered later by way of contrasting the advantages of fixed-wing aircraft. The main advantages of helicopter use are: their excellent emergency response time, their 1-h distance coverage of about three to four times that of a surface vehicle, and their "door-to-door" capability, often obviating the need for surface transport between the airport and the hospital. Because operational costs are a major impediment to exclusive use of helicopters

by any given perinatal transport service, shared usage has evolved in many cases (19). For instance, the perinatal transport service located in Baltimore, Maryland, utilizes the Bell 206B Jet Ranger helicopters of the State Police (50), and that of Columbus, Ohio, utilizes a UH-1H "Huey" helicopter of the Ohio Army National Guard (39). Both helicopters have speeds of 140 miles per hour (mph); the "Huey" has a range of 275 miles, and the Jet Ranger a range of 400 miles.

When a perinatal region is obliged to extend its coverate out to a 400- to 500-mile radius, fixed-wing aircraft participate as transport vehicles. Perinatal regions based at Denver, Colorado; Reno, Nevada; Salt Lake City, Utah; and Tucson, Arizona, are examples of extended radial coverage. Although perinatal transport experts agree that a multiengine, pressurized aircraft is the best type for perinatal air transport, operational costs often dictate the use of single-engine and/or unpressurized aircraft. Transport in single-engine aircraft costs about one-third that of larger, pressurized aircraft (26). Relatively small engine aircraft such as the Piper Lance, Cherokee 6, or Cessna 210 have served as transport vehicles (59). These aircraft have speeds of about 200 mph. Larger twin-engine aircraft such as Piper's Navaho and Chieftain, Cessna's 402 and 421 (pressurized), and Beechcraft's King Air Prop-Jet have speeds of 240 to 330 mph, and flight ranges in excess of 1,000 miles (59). When cost is no object, and great distances must be covered in minimum times, then aircraft such as the 500 mph Lear or Aero Commander Jets (59), or the Mitsubishi MU-2J Prop-Jet (6) have been used.

When critical care of the patient is required during air transport, then adequate cabin space becomes an important consideration. Cabin space in single-engine aircraft can barely accommodate one patient and one medical attendant with little or no room left for monitoring or life-support equipment (17). Minimum space requirements for optimum cabin configurations have been proposed (40). These minima are cabin width of 50 inches, height of 51 inches, and a volume of 220 cubic feet (40). Most of the twin-engine aircraft used in perinatal transport meet or exceed these requirements (42). The remainder of this report will focus its attention mainly on air transport in fixed-wing aircraft.

IV. IMPORTANT CHARACTERISTICS OF A SUCCESSFUL PERINATAL AIR TRANSPORT SYSTEM.

Although emergency perinatal transport is conceptually young, several excellent empirically based transport manuals have been written (9,21,54,66,69). All of these contain major sections on air transport. In addition, two excellent successive conferences on Newborn Air Transport and Maternal Air Transport have recently appeared in print (49,55). Many of the participants in these two conferences (49,55) also participated as updating information sources for this report.

Transfer of an HRPW or HRN to a level II or III facility is indicated when the patient's needs have exceeded local expertise or facilities (39). The decision to transfer the patient should be made when the recognized hazards of the journey do not outweigh the possible advantages to be gained after arrival (69). Transport should be by the fastest and safest means (33).

Mainly because of prohibitive acquisition and operational costs, most perinatal air transport is accomplished by contracting air ambulance services. Specifications for optimum types of aircraft as well as included equipment have been detailed in several publications (9,21,49,54,55,66,69). Duties and responsibilities of the pilot as an integral member of the transport team have been detailed elsewhere (41).

The most important component of a successful perinatal transport system is the medical transport team. The team is dispatched from the CD center to the referral hospital, assumes responsibility for the patient, stabilizes and prepares the patient for transport, and provides critical care and monitoring en route to the receiving facility. Typically, a transport team can be airborne within 50 to 70 min after the referral call is received at the CD center (16,42). Collectively, this team must possess the skills and knowledge to manage a wide variety of perinatal emergency conditions (41). Team members may be appropriately trained physicians, RN's, respiratory therapists (RT's), or emergency medical technicians (EMT's). One member of the team should be a physician or RN (54). The nature of the emergency governs the composition of the team. In between transports, all team personnel are usually full-time staff members of level III perinatal intensive care maternity or nursery facilities. An integral part of their duties at such facilities is to be on standby availability for transport duty (49,55).

The CD center coordinates all aspects of the air transport system. Its main functions have been described earlier. Perinatal air transport has played a successful role in the reduction of HRPW and HRN morbidity and mortality as reflected in published reports (10,13,28,33,38,61,67), and in the experience of our telephone conferees.

V. EMERGENCY MATERNAL AIR TRANSPORT.

A. Indications For Maternal Transport. Several publications (15,28,29,31, 54,69) contain detailed indications for emergency transport of the HRPW. The three major indication categories (15) are obstetrical, medical, and surgical complications. The obstetrical complications of premature rupture of membranes or premature labor at less than 34 weeks of gestation, or with an estimated fetal weight of less than 2,000 gm account for about 75 percent of all maternal transports. Severe eclampsia or other hypertensive complication, multiple gestation, poorly controlled diabetes mellitus, intrauterine growth retardation, third trimester bleeding, Rh isoimmunization, and abnormal premature cervical dilation are all factors which increase the probability of premature delivery. Medical complications include the presence of any acute or chronic severe disease in the HRPW. Surgical complications include those related to accidental trauma as well as abdominal and thoracic emergencies at less than 34 weeks gestation, or with an estimated fetal weight of less than 2,000 gm. The presence of one or more of these conditions usually defines the HRPW.

A maternal air transport service may operate its own CD center based in the intensive care section of an Obstetrics and Gynecology Department, or share a CD center with a nearby Pediatrics Department. The maternal transport team consists primarily of Obstetrics and Gynecology personnel. If birth is anticipated

before or during transport, Pediatric personnel may also participate as team members. Immediately upon arrival at the referring hospital, the maternal transport team assumes responsibility for the patient, assesses and stabilizes her condition as much as time permits.

Perinatologists (including conferees) generally agree that transport of the fetus "in utero" with the subsequent delivery and intensive care for both mother and premature neonate in a level III facility is a far better risk than delivery in a level I facility with subsequent transport to a level III facility (38,45,61,67). Therefore, with the two exceptions of toxemia and substantial blood loss (16,27), pretransport stabilization of the HRPW is secondary to speedy preparation for transport.

Patients at medium, high, and ultrahigh transfer risk are candidates for air transport. If transport time is a critical factor, then air transport is highly probable. In the cases of high or ultrahigh transfer risk, the transport team comes prepared to transport the HRPW under constant medical surveillance, deliver her at the referral hospital or en route, and provide neonatal resuscitation and intensive care (15). Because of the many inherent disadvantages (12,40,57), helicopter transport is considered unacceptable for any HRPW having a possibility of en route delivery.

Perinatologists agree that early detection of risk in the mother or fetus, prior to the rupture of membranes or onset of labor, provides the best chance for stable, safe, unhurried transport to a level III facility (10,38, 45,61,67,71). Early detection of an HRPW is more probable if she has an alerting medical history of disease and/or previous complicated pregnancies (29). However, most emergency transports of HRPW's involve first pregnancies with no prior alerting medical history (28).

B. The Airborne Environment-Cardiopulmonary Factors. Appropriate in-flight care for the HRPW inseparably involves the simultaneous welfare of the fetus. If reasonable preflight stabilization of the HRPW has been achieved, then appropriate in-flight monitoring and support of cardiopulmonary functions will greatly foster a successful transport (16).

During flight, environmental components with adverse cardiopulmonary potential include hypobarism, hypoxia, low environmental temperature, low humidity, motion, noise, and vibration. Many transport aircraft are capable of controlling some, but not all, of these environmental factors.

1. Hypobarism. To prevent all adverse effects directly ascribed to hypobarism (9,16,23,54), perinatologists (including conferees) universally agree that all perinatal air transport should ideally be accomplished in pressurized aircraft. Transport costs often preclude the ideal solution (26). When the condition of the HRPW is considered to be excellent and stable, a maximum cabin altitude of up to 6,000 ft has been recommended as tolerable for transport (9,27). If altitudes in excess of 6,000 ft are anticipated, then a pressurized aircraft is strongly advocated (9).

Reduction of ambient pressure surrounding any enclosed gas-filled volume will cause that volume to expand. For instance, the pressure change

from sea level to 6,000 ft altitude will cause an enclosed gas volume to expand about 25 percent (47). The expansion of such gases in the inner ear or sinuses can be quite painful. If gas is trapped in the gastrointestinal tract of the HRPW, its expansion can be both painful and circulatorily detrimental to the mother and fetus (9,16). In the specific instances of paralytic ileus or bowel obstruction in the HRPW, transport in unpressurized aircraft is contraindicated (9,16).

2. Hypoxia. Proper oxygenation of the HRPW and fetus starts with the provision of an adequate maternal inspired oxygen partial pressure ($P_{I_{O_2}}$). Since the exact relationship between $P_{I_{O_2}}$, maternal arterial P_{O_2} (Pa_{O_2}), and fetal oxygenation is not well understood, it has been recommended (9) that a $P_{I_{O_2}}$ of 135 mm mercury (torr) be supplied to the HRPW during air transport. If evidence of maternal pulmonary disease or fetal distress is present, a maternal $P_{I_{O_2}}$ of more than 240 torr should be provided (9). To provide the required $P_{I_{O_2}}$, the appropriate fraction of inspired oxygen ($F_{I_{O_2}}$) is obtained by monitored blending of regulated flows from tanks of compressed 100 percent oxygen and air. The $F_{I_{O_2}}$ required for a given $P_{I_{O_2}}$ is a function of ambient cabin pressure, and is readily calculated (36).

Proper oxygenation of the HRPW during flight could be titrated if continuous monitoring of the maternal and fetal Pa_{O_2}'s were possible. To prevent hypoxemia in the fetus, the maternal Pa_{O_2} should be maintained well above the critical minimum of 60 torr (11). In-flight monitoring of fetal Pa_{O_2} is considered to be practically impossible. The maternal Pa_{O_2} could possibly be monitored by a transcutaneous (tc) Pa_{O_2} sensor (43,44). According to our conferees, several commercial versions of the $tcPa_{O_2}$ sensor have been used for neonatal Pa_{O_2} monitoring in the intensive care nursery (ICN), and during transport. To date, this type of instrument has not been used for maternal Pa_{O_2} monitoring during transport.

If the maternal hemoglobin concentration is both adequate and stable, oxygenation could be titrated by monitoring maternal oxyhemoglobin saturation (HbO_2) with a tc ear oximeter. The possible use of an ear oximeter for maternal monitoring has been suggested by one of our conferees (11). Its use is most probably impeded by its purchase price, its size, poor portability, and its poor tolerance to environmental extremes and rough handling. Currently, the maternal oxygenation status during air transport is estimated by the attending physician or RN based on the patient's skin color, symptoms, and vital signs. Because the fetus may have more intrinsic protection against hyperoxygenation than against hypo-oxygenation (43), conferee consensus favored the use of maternal $P_{I_{O_2}}$ value, which was slightly greater than one deemed to be fully adequate.

Besides an adequate $P_{I_{O_2}}$, oxygenation of the HRPW and fetus also depends on pulmonary adequacy. In the presence of maternal pulmonary disease, acid/base imbalances can easily result from a highly variable maternal response to altitude hypoxia (11). In the presence of altitude hypoxia, maternal hyperventilation resulting in a respiratory alkalosis could adversely affect the hypoxemic tolerance of the fetus (11). The use of an adequate $P_{I_{O_2}}$ and/or a pressurized aircraft are logical preventive measures (11).

Proper in-flight respiratory management of the HRPW is also important when maternal diabetes and pulmonary dysfunction coexist. Pretransport assessment of arterial blood gases and acid/base balance are highly desirable (11). If the patient is acidotic, has an elevated arterial partial pressure of carbon dioxide (Pa_{CO_2}), and is being infused with bicarbonate, then in-flight oxygen therapy must be titrated with extra care. The $P_{I_{O_2}}$ must be high enough to provide sufficient oxygenation for both mother and fetus, but low enough to prevent a life-threatening maternal CO_2 narcosis (22,48). If available, in-flight monitoring of Pa_{O_2}, Pa_{CO_2}, and arterial hydrogen ion activity (pH) could allow titrated control of $P_{I_{O_2}}$, assisted ventilation, and acid/base status. Portable $tcPa_{O_2}$ monitors are commercially available and have been used on adults in hospitals but not, as yet, during transport (34). The measurement of arterial pH is routinely available in hospitals, but not during transport. Because of general contraindications to arterial catheterization of the HRPW, useful arterial pH information could be deduced from venous pH measurements made at a venous infusion site. To our knowledge, the translation of pH electrode technology to the transport environment has not occurred. Currently, several commercial sources of portable $tcPa_{O_2}$ monitors are attempting to produce a similar instrument for monitoring the $tcPa_{CO_2}$. If transport monitoring of arterial pH should remain a practical impossibility, then the direction of pH changes might be usefully inferred from $tcPa_{CO_2}$ monitoring. Technological advances could play a major positive role in this area.

The maintenance of cardiovascular functions are also important to the oxygenation of the HRPW and fetus. If substantial maternal losses of blood volume have occurred, they should be replaced prior to transport in order to prevent hypotension and/or hypoperfusion effects in both mother and fetus (16). Low blood volume can cause shock, fetal asphyxia, and premature labor and delivery (16). Maintenance of blood volume may be accomplished during transport by carefully monitored supplemental intravenous infusions (16). Catheterizations, intubations, or other delicate procedures should be done prior to transport to avoid the many complications of doing them in the flight environment (16). To aid circulatory stability, the HRPW is usually transported in a lateral recumbent position (9,16).

During transport, maternal blood pressure (BP) is usually monitored by means of systolic radial pulse detection during BP cuff deflation. Heart rate (HR) is monitored by radial pulse counts. The monitored control of BP in the HRPW is especially important because adverse effects can result from either hypotension or hypertension (9,16). Because rupture of membranes and premature labor account for about 75 percent of HRPW air transports (15,16), labor is often arrested during transport by intravenous infusion of tocolytic agents (16). Unfortunately, most tocolytic agents are capable of producing hypotension (16). Therefore, frequent monitoring of maternal BP and HR, and fetal HR (using a Doppler sensor) are necessary to detect incipient signs of maternal hypotension and/or fetal distress (16). The appearance of such signs call for cessation of tocolytic infusion (9,16). Tocolytic agents are usually contraindicated in the third trimester, if significant uteroplacental hemorrhage is present (16).

Hypertensive complications of pregnancy account for about 15 percent of HRPW transports (16). The development of eclampsia may produce seizures,

central nervous system (CNS) hemorrhage, premature labor and delivery, and fetal distress due to uteroplacental insufficiency (16). Magnesium sulfate is usually administered to prevent seizures. The administration of an antihypertensive agent may be considered if diastolic pressures exceed 110 torr. Depression of monitored vital signs and urinary output (from an indwelling Foley catheter) calls for cessation of these medications (9,16). Medical transport personnel maintain monitoring vigilance against potential side effects of any medication used during transport.

3. Environmental Temperature. Most transport aircraft (except helicopters) possess adequate heating systems. The main temperature problem is not only the generation of sufficient heat, but its constant control to produce a neutral thermal environment (NTE) for both the HRPW and fetus. Significant amounts of heat can be lost by radiation to cold window and airframe surfaces (9). Because both overheating and underheating can be stressful to a medically compromised HRPW, care must be exercised to avoid such thermal stresses during air transport, as well as during surface transport linkage between the hospital and aircraft in very hot or very cold weather (45). During air transport, a minimum cabin temperature of 75° Fahrenheit (F) is recommended (23,54,74). Even though delivery during air transport is uncommon (28, 37), the capability for higher cabin temperatures during such a delivery should be present in order to protect the neonate from cold stresses (9,60). Our conferees generally agree that the thermal environment of the HRPW during air transport has been successfully controlled.

4. Humidity. Ambient air becomes drier as a function of increasing altitude. At substantial flight altitudes, relative humidities may approximate desert values of 10 to 12 percent. Inspiration of dry air by a healthy adult for 2 to 3 hours is ordinarily innocuous. However, if pulmonary disease is present in an HRPW, then respiratory therapy with unhumidified oxygen mixtures could aggravate the pulmonary condition, cause stressful pulmonary discomfort in an already compromised patient, and interfere with her required oxygenation. Medical, tank-stored air and 100 percent oxygen each contain less than 10 percent humidity. Our conferees recommended humidification of all oxygen therapy of the HRPW during transport (9). To avoid undesirable thermal stress, the inspired oxygen mixtures should be warmed as well as humidified prior to inspiration. Our conferees agree that warming and humidification of inspired oxygen mixtures are generally desirable as preventive measures.

5. Motion. Motion sickness is a common problem in the HRPW during transport, and nausea and vomiting often occur during labor (9). The use of antiemetics, which have minor labor-inducing properties, should be avoided during transport (9). Usually motion sickness is minimized if the patient's head is facing forward in the aircraft (9). Apart from secondary effects of motion sickness, there are no data on the relationship of motion to specific problems for mother or fetus (9).

6. Noise and Vibration. Noise and vibration are inseparable from the flight environment. Both impede maternal monitoring and communication (54). Measured noise levels are in the 90 to 110 decibel (dB) range in helicopters, 80 to 105 dB in single-engine, fixed-wing aircraft, and 75 to 90 dB in multiengine,

fixed-wing aircraft (70). All medical transport personnel consider auscultative monitoring in the flight environment to be practically useless. Doppler equipment is used routinely to monitor fetal heart activity. A commercially available BP apparatus, which substitutes Doppler blood flow sensing for Korotkov sound detection and provides a visual digital readout, could be quite useful in the flight environment. This method is capable of measuring BP even during circulatory shock with low blood flow.

Medical transport personnel have reported that noise and vibration during transport play an important role in producing headache, visual and auditory fatigue, air sickness, irritability and anxiety in the HRPW (9,42). Noise levels encountered in air transport (especially in helicopters) are considered to be auditorily in a potentially hazardous range (70). Although repeated exposures could be auditorily harmful (14), single exposures are considered harmless (33). Definitive studies on specific noise and vibration effects in the HRPW and fetus have not been done. The conferees agree that the desirability of minimizing noise and vibration favors the transport use of multiengine, fixed-wing aircraft.

VI. EMERGENCY NEONATAL AIR TRANSPORT.

A. Preferability of "In Utero" Transport. As mentioned previously, "in utero" fetal transport with subsequent delivery and neonatal intensive care in a level III facility is preferable to delivery in a level I facility with subsequent neonatal transport to the level III facility (33,38,45,61,67). Early detection of risk in the HRPW or fetus, and early, unhurried transport to a level III facility is highly desirable. Early detection of risk may depend on an alerting medical history of disease and/or previous complicated pregnancy (29). When a maternal medical history indicates the possibility of a premature delivery, one component of potential fetal risk can be assessed. This component, which is the most prevalent risk in the premature neonate, is respiratory disease syndrome (RDS) (2,18,20). This risk is primarily related to insufficient production of surface-active (surfactant) material needed to keep alveoli open to air exchange (3). Surfactant, produced in the lung, begins to reach alveolar surfaces around 26 to 28 weeks of gestation (31). A lecithin/sphingomyelin ratio (L/S) of $\geq$ 2.0 in sampled amniotic fluid usually indicates sufficient maturity of the surfactant-producing system (25,30) When premature birth is considered to be highly probable, a concomitant L/S ratio of $<$ 1.5 (indicating pulmonary immaturity) should signal the need for that premature birth to occur at a level III facility.

In the presence of an otherwise normal pregnancy, early detection of fetal risk, per se, is very difficult at best (15). Fetal HR (Doppler monitored) and fetal activity are two important assessable functions during the third trimester (72). Because HRN's are not always detectable before birth, a substantial percentage of them will continue to be born at level I facilities and require subsequent transport to level III facilities (8,45,61,63,67).

B. The Transport Isolette Incubator. When transported "in utero," the fetus is provided with an ideal environment in its "biological" incubator. When premature birth has removed the HRN from the maternal incubator, an isolette incubator has to provide and monitor adequate substitutes for the intrauterine

environment and its life-supporting functions. This capability has to be maintained during transport of the HRN. Ideal specifications for transport isolettes have been detailed elsewhere (35,63,69). The most important specifications provide for an NTE, humidified oxygenation and ventilation of the patient, visualization and accessibility of the patient, and monitoring of both the neonate's vital functions and the systems which supply life support. All isolette functions are self-contained, and either self-powered (2-h battery pack), or capable of converted use of surface or air vehicle power sources. Size, weight, and maximum portability are also important considerations. The newest generation of isolettes contain several that are considered quite adequate by our conferees.

C. Indications for Neonatal Transport. Several publications (10,13,31,33,54, 55,62,67,69) contain detailed indications for emergency transport of the HRN. RDS, which causes respiratory failure, accounts for about 40 to 50 percent of all HRN transports (10,13,20,62). RDS is primarily associated with premature birth and/or low birth weight (2). Other important causes of respiratory failure are aspiration syndrome, pneumonia, apnea, birth asphyxia, pneumothorax, and pneumomediastinum. All forms of respiratory failure account for a total of about 75 percent of all HRN transports (33). Other important indications for transport include congenital disease and abnormalities, sepsis, CNS abnormalities, hemorrhage, and blood dyscrasias (10,13,64,67). The presence of one or more of these conditions usually defines the HRN. In the presence of any of these conditions, mortality risk is increased proportionally by the degree of prematurity and/or low birth weight (8, 38,62).

The CD center for a neonatal air transport service is usually located in the intensive care section of a Pediatrics Department. The neonatal transport team consists primarily of Pediatrics and Pediatric Anesthesiology personnel. Activation and rapid dispatch of the team is quite similar to that of the maternal transport team. One major difference is the integral inclusion of the transport isolette. After arriving at the referral hospital and assuming responsibility for the patient, the transport team transfers the HRN to the transport isolette and starts preparation for transport. The most important facet of this preparation is stabilization of the HRN within the self-contained environment of the isolette (33).

D. Pretransport Stabilization of the HRN. If necessary, the transport team must be prepared to spend several hours to achieve sufficient stabilization of the HRN for transport (33). Because respiratory distress is usually present, tracheal intubation is often accomplished, and assisted ventilation with a humidified oxygen mixture is instituted. If severe RDS is present, assisted ventilation may be in the form of continuous positive airway pressure (CPAP) after the procedure of Gregory (32). Respiratory stabilization is judged mainly on the external color of the HRN, and on measured values of Pa_{O_2}, Pa_{CO_2}, and arterial pH. When available, a $tcPa_{O_2}$ monitor is positioned at this time for subsequent use during transport. Catheterization of the umbilical artery is also necessary in most cases. Although the umbilical vein may be used, the artery is usually preferred because, besides providing medication access to the bloodstream, it also provides access to HR and BP monitoring, and arterial blood sampling for acid/base and blood gas assessments. The team routinely carries its own equipment and medications for emergency treatment of hypovolemia, hypoglycemia,

acid/base derangements, cardiogenic shock, and electrolyte derangements. If blood gas analyses indicate metabolic or respiratory acidosis, appropriate infusion of bicarbonate is instituted to reverse the acidotic pH, and assisted ventilation adjusted to decrease Pa_{CO_2}, and increase Pa_{O_2}. Prolonged hypothermic acidosis may result in noenatal kernicterus, despite a low total level of bilirubin (23,74). Hypovolemic hypotension, which is usually intensified by bicarbonate infusion, may be corrected by whole blood infusion (if available) or by volume-titrated infusions of albumin or physiologic saline (31) Hypoglycemia (blood glucose < 20 mg percent) is usually treated with a titrated infusion of dextrose in water (31). Electrolyte decreases are similarly titrated. Since the predicted average blood volume of the neonate is about 85 ml/kg (31), infusion volume must be carefully titrated to avoid undesirable effects of hypervolemia. Methods and criteria for titrated correction of hypovolemia, hypoglycemia, as well as acid/base and electrolyte derangements, have been detailed elsewhere (31,33,42,55,69).

If unpressurized flight is anticipated, an orogastric tube is emplaced, the stomach is aspirated, and the tube is left in place to vent any gas distension that may be caused by subsequent altitude expansion (42,54,69). If a pneumothorax is present and causing respiratory distress, its necessary reduction is usually accomplished via a thoracostomy tube attached to a Heimlich valve (42,54,69). The thoracostomy tube is left in place to counteract any altitude expansion of gas.

Pretransport temperature stabilization of the HRN within the isolette environment is very important. Because biologic temperature controls may not be fully developed in the premature HRN, the distressed infant is quite vulnerable to both hypothermia and hyperthermia (74). Our conferees agree that stabilization and subsequent transport control of an NTE is a critical survival factor. Recommended initial isolette temperature settings (relative humidity of 50 percent) for neonates of various birth weights and ages have been detailed elsewhere (66,69).

The achievement of sufficient stabilization for transport is usually reflected by stabilized values of monitored vital signs. Because of the motion, noise, and vibration of the airborne environment, conversion of all monitors to an electronic digital readout mode is highly desirable. Most new-generation isolettes have incorporated this mode of monitoring.

E. The Airborne Environment - Cardiopulmonary Factors. Once stabilization of the HRN is achieved, the isolette and contained HRN are transported to the airport for the initiation of air transport. Once airborne, the transport's success depends mainly on maintaining the stabilization of the HRN by appropriate in-flight monitoring and support of cardiopulmonary functions (33,63).

During air transport of the HRN, environmental components with adverse cardiopulmonary potential are the same as those encountered during air transport of the HRPW. For two adjunct reasons, the HRN during transport is potentially more vulnerable than the HRPW to environmental displacement of cardiopulmonary functions. Because the HRN has a much smaller total mass, and a much larger surface-to-mass ratio than the HRPW, the HRN will react more sensitively and

rapidly to environmental changes. Further, the HRN does not have the capability to orally communicate to medical transport personnel any adverse symptoms as soon as they occur.

1. Hypobarism. Neonatologists (including conferees) universally agree that all adverse hypobaric effects of air transport (9,16,23) could be prevented by exclusive use of pressurized aircraft. If the HRN's preflight condition is considered to be excellent and stable, a maximum cabin altitude of 6,000 ft is considered tolerable for transport (9,49). If higher altitudes are anticipated, the use of pressurized aircraft is strongly recommended (9). In the presence of any entity such as pneumothorax, pneumomediastinum, aspiration syndrome, diaphragmatic hernia, ileus, bowel obstruction, esophageal atresia, and tracheoesophageal fistula, the use of a pressurized aircraft is strongly advocated (42, 47,54,69). Hypobaric expansion of a gas pocket associated with any of these entities is still possible in unpressurized flight despite preflight tube venting of the gas pocket (10). Substantial expansion of any such gas pocket during transport may mechanically compromise respiration and/or circulation, and possibly cause tissue rupture with subsequent sepsis (10,42).

2. Hypoxia. Oxygenation of the HRN during transport is considered a critical survival factor. Proper oxygenation of the HRN depends on many factors. One of these is the provision of an adequate P_{IO_2}. Because prolonged ventilation of a neonate with high F_{IO_2}'s entails a possible risk of retrolentil fibroplasia (23,31,35,54,69), depression of surfactant synthesis (24), and bronchopulmonary dysplasia (1,23), oxygen is used as conservatively as conditions permit. Ideally, a minimum Pa_{O_2} of 50 to 80 torr is desirable (31). Many of our conferees are currently using $tcPa_{O_2}$ monitors during transport to titrate the adequacy of the P_{IO_2}. The $tcPa_{O_2}$ monitor is usually "calibrated" by pretransport arterial blood gas measurements of Pa_{O_2}. Because P_{IO_2} is a function of ambient pressure, the use of a $tcPa_{O_2}$ monitor to regulate the blended value of F_{IO_2} during unpressurized flight can be very important. In the case of severe RDS, in which both a positive pressure for ventilation (e.g., CPAP) and a > 0.7 F_{IO_2} may be needed, the $tcPa_{O_2}$ can be useful in titrating the F_{IO_2} to minimize the risk of pulmonary oxygen toxicity (24). During air transport, about 45 percent of all HRN's require some form of assisted positive pressure ventilation (36). Although conferee use of the $tcPa_{O_2}$ monitor is increasing, they reported that this technology is not trouble free. Maintenance of the Clark electrode sensor requires some degree of experience. However, most conferees agree that the monitoring importance of the Pa_{O_2} exceeds the trouble of technological problems. For many practical reasons, ear oximetry monitoring of arterial oxygen saturation in the neonate is not feasible at this time (46).

Another important oxygenation factor is the maintenance of acid/base balance in the HRN. In a respiratorily distressed HRN, a resulting acidosis is highly probable. Initial measurements of arterial pH, Pa_{CO_2}, and Pa_{O_2} are important because, in the uncompensated presence of an acidotic pH and an elevated Pa_{CO_2}, intrapulmonic oxygen loading is impeded by an acidotic shift in the HbO_2 curve (64). For any desired Pa_{O_2}, a higher P_{IO_2} would be required to load the oxygen into acidotic blood than into blood with a normal or alkalotic pH (58). Further, in the same uncompensated acidotic condition, an oxygenated "pink" infant could incur rapid deterioration via CO_2 narcosis (20,23). Although measurements of

arterial pH, Pa_{CO_2}, and Pa_{O_2} are usually available at the referring hospital during preflight stabilization, they are not available during flight. If available, in-flight monitoring of Pa_{CO_2} and arterial pH, as well as Pa_{O_2}, could enhance the titration control of $P_{I_{O_2}}$, assisted ventilation, and blood acid/base status. A reduced, but still perfectly adequate $P_{I_{O_2}}$, could help decrease the possible intrapulmonic risk of oxygen toxicity (1,23,24). In the case of assisted ventilation, a reduced but still perfectly adequate CPAP, could decrease the in-flight risk of pneumothorax (20,42). The use of portable $tcPa_{O_2}$ monitors during HRN transport is currently increasing. The measurement of arterial blood pH using a pH electrode sensor is available in most hospitals. To our knowledge, the transfer of pH electrode technology to the flight environment has not occurred. The usually present umbilical artery catheter could provide access to the blood for pH measurement. Commercial sources of $tcPa_{O_2}$ monitors are currently attempting to produce a similar instrument for monitoring $tcPa_{CO_2}$. Since blood pH monitoring in the HRN may remain a practical impossibility, the direction of pH changes could be usefully inferred from $tcPa_{CO_2}$ monitoring. The survival importance of initially correcting acidosis and preventing its exacerbation during transport is reflected in mortality statistics. Two studies reported that the mortality of transported neonates who arrived with an arterial pH of < 7.2 was significantly higher than that of the neonates with an arterial pH of > 7.2 (33,64). Obviously, technological advances could play a major positive role in this area.

Another important oxygenation factor is the in-flight maintenance of cardiovascular functions in the HRN. Both arterial BP and HR are usually monitored via transducers at the entrance site of the umbilical artery catheter. The HR should approximate 120 to 160 beats per minute (bpm), and mean arterial pressure (MAP) should approximate 40 to 50 torr (31). Simultaneous bradycardia (< 100 bpm) and hypotension (MAP < 30 torr) could indicate hypovolemia and/or hypoglycemia (31). Ostensibly, both should have been corrected during the preflight stabilization period. During transport, hypotension could result from decreased venous return caused by a pneumothorax (31). In this regard, specific caution is exercised against the use of excessive pressure during CPAP ventilation of the neonate with congenital heart disease (10,52,73). Since hypoperfusion can produce rapid hypoxemic deterioration of the HRN, rapid counteractions to bradycardia and hypotension are indicated. Technically, monitoring HR and BP in the HRN during transport has posed few if any problems to our conferees.

3. Environmental Temperature. The maintenance of an NTE for the HRN during transport is also a critical survival factor. Several studies have reported that the mortality rate of transported neonates who arrived with rectal temperatures of < 35.5° Celsius (C) was significantly greater than that of the neonates with arrival rectal temperatures of > 35.5°C (33,64). Most transport aircraft have adequate heating systems. The heating capabilities and temperature control systems of several new-generation isolettes are considered to be generally excellent (33,63). Instability of the internal biological temperature controls (4,23,69), and the high surface-to-mass ratio (47) are the two main reasons for the HRN's hypothermic and hyperthermic vulnerability. Uncorrected hypothermia or hyperthermia can entrain a rapid chain of adverse effects. Inadvertent cooling or overheating of the HRN usually causes a significant increase in metabolic oxygen consumption. As increased metabolism lowers Pa_{O_2}, raises Pa_{CO_2}, and lowers pH, it produces an increased ventilatory drive. The presence

of any pulmonary condition which impedes gas exchange at the alveolar/capillary level (e.g., RDS, aspiration syndrome, etc.) will decrease the ability of the lung to sufficiently increase oxygen uptake and CO_2 excretion to keep up with the increased metabolic demand. The additional metabolic demand of increased respiratory efforts can cause a further decrease in Pa_{O_2}, an increase in Pa_{CO_2}, and a decrease in pH. The rapidly decompensating hypoxemia, hypercapnia, and acidosis can increase pulmonary vascular resistance, which can further compromise pulmonary gas exchange by reducing pulmonary capillary blood flow, and reopening the vascular shunts of fetal circulation. If unchecked, these decompensations, along with concomitant hypoglycemia, can cause a rapid deterioration of circulatory adequacy culminating in the death of the infant. This complex chain of events can occur within a span of several min (23,31,47,74).

The NTE of the isolette environment usually lies between 36.5° and 37.5°C (35,65). According to criteria suggested by one of our conferees (74), the HRN is probably in an optimum thermal environment when: his abdominal skin temperature is 35.5° to 36.5°C, his rectal temperature is about 0.5°C higher than that of abdominal skin, his extremity skin temperature is 3° to 4°C lower than that of abdominal skin, and his isolette temperature is 1° to 3°C higher than that of abdominal skin. During transport, neonatal temperature is continuously monitored via skin or rectal thermal electrodes. Some of the new-generation isolettes use a monitored intraisolette air temperature to servo-control the isolette's thermal system (35,63). Substantial research has been done on the possibility of using the neonate's temperature to servocontrol the isolette's thermal system (68).

The intraisolette oxygenation of the HRN is also a factor in maintaining a suitable NTE. The oxygen mixture flowing past the HRN must be humidified to impede evaporative water losses, and warmed sufficiently to avoid subjecting the infant to positive or negative thermal gradients (63). Our conferees generally agree that maintaining the isolette NTE, after its initial stabilization within a surrounding stable thermal environment, poses very few problems. Difficulty is possible during transfer of the isolette from the hospital to the ambulance, and from the ambulance to the aircraft in very cold or very hot weather. During air transport, changes in thermal balance are also probable whenever the isolette hood is opened to medically service the HRN (44). New-generation isolettes have improved thermal protection during hood access (35,63). Our conferees agree that proper thermal control is a major factor in successful transport of the HRN.

4. Humidity. If dry gas surrounded the HRN during air transport, substantial gradients for potential loss of heat and water could exist. The rate of such losses are potentiated by the high surface-to-mass ratio of the neonate (47). Further, respiratory therapy with unhumidified oxygen mixtures could aggravate any existing pulmonary condition, cause stressful discomfort, and interfere with adequate oxygenation (57). The HRN is therefore preventively respired with warmed and humidified oxygen mixtures. Several means of humidification were reported by our conferees. These included flowing the oxygen mixture over or through water, over water-soaked surgical sponges, through nebulized water mists, and by placing water-soaked towels within the isolette. Each conferee felt that his/her particular method provided adequate humidification. All the conferees agree that warming and humidification of both the intraisolette environment and the inspired oxygen mixtures were desirable as preventive measures.

5. Motion. During flight, aircraft motions may occasionally be accentuated in rate and amplitude by weather and turbulence. Although motion sickness may produce nausea, BP changes, sweating, pallor, and vomiting in adults, little is known about such effects in the neonate (42,69). One of our conferees has reported that a substantial number of infants who were stable throughout a flight, developed bradycardia, apnea, and vasomotor changes at the time of aircraft descent and approach for landing (42). Another conferee has reported that HRN's dislike motion of a jostling type. In this regard, the conferee has observed substantial apnea responses to jostling, especially during surface vehicle transport between the hospital and the aircraft.

Since en route care of the HRN depends on full functional alertness of the medical transport personnel, motion sickness in a team member could have an adverse effect on airborne neonatal care. Antiemetics are preventively useful if taken 30 to 60 min prior to takeoff. However, the side effect of drowsiness may affect rapidity and sharpness of judgment (42). Since the nausea of motion sickness during flight may be synergized with altitude hypoxia, breathing of supplemental oxygen may be useful (42).

6. Noise and Vibration. Noise and vibration may reach considerable levels during air transport. Noise levels in fixed-wing aircraft have been measured in the 75 to 105 dB range (70). Noise levels of the same order have been recorded inside isolettes during air transport (70). Some new-generation isolettes have successfully incorporated noise suppression technology (63). Single short-duration exposures of these encountered noise levels are not considered to be hazardous (33). Although no definitive studies have been done, possible adverse effects of noise and vibration on the transported HRN should not be ruled out (42). Segal (69) and Roy (67) have reported that neonatal disturbance by noise and vibration may be associated with regurgitation, and that suppression of the gag reflex by vibration may cause aspiration. If the HRN is being transported without tracheal intubation, a lateral decubitus position may provide the best safeguard against aspiration of regurgitated material (67,69).

A substantial portion of HRN's are transported for indications of CNS pathology (17). Although confirming studies are lacking, vibration during air transport is suspected as a causal and/or aggravating factor relevant to intracranial hemorrhage (17). This suspicion is based on the greater incidence of intracranial hemorrhage in neonates transported postnatally as compared to those who were transported "in utero" (17).

The major impact of noise and vibration is on in-flight monitoring. Most monitoring is currently accomplished electronically with digital readout capability (54). Doppler sensing has mainly replaced auscultative functions in flight. With respect to visual monitoring, one conferee has reported that blurred vision may result if the resonant vibration frequency of the eyeball (40 cycles per s) is present (42). The technology of monitoring during air transport has made considerable progress in recent times (33,63). Most conferees agree that the use of large, multiengine, all-weather aircraft should minimize the levels and effects of noise and vibration (6).

VII. SUMMARY.

Regionalization of specialized perinatal care is a fully viable and progressing concept. The development of level III care facilities has resulted in a significant reduction in perinatal morbidity and mortality. Early diagnosis and delivery of the HRPW at a level III facility guarantees the highest probability of a successful outcome for both mother and infant. The technology of early, precrisis diagnosis of risk in a pregnant woman and/or her fetus at level I care is an area in which major advances are needed. Any advance in early diagnosis should have a major beneficial impact on morbidity and mortality because safe, unhurried transport to a level III facility would be enabled. As soon as high risk is detected in the mother, fetus, or neonate, then rapid air transport technology assumes a role of major importance. The medical transport team is the most important component of the transport service. The training of these transport personnel should include not only the pertinent aspects of Obstetrics, Gynecology, Neonatology, and Anesthesiology, but also the related aspects of Aviation Medicine, Physiology, and Safety. These aviation aspects of training are currently not covered as extensively as they should be. The technology of preflight stabilization and preparation of the HRPW and HRN at the referral hospital is another area in which methodological and/or equipment improvements could shorten transport time and enhance the outcome. Another major component of the transport system is the pilot and his aircraft. Besides appropriate aviation aspects, the pilot's training should include relevant medical, physiological, and equipment aspects of perinatal air transport. With respect to the aircraft, there is universal agreement that exclusive use of large, multiengine, fixed-wing, all-weather types would prevent many of the otherwise adverse potentials of the airborne environment. Rapid door-to-door transport is the helicopter's only major virtue. A third major component of the transport system is the equipment and technology of the airborne environment. Because maternal transport has developed more recently than neonatal transport, in-flight equipment and methods for life support and monitoring functions are not yet as developed as those of the neonate. With the exception of Doppler sensing of heart action, fetal monitoring during transport is nonexistent. Recent developments in the technology of transport isolettes have been a major factor in improving neonatal survivability. Although many significant advances have been made in the neonatal life support and monitoring systems, many more are possible and highly desirable. An improved linkage between the neonate's body temperature and servocontrol of the isolette's thermal system would be highly desirable. In-flight noninvasive monitoring of neonatal arterial pH and Pa_{CO_2}, along with the already available $tcPa_{O_2}$, could provide a formidable defense against exacerbation of hypoxemia and/or acidosis.

APPENDIX

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